

On-line continuous measurement of particle size using electrostatic sensors

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Abstract

The development of a reliable, cost-effective instrument for on-line particle sizing remains a challenging area worldwide. This paper presents the design and evaluation of a new electrostatic sensor combined with a novel digital signal processing algorithm for the on-line continuous measurement of the mass median size of particles in a dilute-phase pneumatic suspension. Key design aspects of the constituent elements of the sensor, including a wire-mesh electrode, signal conditioning electronics and digital signal processing algorithm are described. Experimental results obtained using a typical range of particulate materials demonstrate that, under constant mass flow conditions, the processed output of the sensor is capable of indicating the mass median particle size with a relative error no greater than 15%. A critical appraisal of the technique, including advantages and limitations, is also included.

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1. Introduction

On-line particle sizing plays an important part in many areas of industry. For instance, the size of pulverised fuel used in a coal-fired power plant is an important parameter that affects both combustion efficiency and atmospheric emissions of the plant. Particle size is particularly important in quality control applications, such as in a laser toner plant, but can also be necessary for control of critical aspects of a process—in an explosives plant where the particles of individual chemicals must be of well defined size.

The development of a reliable, cost-effective instrument for on-line particle sizing remains a challenging area. To date there is still no reliable technique available for on-line continuous measurement of particle size. As summarized by Chigier [1], particle sizing instruments that are currently available can be classified into two categories, i.e. laser-based and imaging-based according to their operational principles. These instruments suffer from obvious problems when applied to industrial processes. For instance, the phase Doppler particle size analyser, recognized as being the most

widely used off-line instrument, is inapplicable to many realistic solid particles with aspherical shapes. Imaging-based techniques, including photography, cinematography, holography, videography and tomography, have their inherent drawbacks. For instance, the depth-of-field effect associated with back lighting on the measurement accuracy imposes a serious limitation on the imaging-based techniques. Furthermore, the optical probes of laser-based and imaging-based techniques are unsuitable for installations in a harsh environment such as on a pneumatic conveyor where the optical entry and exit windows are often contaminated due to the accumulation of fine particles on the windows [2]. In addition to the laser and imaging based techniques, other methods for particle sizing have also been proposed such as those based on microwave technology [3] and dielectric techniques [4].

Electrostatic phenomena in particulate processes have been widely exploited in recent years to develop various electrostatic instruments for the measurement of velocity and mass flow rate of pneumatically conveyed particles [5–8]. It is known from previous research that the electrical signal derived from an electrostatic sensor on a pneumatic pipeline contains information about particle size. However, little attention has been paid in the past to extract such information for on-line continuous measurement of particle size. This paper presents the design and experimental

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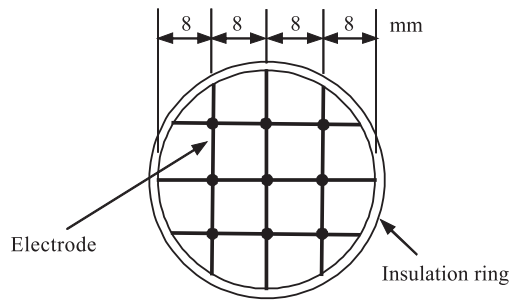


Fig. 1. Electrode.

evaluation of a new electrostatic sensor combined with a novel digital signal processing algorithm for the on-line continuous measurement of the mass median size of particles in a dilute-phase pneumatic suspension. This new technique, once successfully developed, would offer significant advantages over its counterparts including low-cost, low maintenance requirement, easy installation and suitability for application in a harsh environment. Key design aspects of the constituent elements of the sensor, including a wire-mesh electrode, signal conditioning electronics and digital signal processing algorithm are described. Experimental results obtained using common particulate materials are presented. Comparisons between the measured mass median particle size and that obtained using proven off-line particle sizing equipment are made and discussed.

2. Measurement principle

The movement of particles in a pneumatic pipeline generates a certain level of net electrostatic charge on the particles due to particle–particle interactions, particle–wall collisions and particle–air frictions [9]. Although the amount of charge carried on particles is usually unpredictable, the charge can be detected by an insulated electrode in conjunction with a suitable signal processing circuit. The detected charge level can be represented by:

$$V(t) = \alpha \sum q(t) \quad (1)$$

where q is the amount of electrostatic charge carried on each particle, α is a constant depending upon the design of the charge amplifier circuit, and $V(t)$ is the resulting voltage signal. Since the friction and collision of particles in a pneumatic pipeline are entirely random, $V(t)$ is an undeterministic signal. If $V(t)$ is sampled with a suitable sampling frequency, a random discrete sequence $V(n)$ ($n=0, 1, 2, \dots$) is then obtained. From a statistical perspective, it is no doubt that a larger particle must carry higher charge on its surface than a smaller one. In other words, a sequence with a higher magnitude implies larger particles passing through the electrode with a higher probability. This phenomenon forms a fundamental basis of the proposed method for on-line particle sizing. A range of signal processing methods,

including those based on power spectrum analysis, auto-correlation and wavelet transform, may be applied to derive particle size information. In this study, however, a simple time-domain method is proposed and evaluated.

