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A Review on Electrodynamic Tomography

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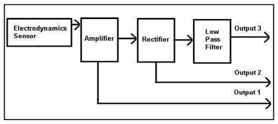
Graphical abstract



Abstract

It has always been in the interest of process industries to image the flow inside pipelines and as such they are always trying to find the most effective way to achieve that purpose. This is an area in which electrodynamic tomography can play a vital role. This paper expounds a review on electrodynamic tomography look at the design of sensors, various types of measurement which have been investigated in the past, and image reconstruction algorithms which have been used with electrodynamic tomography systems.

Keywords: Electrodynamic; sensor; tomography

■1.0 INTRODUCTION

Process tomography is an inexpensive, efficient and non-invasive industrial process imaging method which can be used in many industries for imaging and measurement [1]. The novelty of tomography is that the complexities of structure can be determined without invading the object of interest [2]. Tomography is widely applied in medicine; for example, tomographic scanners are used for the human body. It is also utilized in industrial processes as there is a requirement to directly analyze the internal characteristic of process plant so as to enhance the design and functionality of equipment [3]. Pneumatic conveyors are extensively utilized to transfer pulverized and granular materials from one level to another in process industries involving the handling and control of bulk solids [4]. They are also used as a transportation medium for various industrial processes such as chemical, pharmaceutical, and food.

To obtain high efficiency in the utilization of energy and raw material, it is vital to investigate the parameters such as volumetric flow rate, volumetric concentration, solids' velocity and the mass flow rates. The sensors in an electrodynamic tomography system can detect charge generated by pneumatically pipelines and measure the required parameters [5,6].

Particle movement along a pipeline causes an electrostatic charge to be induced. The charge is detected by an electrode and is converted into voltage. Electrodynamic transducers have been used to determine the velocity of conveyed materials [7, 8], the solids' volume flow rate [9] and to measure the concentration profile of dry powders [10] in pneumatic pipelines.

■2.0 ELECTRODYNAMIC SENSOR

2.1 Sensor

Sensors are the backbone of an eletrodynamic tomography system. As such careful selection and design of electrodynamic sensors is extremely important. Among the factors that should be taken into consideration are the types of sensors, sensor sensitivity and spatial filtering effect. Subsequent subsections will briefly discuss these factors. A block diagram of an electrodynamic tomography system showing the sensor at forefront of the system is shown in Figure 1.

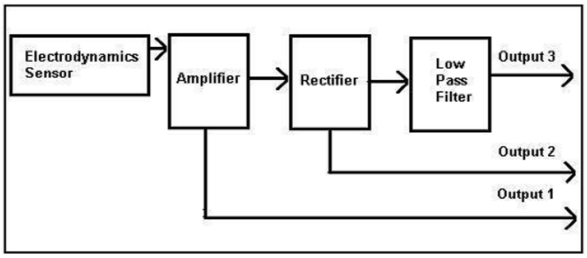


Figure 1 A block diagram of an electrodynamic tomographic system

2.1.1 Types of Sensors

Sensors are suitably located around a pipeline to detect the charge generated by the material moving in that pipeline and enable various measurements to be performed, such as the concentration profile and mass flow rate [11, 12]. Various types of sensors have been designed. Investigations using various shapes of sensors have been carried out using circular or hemispherical, rectangular and ring-shaped sensors [13,14,15]. Machida and Kaminoyama carried out an investigation of three rectangular electrodes of different dimensions involving sensors of 36 mm x 20 mm, 8 mm x 20 mm and 8 mm x 90 mm (Figure 2). From the experiment it was found that the electric current signal from the electrodynamic sensor decreases with the decrease of the surface area of the sensor. It was also found that the length of the sensor changes the signal's characteristics [16].

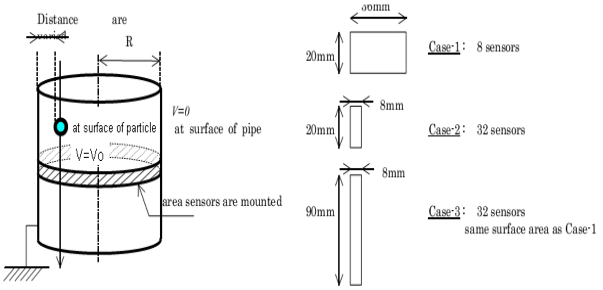


Figure 2 Machida's investigation involving three different sensor sizes

An electrodynamic tomographic system using a ring-shaped electrode combined with a neural network was developed by Yan et al. [17] to perform measurements on the mass flow rate of very small particles in a pneumatic conveying pipeline. They claimed that their system was cost-effective even though their relative measurement errors had a tolerance of 15%, which is quite large. Another investigation making use of a ring-shaped electrode by Zhang and Coulthard [18] resulted in a non-uniform spatial filtering sensitivity. Lower frequency components dominated the output of their system, although they had used wide-band amplifiers. It was observed that the solids that were moving near the pipe wall contributed to the higher frequency components and had higher amplitudes than the solids flowing near the center of the pipe.

