PARTICLE SIZE MEASUREMENT USING ELECTROSTATIC SENSOR THROUGH SPATIAL FILTERING METHOD

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
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MARCH 2014

This thesis is dedicated to my respected parents,
Yarmohammad Tajdari and Malekkhatoon Paydar,
and to my beloved wife,
Fatemeh Tajdari

ACKNOWLEDGEMENT

I would like to thank my supervisor, Prof. Dr. Mohd Fua'ad bin Hj. Rahmat, for his inspirational guidance, selfless service, patience and encouragement, without which the study could not have been possible. His blend of character has been unique and worth emulating.

I also wish to thank my entire family members, my father-in-law and my mother-in-law for their understanding and encouragement during my PhD program. Without such support, my mind could not have been at peace to allow me to concentrate on and carry out the PhD research that has led to this thesis.

My sincere appreciation also goes to everyone whom I may not have mentioned above, including all those who have helped directly or indirectly in the completion of my project.

ABSTRACT

Particle size measurement is important in powder and particle industries in which the particle size affects the productivity and efficiency of the machine, for example, in coal-fired power plants. An electrostatic sensor detects the electric charge from dry particles moving in a pipeline. Analysis of the detected signal can provide useful information about the particle velocity, mass flow rate, concentration and size. Using electrostatic sensors, previous researches studied particle sizing using magnitude dependent analysis which is a highly conditional method where the results can be affected by other parameters such as particle mass flow rate, velocity and concentration. This research proposes a magnitude independent analysis for particle sizing in the frequency domain called spatial filtering method. The solution was started by modeling and analysis of the charge induced to the ring electrode using finite-element analysis to find the sensitivity of electrode. A mathematical model was provided to compute particle position on the radial axis of the electrode and then a new technique was proposed to extract a single particle size from the calculated particle radial position. To validate the proposed method experimentally, a sensor was designed and five test particles ranging from 4 mm to 14 mm were selected for measurement. The results show a 0.44 mm estimation error between the estimated and expected results. The results also show that the method is promising for the establishment of a reliable and cost-effective solid particle sizing system.

ABSTRAK

Pengukuran saiz zarah memainkan peranan yang penting dalam industri serbuk dan zarah, di mana ianya boleh mempengaruhi tahap produktiviti dan kecekapan mesin, sebagai contoh di loji kuasa arang batu. Sensor elektrostatik mengesan cas elektrik dari zarah kering yang bergerak dalam saluran paip. Analisis terhadap isyarat yang dikesan memberikan maklumat yang berguna mengenai halaju, kadar aliran jisim, kepekatan dan saiz zarah. Dengan menggunakan sensor elektrostatik, penyelidikan terdahulu telah membuat kajian terhadap saiz zarah dengan menggunakan analisis magnitud bersandar iaitu satu kaedah yang sangat bersyarat di mana keputusannya boleh dipengaruhi oleh parameter lain seperti kadar aliran jisim, halaju dan kepekatan zarah. Kajian ini mencadangkan satu analisis berdasarkan magnitud bebas untuk mengukur saiz zarah dalam frekuensi domain, iaitu kaedah ruang penapisan. Penyelesaiannya bermula dengan pemodelan dan analisis terhadap cas yang teraruh pada elektrod bentuk cincin dengan menggunakan analisis unsur-terhingga untuk mencari sensitiviti elektrod. Model matematik telah diterbitkan untuk mengira kedudukan zarah pada paksi jejarian elektrod dan satu teknik baru telah dicadangkan untuk mendapatkan saiz zarah tunggal dengan berpandukan kedudukan jejari zarah yang dikira. Untuk mengesahkan kaedah yang telah dicadangkan secara uji kaji, sensor telah direka dan lima ujian yang terdiri daripada zarah yang bersaiz dari 4 mm hingga 14 mm telah dipilih untuk pengukuran. Keputusan menunjukkan ralat anggaran di antara keputusan yang dianggarkan dan diharapkan adalah sebanyak 0.44 mm. Keputusan juga menunjukkan bahawa kaedah ini dapat menghasilkan sistem saiz zarah yang boleh dipercayai dan kos efektif.

