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# Review of Electrostatic Sensor Applications

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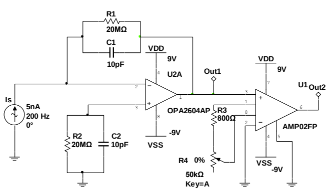
**Graphical abstract**




**Abstract**

Electrostatic sensors have a simple but robust structure, which can detect the electric charge from moving charged particles. Measurement of the dry particle mass flow rate, velocity, and concentration in a conveyor are the main areas of sensor application. This paper considers the measurement methods and techniques that utilize electrostatic sensors for instrumentation. The most significant applications of the sensor are reviewed and a newly developed technique in particle sizing using the spatial filtering method is explained. The results of the study re-emphasize the flexibility, reliability and cost-effective features of the electrostatic sensor for industrial applications.

*Keywords*: Velocity; mass flow rate; concentration; cross-correlation; spatial filtering; particle sizing



## ■1.0 INTRODUCTION

An interesting area in developing reliable and cost-effective instrumentation in particle and powder industries has been the designing of the measurement systems based on electrostatic sensors, which has led to a great deal of research and development in sensor applications. Particle movement inside a pipe or a conveyor produces a small amount of electric charge on the particle surface due to particle-to-particle and particle-to-pipe-wall friction and collision. This charge on the particle surface can be detected using an electrostatic sensor. The magnitude and frequency components of the detected signal depend on the physical characteristics of the particle and its dense flow parameters, such as velocity, concentration and mass flow rate. The particle flow information can be extracted from the electrostatic sensor output signal using suitable signal processing algorithms. Using an electrostatic sensor the velocity of the moving particle can be measured using the cross-correlation technique [1] or the spatial filtering method [2]. The indirect particle mass flow rate measurement method [3], concentration profile mapping using process tomography [4], and particle flow dense mean-size measurement [5] are examples of other studies employing electrostatic sensor capabilities.

This paper provides a review of the electrostatic sensor and its applications, including measurement of mass flow rate, velocity, concentration, particle size, and humidity. Finally, the sensor is investigated for particle size measurement using the spatial filtering method.

## ■2.0 ELECTROSTATIC SENSOR

Electrostatic sensors (electrodynamic sensors) consist of two main parts: the sensor electrode and the signal conditioning circuit. The electrode is a conductive metal that can detect the electrostatic flow noise from a moving charged particle. The charge induced to the electrode needs to be collected and amplified to an acceptable level using a suitable signal conditioning circuit. Then the output signal from the sensor can be sent to a PC using a data-transfer card for signal visualization or further analysis.

Geometric properties of the electrode dramatically affect the output signal magnitude and its frequency. Depending on their areas of application, electrodes are of different shapes, including ring electrodes, pin electrodes and plate electrodes. The electrode can be installed using either the intrusive or non-intrusive method. In the intrusive method, the electrode will be installed inside the conveyor in which it is in direct contact with the particle flow, following the same method as that employed by Rahmat and Lee [6]. In the non-intrusive method, the electrode will be installed within the pipe's circumference [7, 8].

A typical signal conditioning circuit for an electrostatic sensor consists of a signal collector (pre-amplifier) and a signal amplifier. In some applications, such as process tomography, an AC-to-DC converter is added to the circuit to convert the output signal to its equivalent DC level. The signal conditioning circuit deals with a random and a very small range of electric charge fluctuations. Due to the high level of amplification, the sensor is very susceptible to detecting noise from external electromagnetic sources. Figure 1 shows a typical signal conditioning circuit, designed by Tajdari *et al*. [9], which is suitable for a wide range of electric charge detection systems. In this circuit, the electric current source represents the metal electrode; for the pre-amplifier a current-to-voltage converter is employed and an instrumentation amplifier is used for the amplification stage.