It is known that a random process can be described by its ensemble samples. In order to derive particle size information, a parameter called *particle size indicator* has to be introduced here. Assume $V(n)$ is a sequence of length N within which there are N_1 samples falling in the region $(\bar{V}-k\sigma, \bar{V}+k\sigma)$ and N_2 samples are beyond the region ($N=N_1+N_2$), where $\bar{V}$ denotes the average value of $V(n)$, σ represent its standard deviation, and k is a constant. $k\sigma$ acts effectively as a threshold in the processing of the sequence and k is set to 1.7 in this study, which is determined following an extensive series of experimental tests. The particle size indicator, R , is defined as:

$$R = 10 \log \frac{p_1}{p_2} \quad (2)$$

where $p_1 = (1/N_1) \sum_{n_1} V^2(n)$ and $p_2 = (1/N_2) \sum_{n_2} V^2(n)$ represent the average powers of the two subsequences arising from the original sequence, respectively. It should be noted that R is independent of the dielectric property of the particulate material as it is a ratio between p_1 and p_2 , which are derived from the same signal generated by the same particulate material.

3. Sensor design

Electrostatic sensing elements, or electrodes, can have a number of different shapes some of which are nonrestrictive such as a ring flush with the pipe wall and some are intrusive such as a rod. Although an intrusive electrode disturbs the flow pattern it has advantages over nonintrusive ones such as higher spatial sensitivity and more uniform sensing volume. Fig. 1 shows the geometrical details of the electrode that has been used in this study for on-line particle sizing. The electrode is made up from two mutually perpendicular strands of copper wires of a diameter 0.5 mm with an even spacing of 8 mm between the wires. The electrode is housed in an insulation ring, which is then

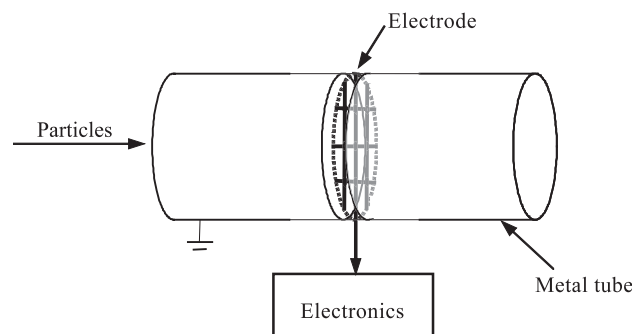


Fig. 2. Electrostatic sensing head.

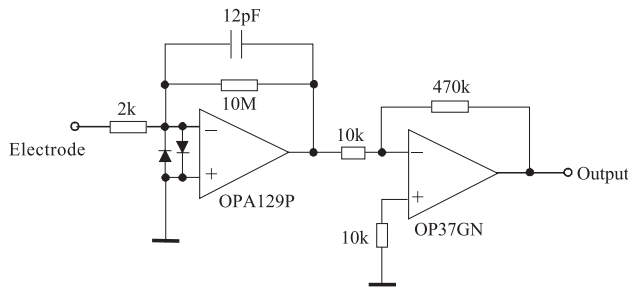


Fig. 3. Signal conditioning circuit.

coupled with two sections of earthed metal pipelines, as depicted in Fig. 2. The electrode is connected to a signal conditioning circuit, which converts the raw electrostatic signal into a voltage signal. A simplified version of the circuit diagram is shown in Fig. 3.

The advantages of using such a restrictive design of electrode are as follows:

- (1) The sensing field created has higher spatial sensitivity and is more uniform than any other forms of electrode such as a rod or a ring [10];
- (2) This design allows the coverage of a large diameter pipe without the loss of sensitivity of the sensing field particularly in the central region of the pipe [10].
- (3) The installation of the sensor is relatively easy due to the simplicity of the electrode [5,6].
- (4) The system would be low in cost and hence highly suited for installation on hostile industrial processes.

This sensor design does, however, have a drawback that the electrode can obstruct the flow of particles in the pipeline and hence suffer from potential wear problems. The degree of such obstruction depends of course on the diameter of the wires used and the spacing between them. In this study, the overall blockage of the pipe cross-sectional area by the sensing grid is less than 7%. This

implies that the probability that the moving particles impact with the electrode will be very low. In view of the dilute nature of particulate flow in the intended industrial situations such as pulverised fuel flow in power station pipelines, the shortcoming of this sensor design is outweighed by its advantages.