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LIST OF ABBREVIATIONS

PC	-	Personal computer
AC	-	Alternating Current
DC	-	Direct Current
2D	-	Two Dimensions
3D	-	Three Dimension
PSD	-	Power Spectrum Density
CCD	-	Charged-Coupled Device
DMA	-	Differential Mobility Analyzer
FEM	-	Finite Element Modeling
FFT	-	Fast Fourier Transform
CS frequency	-	Frequency at the Crest of Spectrum
HV	-	High Voltage
PCB	-	Printed Circuit Board
ESZ	-	Electrical Sensing Zone
OD	-	Outside Diameter
ID	-	Inside Diameter
CAD	-	Computer-Aided Design
DAQ	-	Data Acquisition
SEE	-	Standard Error of Estimation
RMSE	-	Root Mean Square Error
FET	-	Field-Effect Transistor
HHT	-	Hilbert-Huang Transform

LIST OF SYMBOLS

t - Time

m - meter

mm - millimeter

kg - kilogram

k - kilo (1000), Proportionality Constant

M - Mega (10^6)

μ - micron (10^{-6})

n - nano (10^{-9}), Number of Electric Charges

p - pico (10^{-12})

f - Frequency

Hz - Hertz

d_p - Particle Diameter

e - Electric Charge Unit

C_c - Cunningham Slip Correction

λ - Mean Free Pass, Wave Length

r_{inner} - Radius of the Inner Electrode

r_{outer} - Radius of the Outer Electrode

L - Length of the Electrode

x - x axis, Wave Distance to Transmitter

α - Attenuation Coefficient, Constant

A_x - Wave Amplitude in Receiver

A_0 - Wave Amplitude in Transmitter

q - Electric Charge on Particle, Induced Charge to Electrode

Q - Electric Charge on Particle, Induced Charge to Electrode

q' - Induced Charge to Electrode

C - Capacitance, Coulomb (Electric Charge Unit)

s - Second, Laplace Notation, Surface Notation

A - Ampere, Constant

R - Resistance

R_f - Feedback Resistance

C_f - Feedback Capacitance

F - Farad

I_s - Electric Current

W - Axial Length

θ - A selected Angle

ϕ - Electric Potential

U - Output Voltage

τ - Time Constant

σ - Charge Density

∇ - Del Operator

ρ_v - Volume Charge Density

ρ - Volume Charge Density

Γ_s - Boundary Conditions for Metal Screen

Γ_e - Boundary Conditions for Electrode

Γ_p - Boundary Conditions for Pipe

r_0 - Radius of the Particle, Initial Radial Distance to Rotation Axis

r - Distance from Center of the Particle, Distance from Center of the Ring electrode, Particle Radial Position

ε_0 - Electric Permittivity for Free Space

f_{cs} - Frequency at the Crest of the Frequency Spectrum

D - Particle Diameter, Electrode Diameter

η - Fluid Viscosity, Air Viscosity

ρ_s - Density of the Solid

ρ_f - Density of the Liquid

g - Gravity Acceleration, Constant

V - Voltage
v - velocity
ω - Angular frequency
ϖ - Angular frequency
r_f - Final Radial Distance to Rotation Axis
Z_p - Electrical Mobility
E - Electric Field
Q_s - Air Flow for Aerosol-Free Air
Q_a - Air Flow for Positively Charged Aerosols
$S(x)$ - Electrode Sensitivity in x axis
$S(z)$ - Electrode Sensitivity in z axis
$S(r)$ - Electrode Sensitivity in r axis
$i(x)$ - Electrostatic Noise
$h(t)$ - Impulse Response
$H(f)$ - Frequency Response
$P(\varpi)$ - Sensor Frequency Response
$T(\varpi)$ - Sensor Frequency Response
$H_r(\varpi)$ - Electrode Frequency Response
b - Axial Length
f_c - Cutoff frequency
C_d - Capacitance between Particle and Electrode
C_e - Capacitance between Particle and Electrode
r_d - Input Resistor of the Pre-Amplifier
R_a - Input Resistor of the Pre-Amplifier
C_n - Capacitance between Electrode and Ground
r_n - Resistance between Electrode and Ground
r_1 - Gain adjusting Resistor of the Amplifier
r_2 - Gain adjusting Resistor of the Amplifier
a - Sensitivity Equation’s Constant
b - Sensitivity Equation’s Constant