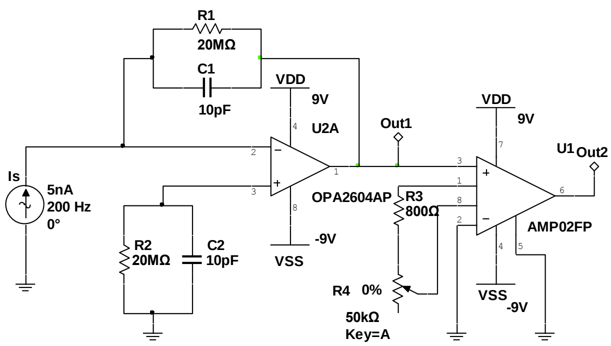



**Figure 1** A typical electrostatic signal conditioning circuit [9]

In designing a measurement system using an electrostatic sensor, it is important to know and analyse the sensitivity and the frequency response of the electrode. Information regarding the electrode's sensitivity and frequency response is needed in making decisions about the amplifier gain and the design of the noise reduction circuit. Figure 2 shows an electrostatic sensor with a ring electrode [9].

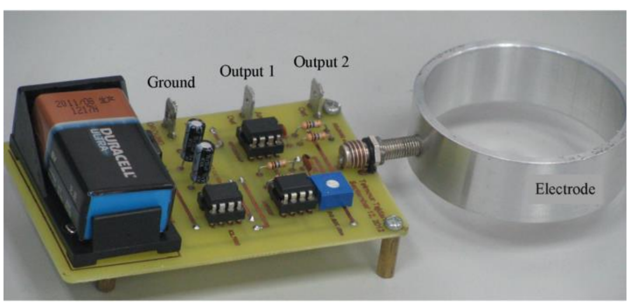



**Figure 2** A typical electrostatic sensor [9]

In sensor applications, the electrode must be installed on a dielectric conveyor which is transparent to the electric field [10]. Then, the electrode will be covered with a grounded metal screen to protect it from the external magnetic field and to protect the sensor wirings from the charge detection of the moving particles inside the pipe.

## 3.0 MASS FLOW RATE MEASUREMENT

In the powder and granules industry, mass flow rate measurement of moving particles in a pneumatic conveyor is one of the important parameters that should be measured and controlled. The amount of electric charge carried by particles in a pipeline has direct relation with the mass flow rate. Detecting and analysing the electrostatic noise will provide relevant information about the particle mass flow rate. The particle mass flow rate in the pneumatic conveyor can be measured in two ways: by the direct method and the inferential method (indirect method).

As explained by Yan [11] and later by Zheng and Liu [12], in the inferential method, mass flow rate at any time is proportional to the product of instantaneous velocity and instantaneous particle volumetric concentration in the pipe cross section. In this method, an electrostatic sensor can be hired either to measure the particle velocity or to measure volumetric concentration or even both. Green *et al*. [13] employed an electrostatic sensor to find both the volumetric concentration using process tomography and the velocity using the cross-correlation technique. Then the mass flow rate map of the pipe cross section is given by multiplying the concentration profile and the velocity for each pixel. Cater and Yong [14] measured the mass flow rate utilizing the indirect method where the electrostatic sensor is used to measure the velocity using the cross-correlation technique, and the volumetric concentration is found by the digital imaging technique.

As described by Zheng and Liu [15], in the direct method, the sensing element is compared directly with the mass flow rate. The particle mass flow rate can be compared directly with the averaged output signal level. Gajewski *et al*. [16] and later Gajewski [17] used a measurement system based on a model in which the average output voltage of the electrostatic sensor is a function of the velocity and mass flow rate. If the velocity is known, the variation in output voltage of the system directly follows the variation in mass flow rate. Figure 3 shows a typical direct method mass flow rate measurement using an electrostatic sensor by Rahmat and Tajdari [18]. In Figure 3, $M_r$ is a variable that represents the variations of the magnitude in the output signal.