It is clear from the above description that the sensing mechanism lies in the combination of the electrostatic inductive effect when the particles pass through the electrode and the triboelectric effect due to the direct contact between the particles and the electrode. As the sensing grid occupies only a small fraction of the pipe cross-sectional area, the electrostatic induction is the dominant interaction in the sensing process. One might suspect that the sensing grid may become contaminated with particles, but this should not cause any significant effect on the particle size measurement.

4. Experimental results

To evaluate the effectiveness of the proposed particle sizing method, a series of experimental tests was conducted on a particulate flow test rig. A schematic diagram of the test rig is shown in Fig. 4. The variation in mass flow rate of particles was achieved by adjusting the feed rate of the vibratory feeder. The air velocity (approximately the particle velocity) in the pipeline could be varied by adjusting the suction fan but in this study a fixed setting was used. The voltage signal from the signal conditioning circuit (Fig. 3) was further amplified, filtered and fed into a PC via an A-to-D converter at a sampling frequency of 5 kHz. Dedicated data acquisition and signal processing software was developed to process the signal for on-line particle sizing. The particulate materials that were tested along with their mass median particle sizes are listed in Table 1. The mass median particle sizes were obtained using a proven off-line particle size analyser (Malvern Mastersizer). All

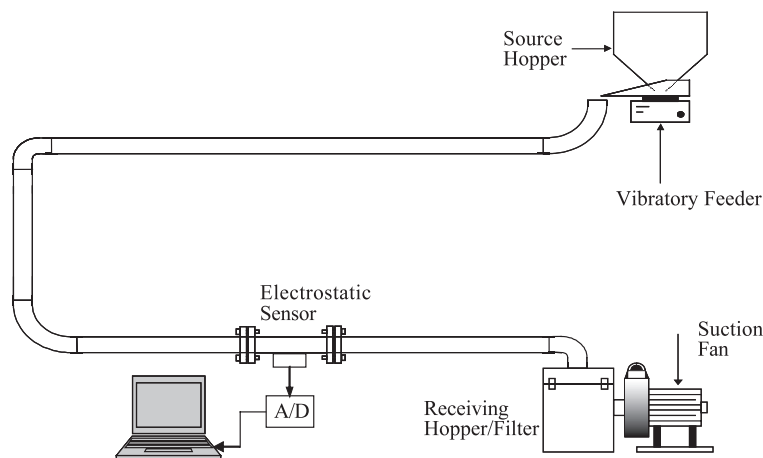


Fig. 4. Layout of the test rig.

Table 1
Materials tested and mass median particle size

Particulate material	Mass median particle size (μm)
F208 cement	98
Builders sand 1	300
Builders sand 2	388
Soda lime beads	619
Pulverised fuel mixed with soda lime beads 1	714
Pulverised fuel mixed with soda lime beads 2	745
Coarse pulverised fuel	913

materials tested had a narrow range of particle size distribution (not mixtures of large particles and fine powder) and were all stored under normal laboratory conditions before being conveyed.

The particle size indicator R obtained using Eq. (2) as a function of particle size for a constant mass flow rate of 1.75 g/s is shown in Fig. 5, where the four legends represent four independent test series conducted. Fig. 5 implies that a monotonous relationship exists between R and the mass median particle size. In order to infer particle size from calculated R during actual measurement, a calibration was necessary. Twenty independent measurements of R for each of the test materials were averaged. Once the calibration was performed, a regression analysis of the data obtained resulted in the following relationship between R and the mass median particle size S :

$$S = -3.47R^2 + 123.61R - 24.38 \quad (3)$$

Eq. (3) is then used in the system software for on-line particle size calculations. To reduce uncertainty in the actual particle size measurement, R in Eq. (3) is replaced with an average of five consecutive instantaneous values. Fig. 6 shows the relative error of 105 independent measure-

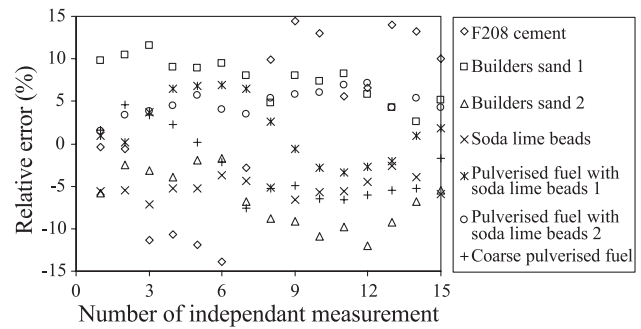


Fig. 6. Relative error in particle size measurement.

ments for all the seven test materials with 15 independent measurements being performed for each material. It can be seen that the relative error is no greater than 15% in all cases. This relatively large error is expected and is known to stem from the dependence of the surface charge carried on the particles on many other factors including chemical composition of the particles, pipe material, humidity and ambient temperature as well as the conditions under which the particles are conveyed.