c	-	Sensitivity Equation’s Constant
d	-	Sensitivity Equation’s Constant
$f_{\max}$	-	Frequency at the Crest of the Frequency Spectrum
v_m	-	Velocity
$\vec{D}$	-	Electric Flux
ε_r	-	Relative Permittivity
C_a	-	Input Capacitance of Pre-Amplifier
r_p	-	Pipe Radius
r_r	-	Ring Electrode Radius

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CHAPTER 1

INTRODUCTION

1.1 Motivation and Introduction to Electrostatic Sensor

One of the interesting areas to develop a reliable and cost-effective instrumentation in particle and powder industries have been designing the measurement systems based on electrostatic sensors, which has led to a great deal of research and development on the sensor application. 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 component of the detected signal depends on the physical characteristics of the particle and its dense flow parameters such as velocity, concentration and mass flow rate. The particles flow information can be extracted using suitable signal processing algorithms from the electrostatic sensor output signal. Using the electrostatic sensor the velocity of the moving particle can be measured using the cross-correlation technique (Xu *et al.*, 2010b) or the spatial filtering method (Xu *et al.*, 2013). Particles' mass flow rate measurement in direct method (Gajewski, 1999a), concentration profile-map utilizing process tomography method (Rahmat *et al.*, 2009c), and particle flow dense mean-size measurement (Zhang and Yan, 2003) are some other studies that employed the electrostatic sensor capabilities.

This research deals with the electrostatic sensor application to measure the mean-size of a single particle. To the sensor, a particle seems as a point charge and particle size does not mean anything to the sensor. A new technique is proposed and studied in detail to acquire the particle size information utilizing electrostatic sensor.

1.2 Electrostatic Sensor

Electrostatic sensor (electrodynamic sensor) consists of two main parts which are 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 using a suitable signal conditioning circuit to an acceptable level. Then the output signal from the sensor can be sent to a PC using a data-transfer card for signal visualization or further analysis.

Geometrical properties of the electrode dramatically affect the output signal magnitude and its frequency. Depending on their area of application, the electrodes are designed in different shapes including ring electrode, pin electrode and plate electrode. 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 (2004) in their study. In the non-intrusive method, the electrode will be installed in the pipe circumference (Gajewski, 1999b).

A typical signal conditioning circuit for 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 detect the noise from external electromagnetic sources.

Sensitivity of the electrostatic sensor describes the ability of the electrode in detecting the electric field strength at any point within the space. It can usually be described as the ratio of the charge induced to the electrode over the total charge existing in the source (Xu *et al.*, 2007). The sensitivity of the sensor is highly dependent upon the physical properties of the electrode, especially the size and physical geometry of the electrode. In addition, it is a function of the electric charge location in the coordinate system. When the electrode sensitivity is considered against particle location within the space, it is usually called the electrode spatial sensitivity. The electrode sensitivity can describe the electrode spatial filtering effect.

Spatial filtering effect of the sensor describes the frequency bandwidth properties and the frequency response of the sensor electrode. It has a direct relation with the size and shape of the electrode. In fact, a moving particle remains for a longer time in the electrode detection area with longer axial length. As a result, the induction to a bigger size electrode happens in smaller frequency and vice versa.