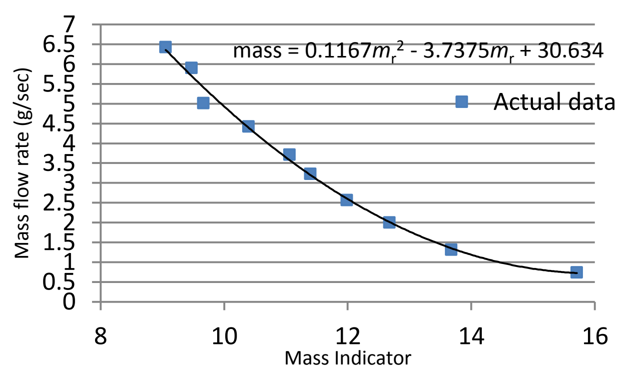



**Figure 3** Mass flow rate measurement using the direct method [18]

However, when the velocity is unknown, the relation between mass flow rate and velocity with the signal quantified characteristics is complex and non-linear. Lijun *et al*. [19] used a novel approach by training a back-propagation neural network to establish the relation between signal characteristics and mass flow rate, and the velocity of the particles; that worked with a measurement error of 20%.

The direct method obviously has a simpler measurement setup than the indirect method. However, when the velocity is an unknown variable, the system shows a large measurement error. In addition, measuring the velocity using other methods eliminates the simplicity advantage of the system. The inferential method is more complex than the direct method, but it can provide useful information about mass flow rate, velocity and volumetric concentration simultaneously.

## ■4.0 VELOCITY MEASUREMENT

Electrostatic sensor applications in particle velocity measurement are the most researched and developed areas for this sensor. The reason is that the velocity variation has a significant effect on the sensor output signal components both in the time domain and the frequency domain. There are two main techniques that use electrostatic sensors for velocity measurement: the cross-correlation technique and the spatial filtering method.

### 4.1 Cross-correlation Technique

The ross-correlation technique uses two identical electrodes on the pipe, aligned and installed in one line along the flow direction over a distance from each other as shown in Figure 4 [6].

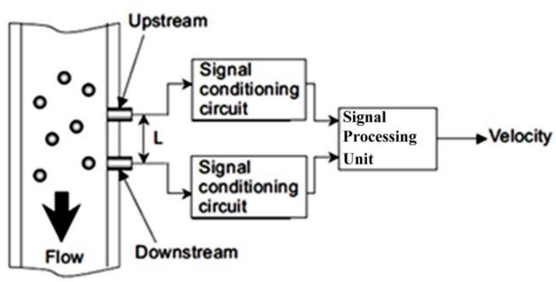



**Figure 4** Block diagram of velocity measurement using the cross-correlation technique [6]

The electrodes are called upstream and downstream electrodes, respectively. The cross correlation of the sensor output gives the transit time taken by the particle to cover the distance between these two electrodes [20, 21]. Velocity can be easily calculated when the distance between the electrodes is known, and the particle transit time is measured. This technique was applied very early by Gajewski *et al*. [22, 23] and later Gajewski [24] for velocity measurement instrumentation in which the electrostatic sensor was used with the ring electrodes. A commercial prototype of a velocity measurement system using the cross-correlation technique was designed by Ma and Yan [25], and the instrument performance was evaluated with different shapes of non-intrusive electrodes. The prototype was tested on the pneumatic particle conveyor which showed a response time of less than 2.5 s and repeatability better than ±2%.

The cross-correlation technique employing electrostatic sensors was used by Yan *et al*. [26] and later by Rodrigues and Yong [27] for strip and cable speed measurement, which is applicable in the electrical and fibre-optic cable industries. To achieve a better accuracy, Xiangchen and Yong [28] and Qian *et al*. [29] used an array of electrostatic sensors instead of applying two electrodes. In this method, cross correlation of the output signals from every two adjacent electrodes is calculated, and then the measurement results are acquired from a data fusion algorithm.