Krabicka and Yan [19] made use of rod or discrete electrodes for the flow measurement of pneumatically conveyed solids. Identification of the effective sensing zone of sensors was carried out using a Finite Element Model (FEM) technique. Results obtained from modelling were compared with laboratory tests to cross-validate between them and to quantify the spatial sensitivity and bandwidth of the sensor. The novelty of their research is that it was an investigation the charge induced onto electrostatic sensors based on fitting a Lorentzian curve to the results of a finiteelement model of the electrostatic sensor and pipeline. Validation of the modelling technique was performed by comparing the modelling results of a non-intrusive circular electrode with an established analytical solution.

Peng *et al.* [20] designed a system which made use of eight arc electrodes, two grounded guard rings, a grounded metal screen to prevent electromagnetic interference, and a dielectric pipe in order to isolate the electrodes. From their research, it was observed that the sensitivity near the pipe wall is significantly higher than in other space zones. The greater the length of the electrode, the higher the sensitivity becomes. They also observed that the space position, the length of the electrode and particle velocity all have a significant effect on the temporal frequency characteristics of their system.

2.1.2 Sensor Sensitivity

Several investigations have been conducted to determine the relationship between sensor sensitivity and sensor size [11]. The sensitivity can be determined by carrying out tests using sensors of various sizes and observing the result when sand is dropped past the sensors placed around a pipe [21]. Quantification of the charge level on the flowing sand is difficult. However, the sand was dropped at different flow rates. From the experiment, the graph of average voltage versus flow rate can be plotted, as shown in Figure 3, where the slope of the graph represents the overall sensitivity of the sensor. The electrode sensitivity was obtained by measuring the gain of each electronic amplifier and dividing it into the overall sensitivity of the appropriate channel. The results are summarized in Figure 4, showing that there is a linear relationship between electrode sensitivity and electrode area.

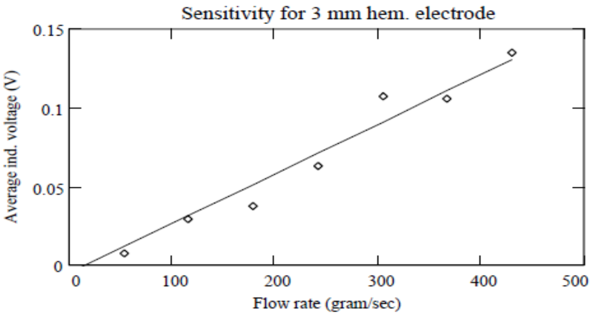


Figure 3 Mass flow rate versus averaged induced voltage using 3 mm hemispherical electrode

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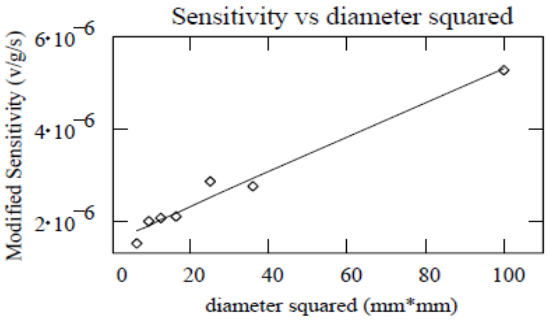


Figure 4 Graph of sensitivity versus electrode diameter squared (hemispherical sensors)

2.1.3 Spatial Filtering Effect

This spatial filtering effect shows the relationship between the size of sensor and the frequency bandwidth of the transducer determined from the frequency response which corresponds to a detectable particle. The velocity of discontinuously flowing material is related to the frequency bandwidth of the sensed signal [20,21]. This concept can be applied in the case of electrodynamic tomography [22].

The experiment shows that the different shapes of electrodes will produce a different spatial filtering effect. To investigate the spatial filtering effect, the frequency response characteristics of a circular electrode give a sinc function response and produce a linear relationship between the cut-off frequency and the circular electrodes A rectangular electrode givesa combination of sinc and cos function response and produces an asymptotic relationship between the cut-off frequency and the rectangular electrodes.

Both sensor sizes are suitable to be applied in process tomography and investigation of solid particle sizing [21].

In order to analyse the spatial filtering effect, the electrodynamic sensor measures the rectified voltage signal. Then the signal will be inverted and converted into the frequency domain using a Fourier transform technique. Various investigations have been conducted concerning the relationship between spatial filtering, and the size and shape of the electrode [6, 11]. In the case of the circular electrode, the response is in the form of a sinc function, whereas in the case of the rectangular electrode, the response is in the form of a combined sinc and cos function. Increasing the length of the rectangular electrode will result in an increase in the cut-off frequency.