In designing a measurement system using an electrostatic sensor, both sensitivity and spatial filtering effect of the electrode are important to be known and analyzed. Information regarding the electrode sensitivity and frequency response is needed in making decisions about the amplifier gain and the design of the noise reduction circuit.

1.3 Research Background

In the industries that deal with particle conveyors, the measurement of particle flow parameters is important to control the machine productivity and efficiency. These parameters can be the amount charge on particles, velocity, mass flow rate, particle size, and humidity. For instance, in coal-fired power stations the particle size, flow velocity and mass flow rate of pulverized fuel are important to be measured and monitored in order to control the combustion quality. This control will result in better productivity of the burner and to higher efficiency in energy consumption.

Electric charge in a particle is a single parameter that can provide a great amount of information regarding the particle behavior when it is moving in a pipeline. Due to its simple and robust structure, electrostatic sensor is a good candidate for use in the dusty and harsh environment of such industries. This section is dedicated to a brief background about the electrostatic sensor application in two-phase flow measurement systems.

1.3.1 Mass Flow Rate Measurement

In powder and granule 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 analyzing the electrostatic noise will give decent information about particle mass flow rate. The particle mass flow rate in the pneumatic conveyor can be measured in two methods, namely direct method and inferential method (indirect method).

As explained by Yan (1996) and later by Zheng and Liu (2010), in an 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, electrostatic sensor can be hired either to measure the particle velocity or to measure volumetric concentration or even both. Green *et al.* (1997a) have employed an electrostatic sensor to find both the volumetric concentration using process tomography and the velocity using 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. Carter and Yong (2005) have measured the mass flow rate utilizing the indirect method where the electrostatic sensor is used to measure the velocity using cross correlation technique, and the volumetric concentration is found by digital imaging technique.

As described by Zheng and Liu (2011), 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.* (1993a) and later Gajewski (1996b) invented and developed a measurement system based on a model in which the average output voltage of the electrostatic sensor is a function of velocity and mass flow rate. If the velocity is known, the variation of output voltage of the system directly follows the variation on mass flow rate. However, when the velocity is unknown, the relation between mass flow rate and velocity with the signal quantified characteristics are complex and nonlinear. Lijun *et al.* (2005) 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 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.

1.3.2 Velocity Measurement

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

Cross-correlation technique uses two identical electrodes on the pipe, aligned and installed in one line along with the flow direction over a distance from each other. The electrodes are called upstream and downstream electrodes, respectively. The cross-correlation of the sensor output gives the transit time that takes the particle to pass the distance between these two electrodes (Yan and Ma, 2000). Velocity can be easily calculated when the distance between the electrodes is known, and the particle transit time is measured. The very early application of this technique was incorporated by Gajewski *et al.* (1990) and Gajewski *et al.* (1993b) and later Gajewski (1994) 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 (2000), and the instrument performance was evaluated with different shapes of non-intrusive electrodes. The prototype is tested on the pneumatic particle conveyor which showed a response time less than 2.5 s and repeatability better than ±2%. The cross-correlation technique employing electrostatic sensors was used by Yan *et al.* (2010) and later by Rodrigues and Yong (2012) for strip and cable speed measurement, which is applicable in electrical cable and fiber-optic cable industries. To achieve a better accuracy, Xiangchen and Yong (2012) and Qian *et al.* (2012) instead of applying two electrodes, used an array of electrostatic sensors. In this method, the output signals from every two adjacent electrodes cross correlated, and the output resulted from a data fusion algorithm.

Spatial filtering method relates the frequency components of the electrostatic sensor output signal to the particle velocity. Hammer and Green (1983) 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.* (1995) and Gajewski (1996a) showed that the same relation exists for the electrostatic sensor. Zhang (2002) proposed a mathematical model that showed the velocity of a single particle passing through an electrostatic sensor has 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.* (2008) and Xu *et al.* (2009) to be applied to measure particle dense flow velocity in a pneumatic conveyor with particle concentration of $0.067-0.130 m^3 m^{-3}$. The advantage of this method was its simplicity due to using a single electrode. However, this method has a broad spectral bandwidth that reduces the frequency reading accuracy. Xu *et al.* (2012b) and Li *et al.* (2012) proposed a new method based on spatial filtering technique using two sensor arrays. The sensor arrays together, along 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.