### 4.2 Spatial Filtering Method

The spatial filtering method relates the frequency components of the electrostatic sensor output signal to the particle velocity. Hammer and Green [30] showed that the velocity of the particles passing through a capacitive sensor, which is functionally similar to the electrostatic sensor, has direct relation with the frequency component of the output signal. Yan *et al*. [31] and Gajewski [32] showed that the same relation exists for the electrostatic sensor. Zhang [33] proposed a mathematical model showing that the velocity of a single particle passing through an electrostatic sensor has a direct relation with the frequency at peak of the signal power spectrum density or PSD. In higher velocities, the particle induces the electrostatic noise to the electrode with higher frequency. The method was then developed by Xu *et al*. [34, 35] to be applied in measuring the particle dense flow velocity in a pneumatic conveyor with particle concentrations of $0.067-0.130 m^3 m^{-3}$. The advantage of this method was its simplicity due to using a single electrode. However, in the case of particle dense flow velocity in pneumatic conveyor measurements, this method has a broad spectral bandwidth that reduces the frequency reading accuracy. Xu *et al*. [36] and Li *et al*. [37] proposed a new method based on the spatial filtering technique using two sensor arrays. The sensor arrays together with using a differential amplifier, showed a narrow spectral bandwidth indicating that the frequency at the peak of the PSD is directly related to particle flow velocity [38].

## ■5.0 PROCESS TOMOGRAPHY SYSTEM

Process tomography is an imaging technique that uses an array of sensors around the pipe circumference, and the images produced provide 2D or 3D views of the flow parameters inside the pipe [39, 40]. There are different types of devices that can be used for process tomography purposes, such as capacitive sensors, optic sensors, ultrasonic sensors, CCD cameras, and electrostatic sensors. Due to its non-intrusive nature and simple structure, the electrostatic sensor has been a suitable candidate in process tomography. Figure 5 is a typical electrostatic sensor arrangement for process tomography by Rahmat *et al*. [41].

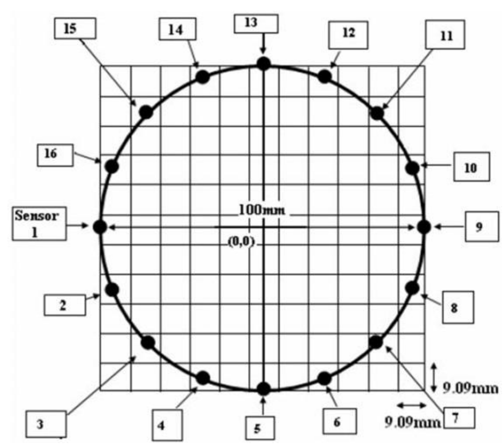



**Figure 5** Sensor arrangement for 11x11 rectangular array maps on a cross section pipe [41]

Green *et al*. [42] used 16 electrostatic sensors to calculate the concentration of the particle flow in a pneumatic pipeline. The back projection algorithm was utilized to provide a 2D image from the measured sensitivity map. The same technique was applied by Rahmat and Rahiman [43] using two arrays of 16 electrostatic sensors to find a 3D velocity profile of moving particles. Machida and Scarlett [44] discussed that the back projection algorithm is unable to distinguish between two adjacent point charges in the detection area. The least-square algorithm with the combination of the back projection algorithm is used to achieve a clearer image.

The research on process tomography using electrostatic sensors follows almost the same hardware setup, and the differences come from the number of electrodes and the type of image reconstruction algorithm. For instance, neural network training has been used to find the type of flow pattern on the pipe cross section [45, 46] or similarly, the fuzzy logic algorithm has been applied by Rahmat *et al*. [47].

## ■6.0 MISCELLANEOUS APPLICATIONS

Mass flow rate measurement, velocity measurement and process tomography imaging have been the most interesting areas of electrostatic sensor application. However, the simplicity and flexibility of the sensor structure has led to some other innovative applications.

Particle mean-size measurement using electrostatic sensors in a particle dense flow conveyor was investigated by Zhang and Yan [48]. Most probably the larger particles carry a greater electric charge. When the particles transfer in a constant velocity and mass flow rate, the variation in particle size will change the magnitude of the sensor output signal. Zhang and Yan [48] used different material to validate the proposed method, and the results show a high measurement error of about 15%, which demonstrates that the material type of the particles affects the measurement results in a magnitude-dependent analysis.