■3.0 MEASUREMENT

In an electrodynamic tomography system, measurements are based on the charge being induced in the sensors as they are passed by the flowing charged particles [10]. Then the charges are converted to voltages and amplified before being transferred to a data acquisition system. The signal is then digitized and input into a computer which processes the signal using a suitable algorithm to be displayed on the computer screen. Industries are usually interested in measuring mass flow rates. There are two categories of solid mass flow rates measurement in pneumatic conveying pipelines, which are indirect and direct measurement. For indirect measurement, in order to determine the mass flow rate of solids in the pneumatic conveying system, both the instantaneous concentrations and the instantaneous velocity of solids over the pipe cross-section need to be measured [23].

Rahmat *et al*. [12] developed a system which can validate the results obtained using a digital imaging technique. In their system, a digital imaging technique was used to interrogate the flow in the pipeline around the sensing area using a CCD camera. It was found that there is a good match between the Least Square with Regularization (LSR) method of image reconstruction and image capture bythe CCD camera due to the similarity of both images. This study implies that the LSR method produced images that are stable and accurate as well as applicable for industrial use.

3.1 Velocity Measurement

Cross-correlation analysis or a spatial filtering technique was implemented to measure the velocity of solids in the pneumatic conveying pipeline. Cross-correlation involved calculating the velocity of flow by dividing the distance between the upstream and downstream sensors over the transit time of the fluid flowing through a pair of parallel mounted sensors on the pipelines. The advantage of using cross-correlation is that it cannot be influenced by external factors such as the physical and chemical properties of particles or variations of atmospheric factors such as humidity and temperature [4]. In order to measure velocity, the sensors must be placed upstream and downstream. Some previous works have described the use of electrodynamic arrays for velocity measurement [7,14]. Yan *et al*. [14] claimed that their system which utilized ring-shaped sensors using gravity-fed solids flow has a repeatability of within +/-0.5% over the velocity range of 2-4 m/s for volumetric concentrations of solids no greater than 0.2%. Furthermore, trials using a pilotplant showed that the system can achieve a repeatability better than +/-2% and linearity within +/-2% over the velocity range 20-40 m/s for volumetric concentrations of solids in the range 0.01-0.44%.

Ma and Yan [13] developed electrostatic sensors combined with cross-correlation to measure the velocity of pneumatically conveyed solids with a repeatability of 2% and response time of less than 2.5s over a velocity range of 6-45m/s. Shao *et al*.[24] investigated recent developments of intrusive electrostatic sensors for continuous velocity measurement of solids in a pneumatically conveyed pipeline. With the material of pulverized coal and biomass particles as a test object, an online experimental test was conducted to determine the relationship between electrode dimension, intrusion depth of the sensor and correlation-based velocity measurement. The results summarized that the electrodynamic sensor was capable of providing reliable velocity measurement of pneumatically conveyed solids with good repeatability and a fast dynamic response in an industrial environment.

The spatial filtering technique for measuring particle velocity has the benefit of the simplicity of the measurement system and convenience of data processing. Xu *et al*. [25] measured the mean velocity of solid flow in a pneumatic conveying pipeline utilizing the spatial filtering effect of the electrostatic sensor. The experiments made use of a bench-scale gravity-fed particle flow rig. The results were obtained from an off-line experiment and they claimed that the system repeatability is within ±5% over the velocity range of 2–6 m s^{-1} for concentrations of solid particles in the range of 0.5–6.0%. The following year,Xu *et al*. [26] published results for experiments performed on a pilot dense phase pneumatic conveying rig at high pressure. They applied the spatial filtering method for solid particle velocity measurement based on an electrostatic sensor.The experimental results show that the system repeatability is within ±4% over a gas superficial velocity range of 8.63–18.62 m s^{-1} for a particle concentration range of 0.067–0.130 m^3m^{-3}. Although it is easy to implement data processing of the spatial filtering method to measure velocity [26], the low signal-to-noise ratios make this difficult in dilute phase application [17].