1.3.3 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 view of the flow parameters inside the pipe. There are different types of devices that can be used for process tomography purpose, such as capacitive sensor, optic sensor, ultrasonic sensor, CCD camera, and electrostatic sensor. Due to its non-intrusive nature and simple structure, the electrostatic sensor has been a suitable candidate in process tomography.

Green *et al.* (1997b) 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 (2001) using two arrays of 16 electrostatic sensors to find a 3D velocity profile of moving particles. Machida and Scarlett (2005) 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 get a clearer image.

The researches on process tomography using electrostatic sensor follow 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 the flow pattern on the pipe cross section (Rahmat and Sabit, 2004, 2007) or similarly, fuzzy logic algorithm has been applied by Rahmat *et al.* (2009b).

1.3.4 Miscellaneous Applications

Mass flow rate measurement, velocity measurement and process tomography imaging have been the most interesting areas for the 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 sensor in a particle dense flow conveyor was investigated by Zhang and Yan (2003). Most probably the bigger size of particles carries a larger amount of 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 (2003) used different material to validate the proposed method and the results did not show a measurement error larger than 15%.

Portoghese (2005, 2008) have worked on monitoring the moisture and drying end point in 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 impact and 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 drying the bed stages. The results showed that the magnitude of the detected electric charge (in the form of an electric current in the sensor output) follows the moisture content in the particle container. Less moisture of particles results in higher magnitudes of the output signal.

The following flow chart shows the electrostatic sensor applications and research areas which were discussed throughout this section.

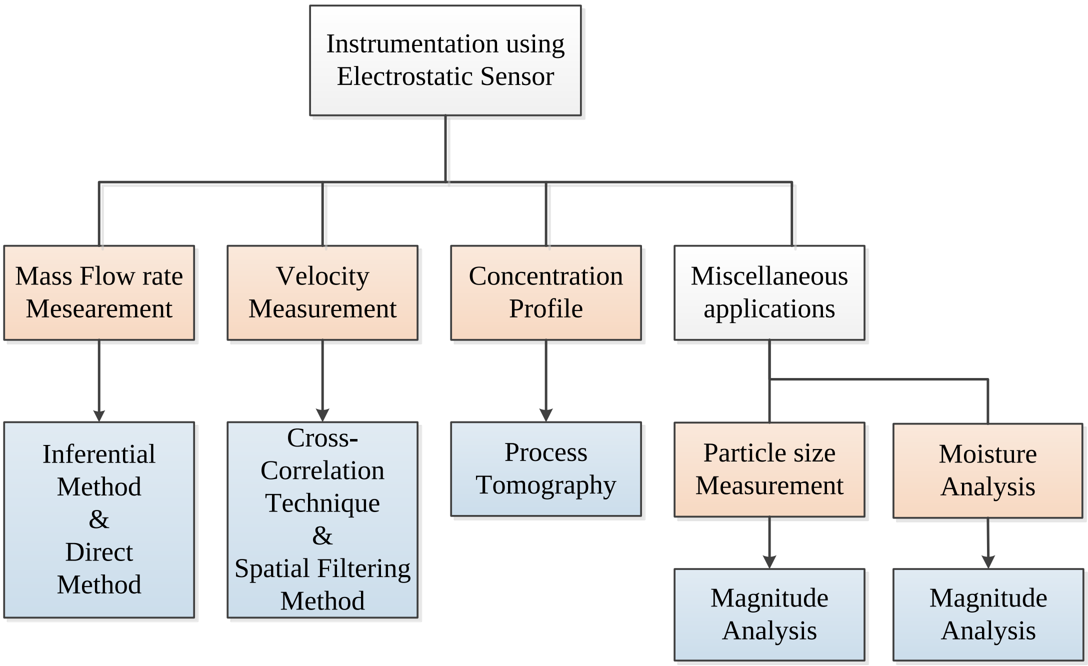

Figure 1.1 Application and research areas for the electrostatic sensor

Three main areas of research for the sensor are mass flow rate, velocity, and concentration measurement. Particle size measurement and moisture analysis are categorized as miscellaneous applications because fewer research works have been done on these subjects.