Portoghese [49, 50] worked on monitoring the moisture and drying end point in a bed of fluidized particles using triboelectric sensors. The triboelectric sensor is another name for the electrostatic sensor where the electric charge directly produced by particle impacts and produces friction with the metal electrode. The moisture control is important in powder industries. The electrodes in their study were used to detect the electric charge from the liquid injection to the particles in the drying bed stages. The results showed that the magnitude of the detected charge (in the form of electric current in the sensor output) follows the moisture content in the particle container. Less moisture in the particles results in higher magnitudes of the output signal.

## ■7.0 PARTICLE SIZING USING THE SPATIAL FILTERING METHOD

Particle size measurement based on electric charge measurement has received less attention. The only provided method uses an electrostatic sensor and proposes that the mean size of the particles in a mass flow has direct relation with the electric charge level produced by the moving particles in a pipeline (magnitude-dependent analysis) [48]. Nevertheless, the electric charge level on particle flow can be much more influenced by flow velocity and mass flow rate rather than the particle size. As a result, the small change in flow velocity and mass flow rate easily demolish the entire size measurement results.

The mean size measurement of a single particle in a magnitude-dependent analysis is challenging. At first, hardly two particles with equivalent sizes, material types and densities can produce an equal amount of electric charge on their surfaces. Therefore, they induce different levels of electrostatic noise in the sensor which produces distinct results in the measurement system for two particles of the same size. The problem mostly occurs in the measurement of the particles with dissimilar material types where each of them has specific relative permittivity and different behaviour in an electric field. Second, the electrostatic sensor basically detects the particle as a point charge not as a particle. For example, if we have two particles of different sizes with the same electric charge on their surfaces (a case which may happen due to random processes of particle charging), the measurement system will show that the particles are the same size which would be a wrong result.

To target the above mentioned problems, Tajdari *et al*. [51] proposed methods to deal with both challenges. In order to solve the first problem, the spatial filtering technique was employed. The method undertakes the measurement in the frequency domain, and it is independent from the amount of electric charge on the particle surface. However, the second problem will not be solved merely by using the spatial filtering method. Zhang [33] and later Xu *et al*. [52] showed that in a ring electrode when a particle drops at a different radial position, the frequency at the peak of the frequency spectrum increases when the particle drops closer to the electrode wall. Tajdari *et al*. using this feature proposed that if the particles drop tangential with the pipe wall each particle produces a unique peak frequency which is proportional to the particle size. They used a ring electrode and tested five differently sized spherical particles for which the results are shown in the following figure.

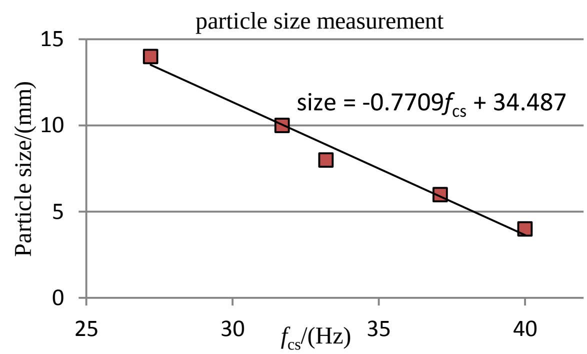



**Figure 6** Particle size measurement results with frequency

Figure 6 shows the relation between the sizes of the particles and the frequency at the crest of the spectrum ($f_{cs}$). The regression analysis provided an equation which gives the particle size in different crest frequencies.

## ■8.0 CONCLUSIONS

From the reviewed studies on the electrostatic sensor, it can be concluded that the sensor has the potential to be used for dry particle mass flow rate measurement in a magnitude-dependent analysis. Among other sensor applications, only velocity measurement using the electrostatic sensor has been developed for real industrial instrumentation. The reason is the measurement for particle velocity is independent from the magnitude of the signal which can vary over the measurement period. Concentration measurement using process tomography showed promising results where the application of the electrostatic sensor can dramatically reduce the instrumentation price. Miscellaneous applications of the sensor include moisture analysis and particle size measurement. The results of the study show that the electrostatic sensor has a simple structure, and its flexibility, reliability and non-intrusive features are promising for industrial applications.

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