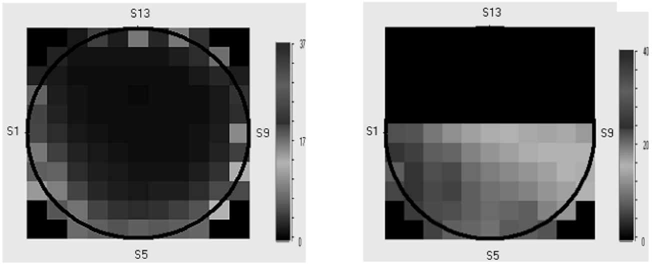
3.2 Concentration Measurement of Solid

It is vital to measure the concentration profiles of particles flowing in pneumatic and gravity conveyors so as to obtain the volumetric flow rates [10]. An image reconstruction algorithm is required in order to display the concentration profile of charge distribution in the pneumatic conveyor. Nonetheless, the ill-posed problems from the sensitivity matrix of forward modellingcreated a problem in scientific computing [27] and had a big impact in industry for the control and monitoring process. As such, image reconstruction was needed to improve the quality of the concentration profile displayed on the computer.

■4.0 IMAGE RECONSTRUCTION ALGORITHM

In order to reconstruct the tomographic images, two aspects must be considered, i.e. the forward problem and the inverse problem. The forward problem generates the theoretical output of every sensor when the sensing zone is two-dimensional and assuming that charge (in coulombs per square meter) is uniformly distributed. The inverse problem has to be solved in order to obtain the profile of charge concentration distribution in the pipeline.

The results of an electrodynamic tomographic system using 16 circular-shaped electrodes were illustrated by Green *et al*. [10]. The sensors detect the charge generated by the particles flowing inside a pipe and subsequently the charge is converted into voltage. The concentration profile was obtained using Linear Back Projection (LBP) based on the measured sensor values. Although LBP is simple, nonetheless it produces a smearing effect which affects the quality of the tomographic images. To minimize this problem, a filter can be applied to the images and this is called the Filtered Back-Projection (FBP) algorithm. The concentration profile based on FBP is attained by combining the concentration profile obtained using LBP with its corresponding filter masks. Rahmat [1] shows that results using the LBP show lower pixel values towards the centre of the pipe. However, the concentration profiles generated using FBP overcame this limitation by applying filter masks to the linear back projection profiles. Samples of Rahmat's results are shown in Figure 5. Figure 5(a) shows the results obtained using LBP, which do not accurately represent a half flow, whereas Figure 5(b) shows the result obtained using FBP, which shows much more clearly the half flow inside a pipe.



(a) (b)

Figure 5 Concentration profiles for half flow at 125 g/s (LBPA) and (FBPA)

Various techniques can be implemented to improve the resolution of images. Among the proposed techniques to improve the image resolution is the use of ring-shaped electrodynamic sensors by combining two methods, namely LBP and the Least Square (LS) method. LBP is accurate in detecting the position of the electrostatic charge and is capable of detecting the size of the object. On the other hand, the limitation of LBP is that it cannot differentiate the location of two charges at different locations. LS has the ability to distinguish charges at two different locations. A combination of these two methods can improve the image reconstruction [10].

An image reconstruction is typically an ill-posed problem. Small fluctuations in the data result in arbitrarily large fluctuation in the solution, and this is reflected in poor conditioning of the matrix sensitivity of the discrete model [28]. The ill-posed inverse problem can be solved using the Tikhonov Regularization (TR) or Least Square with Regularization (LSR) method [27]. This regularization of the problem is needed to minimize the influence of the noise. This method relies on regularization parameters which control how much filtering is introduced by regularization without losing too much data in the computed solution. The aim of regularization optimization is to generate an efficient and numerically stable method which will approximate the desired unknown solution [12]. Investigation of the theory of the ill-posed problem has been presented in many papers [29-31]. Validation of the images can be performed utilizing the digital imaging technique and Singular Value Decomposition (SVD) method [32].From the images it is observed that the LBP algorithm has high concentration values focused on the sensor (the edge of the sensing area) itself, whereas the images obtained using the FBP algorithm show that the concentration is high near the sensor, which reduces the value of charge away towards the centre such that the FBP algorithm cannot differentiate any charges which exist in that area. Generally, both the LBP and FBP methods are unsuitable for industrial processes [5]. The LSR method provides results which show the high concentration area on the image reconstruction. It is identical to the real image recorded by the CCD camera area. This shows that the LSR method is capable of distinguishing two or more charges in the sensing area [32]. Isa *et al*. [33] stated that the LSR method produces better image stability than LBP, FBP and is even better than the results produced by CCD camera.

■5.0 CONCLUSIONS

Electrodynamic tomography is a promising method of imaging various process parameters. There are plenty of opportunities to explore the shapes and sizes of electrodynamic sensors in order to obtain the best result. Although electrodynamic sensors have non-linear characteristics which can affect process monitoring, this limitation can be compensated. One such compensation technique is the use of filter masks corresponding to various flow regimes. The least square method with regularization (LSR) method can improve the quality of the reconstructed image produced in pneumatic conveyors. More work needs to be done to improve the quality of images inelectrodynamic tomography systems.

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