1.4 Problem Statement

Instrumentation based on monitoring electric charge variations in a particle or in a particle dense flow using electrostatic sensor is well-developed and researched. The sensor has been mostly utilized for velocity measurement using the cross correlation as well as the spatial filtering techniques. Even the commercial version of the instrument is available (Yan and Ma, 2000). Other applications for the sensor so far include the measurement of mass flow rate and concentration profile using direct method and process tomography. Alongside the velocity and mass flow rate measurement, the particle size can affect the particle charging process. From that idea, there have been methods and research studies developed using the electric charge on a particle as a variable for particle size measurement.

There are two methods that employ particle charge properties to measure particle size. One of the methods is called the Differential Mobility Analyzer or DMA, which uses the electric mobility properties of charged aerosol to find size distribution of the aerosols within the air. The technique is well-researched and developed in both academic area (Guha *et al.*, 2011) and commercial models (Intra and Tippayawong, 2007). However, the method is limited to only aerosols and micron sized particles. The area for large particle size measurement based on the electric charge measurement has received less attention. The only provided method uses an electrostatic sensor and proposes that the mean size of particles in a mass flow has direct relation with the electric charge level produced by moving particles in a pipeline (Zhang and Yan, 2003). 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 on 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 get an equal amount of electric charge on their surface. 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 behavior 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 same electric charge on their surface (the case which may happen due to random processes of the particle charging), the measurement system will show that the particles are the same size which would be a wrong result.

To target the mentioned problems, this study is proposed which has pursued a new technique to deal with both challenges. In order to solve the first problem, the spatial filtering technique was employed. The method performs 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. A new modeling technique in conjunction with spatial filtering method is introduced to form a complete solution for the problem.

1.5 Research Objectives

The main purpose of this research work is to measure the mean size of a single particle using electrostatic sensor. To reach this purpose, the following objectives are defined for different steps of the work:

(i) To design the electrode and the signal conditioning circuit of the sensor and to find its sensitivity properties.
(ii) To formulate the frequency response of the electrostatic sensor.

(iii) To formulate a mathematical model that provides the particle size information through spatial filtering method.

(iv) To validate the proposed method via the experimental approach.

The proposed technique will be based on spatial filtering method where the measurement principles result from output signal analysis in the frequency domain. Mathematica software was used to verify modeling equations and Ansoft Maxwell software will be used for field simulation. Ansof Maxwell uses Finite-Element Modeling method for field analysis. Excel and FindGraph software programs are utilized for plotting the graphs and for regression analysis. Multisim software is applied for design and analysis of the signal conditioning circuit. Dewetron data transfer card and DEWESoft software are employed for data collecting purposes in experimental tests.

1.6 Research Scope and Limitations

As the Project scope, the current electrostatic sensor applications and developments were studied. The information about the present technologies for particle sizing and the methods to measure the electric charge on particles were collected. The electrostatic sensor design, the methods to model the charge induced to the electrode and the spatial filtering effect of the electrode and spatial filtering method were investigated. To implement the proposed method, the sensor electrode and signal conditioning circuit were designed. The mathematical modeling of the frequency response of the sensor and relation between particle radial position and the frequency at the crest of the frequency spectrum (f_{cs}) were conducted to find the relation between particle size and f_{cs}. Finally, the proposed method was validated using the experimental tests.