Further experimental work has revealed that the mass flow rate of particles influences significantly the calibration equation and hence the measurement technique. Fig. 7 shows the results obtained from six independent tests for two different mass flow rates of particles. The relative error in either case is still less than 15%. It appears, however, that R varies with the mass flow rate of particles, suggesting that the calibration equation differs from one flow rate to another. This means that the mass flow rate of particles should be measured in parallel with the particle size measurement in order to achieve on-line particle sizing using this technique. Fortunately, there are established techniques now available for on-line mass flow measurement of particles in a pneumatic suspension

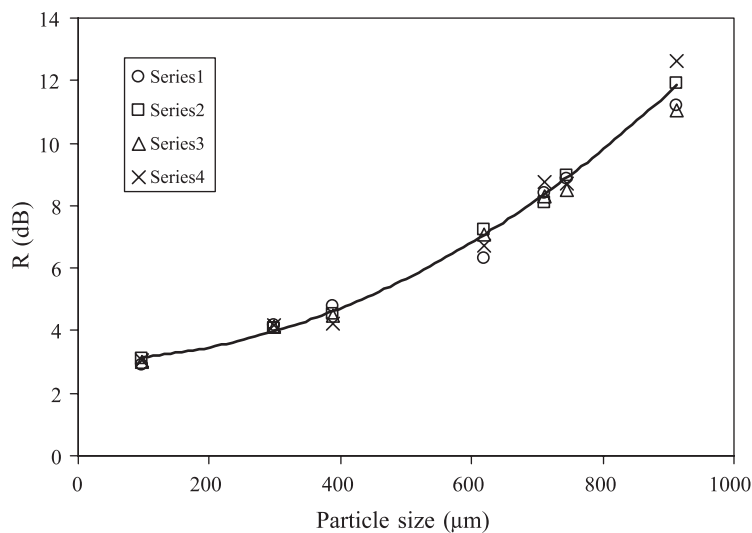


Fig. 5. Variation of R with mass median particle size for mass flow rate of 1.75 g/s.

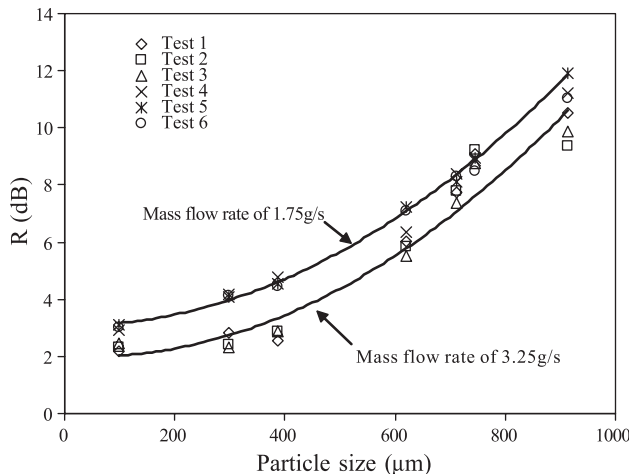


Fig. 7. Variation of R with mass median particle size for two different mass flow rates of particles.

[5,6]. The incorporation of an on-line mass flow sensor in the on-line particle sizing system may well be the best way forward.

5. Conclusions

A new technique for on-line continuous measurement of mass median particle size in dilute pneumatic conveyance has been described. The technique is based on the innovative design of an electrostatic sensor and the implementation of a novel signal processing algorithm. Experimental results obtained using seven particulate materials circulated on a dilute-phase pneumatic conveyor have demonstrated that the new method is capable of producing a parameter that can indicate the mass median particle size with a relative error of no greater than 15%.

The new technique, like any other method of measurement, has obvious advantages as well as drawbacks. One possible drawback is the obstruction of the sensing grid to the particulate flow, which can result in wear problems. Another drawback is that the particle size indicator as

derived from the electrostatic signal is dependent upon the variation in mass flow rate of particles. It is envisioned that the incorporation of an on-line mass flow sensor in the on-line particle sizing system should effectively remove this dependence allowing independent on-line measurement of particle size to be achieved.

List of Symbols

k	constant
n	integer
N	length of a digital sequence
N_1	number of samples falling in the region $(\bar{V} - k\sigma, \bar{V} + k\sigma)$
N_2	number of samples beyond the region $(\bar{V} - k\sigma, \bar{V} + k\sigma)$
p_1	average power of subsequence N_1
p_2	average power of subsequence N_2
q	amount of electrostatic charge
R	indicator of mass median particle size
S	mass median particle size
t	time
V	voltage
$\bar{V}$	average value of V

Greek letters

α	constant
σ	standard deviation of V

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