However, the system is limited for the round particles. The accuracy of the measurement system is limited by the resolution frequency spectrum. The system cannot measure non-chargeable particles; nevertheless, the particle does not need to be charged by an external source. When small sized particles (<1mm) drop tangent to the pipe wall, the electric charge on the pipe body either attracts or repels the electric field on the particle body which makes a drift on particle direction. Shielding the pipe reduces this effect, but it does not eliminate it completely. Directing the particles through the air flow would be a better solution. The particle does not need the external charger; however, the system cannot measure non-chargeable particles.

1.7 Research Contributions

The main contributions of this research are as follows:

(i) The mathematical model is provided to explain a ring electrode behavior in the frequency domain when a particle moving in a radial direction.
(ii) A new technique is introduced to provide the particle size information through spatial filtering method.

The design of the sensor included a ring electrode and signal conditioning circuit design. To monitor the electrode behavior in an electric field, a field simulator was employed to find the sensitivity of the sensor. The sensitivity of the sensor for different radial position of particle was recorded. The mathematical modeling was performed to find the relation between particle radial position and output frequency and in the same manner between particle size and output frequency. A gravitational test rig was designed, and the experimental results were compared with modeling results.

1.8 Thesis Outline

Chapter 1 provided a brief introduction of the entire research. Motivation and the reasons for conducting the research are explained. The structure and the modus operandi of the electrostatic sensor are described. A brief background of the electrostatic sensor application is provided. The problem statements highlighting the existing problems in particle sizing using electrostatic sensor are given in detail. The research objective and project contribution to previous studies are provided.

Chapter 2 presents a concise literature review that consists of two main parts. In the first part, the most common methods in particle sizing are reviewed. The methods include physical methods, laser diffraction, imaging method, DMA, Coulter counter and miscellaneous methods. The second part is dedicated to everything about the electrostatic sensor in detail. The methods for electric charge measurement are described, the electrostatic sensor design is explained, and the methods to mathematically model the sensor are provided. In the last part, the spatial filtering effect and frequency properties of the electrode are described in detail.

Chapter 3 focuses on the measurement principles. Mathematical models, simulation process and hardware setup for experimental test are explained in this chapter. The mathematical models describe the spatial sensitivity of electrode, frequency response of electrode and frequency response of the sensor. The simulation procedure incorporated in finding the amount of the charge induced to electrode using the FEM field simulator is described in detail. The signal conditioning circuit design is explained. Lastly, the proposed method to find the particle size in the frequency domain is provided.

In chapter 4, the mathematical modeling results and experimental results are explained in detail. The chapter begins with the electrode design. The spatial sensitivity equation of the electrode is mathematically calculated. The spatial filtering effect and the electrode frequency response are analyzed. The sensor frequency response is calculated. The chapter closes with detailed explanation of the particle sizing algorithm, and the results from mathematical modeling and experimental tests are provided to validate the proposed method.

Chapter 5 presents the conclusion and possible future works. In this chapter, the contributions of this research work are explained. The limitations of this research as well as the suggested solutions are described. Finally, two proposals are suggested as future works which can develop the basic idea of particle size measurement used in this research.

1.9 Summary of the Introduction

Electrostatic sensor is widely researched for use in powder and particle industries. It is a robust sensor which consists of two main parts: the sensor electrode and signal conditioning circuit. The most important part of the sensor is the electrode whose geometrical shape and size determine the spatial sensitivity and spatial filtering effect of the sensor. The electrostatic sensor is studied to be used in mass flow rate measurement, velocity measurement and in process tomography. In this research, the application of electrostatic sensor was investigated in particle size measurement. A new technique which uses the spatial filtering method for particle size measurement was introduced. The proposed method is validated using mathematical modeling and experimental tests.

This chapter is started with explaining the motivations of doing the research. A brief explanation is provided about the electrostatic sensor structure. In the research background, the applications of the sensor are reviewed. These include mass flow rate measurement, velocity measurement, process tomography and two miscellaneous applications. The remaining parts of this chapter were dedicated to the research problem statement, the research objectives, the research scope and the research contributions. At the end, the thesis outline is provided.

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