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Finite-element method modeling in 4 and 16 sensors electric-charge tomography systems for particles moving in pipeline

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ABSTRACT

Tomography determines the distribution of materials by the use of sensors that captures information on the materials in regions of interests such as cross-section of pipelines or process vessels. In this paper, system equation for the 4 and 16 sensor systems is derived based on the Cartesian coordinate system, the elements' technique of the finite-element method, Gauss's and Coulomb's theories. The derived equation relates the electric charge distribution in a pipeline cross-section and the installed sensors at the periphery of the pipeline. From the developed system equation, sensitivity matrices for the two systems resulting from the assumed spatial electric-charge distribution on the pipeline cross-section were made. The developed sensitivity matrices of the two systems were in turn used for the reconstruction of the tomography images or concentration profiles of the moving particles across the pipeline cross-section. This research is carried out in order to explore the possibilities of reducing the 8 to 32 electrodynamic sensor systems that are normally used in electric charge tomography systems. A comparison between the reconstructed images of the 4 and 16 sensor systems was made, and the results show that the 16 sensor system produced more accurate images than the 4 sensor system. Nevertheless, the 4 sensors' system could be used in quantitative applications.

1. Introduction

Many industries utilize pneumatic pipeline conveying techniques for transportation of bulk solid materials from one point to another [1]. One of the advantages of pipeline conveyance is that it reduces operational risk, because transportation of materials is done remotely from safe points to hazardous points or vice versa. The practical applications of the pipeline conveyance are in the transportations of coal in coal power plants, cement powder in cement industries, flour and grains in food processing industries, etc. In order to optimize the production efficiencies of these industries; information on material bulk flow rate, velocity, particle sizes and concentration profiles of the convey materials is necessary [2]. To obtain this information, several methods of measurements that avoid physical contact with measured materials have been proposed such as electrical (capacitance, electrostatic, impedance, and electromagnetic), optical, attenuation, process tomography, and nuclear magnetic resonance, with each having its advantages and disadvantages [3].

The tomography determines the distribution of materials in some region of interest [4] such as cross-section of a pipeline, process vessels, etc., by the use sensors that capture information on the convey materials or processing. However, in the case of solid particle movement, the interaction between the particles and the conveying gas, and the pipeline wall create electrostatic charges on the moving particles [5]. When the charged particles pass through the sensing zone, the installed electrodynamic sensors detect the electric charges on the particles, leading to induce charges on the sensors [6]. Consequently, flow parameters, such as velocity, bulk, mass flow rate, size and tomographic images of the charged flowing particles can be obtained through the suitable electrostatic sensors in conjunction with the appropriate signal processing, analyzing equipments and technologies [7–9]. It is worth to note that the dominant sensors in process tomography are capacitive and electrodynamic, which have different sensing phenomena. The electrodynamic sensing feature is based on the effect of the electric field on the sensor electrode due to electrical charges in the sensing zone. Machida and Scarlet [10] have established that "the finite time flight of a charged particle is equivalent to a finite current in electromagnetism, which is a source of magnetic field which generates electrical flux that induces charge on the sensor electrodes". It is the electric field effect that derives the charges in the sensor electrodes of the electrodynamic sensors, thereby converting charges into the voltage signals which are captured by the data acquisition equipment and used for the tomography image reconstruction. Since the sensing techniques

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of the electrodynamic sensors in solid particles flow are based on magnetic and electric fields, created by the charges on the flowing solid particles, the permittivity of the medium and the conveying pipeline is not a factor to be considered as can be seen in the development of the system equation reported in [11] that is used in this paper. On the other hand, the capacitive sensing phenomenon is based on the permittivity of the sensing zone, which changes with change in the permittivity of the medium. The change in the permittivity of the medium of interest (conveying pipeline cross-section) is due to the permittivity of the material to be measured, and is the subject of interest in the capacitance tomography system. An intensive research has been conducted on the effect of shielding on capacitance sensor's response in tomography [12] in which the results have shown that the permittivity of the conveying pipeline is a considerable factor.

Finite-element method (FEM) is an application of finite-element analysis (FEA) for finding approximate solutions of integral and partial differential equations. The benefits of FEM include improved standard of designs and methodology of an industrial process [13]. These benefits of FEM have not been much explored in the field of process tomography, especially electric charge tomography (EChT) system. However, FEMs were employed in other tomographic imaging, where software packages were used for modeling, as reported in [14–17] but not on electric charge tomography imaging. The available works on electric charge tomography using FEM [5,18,19] are mostly on flow parameters such as velocity, mass flow rate and parameter selections. In those applications, the FEM software packages were used for automatic mesh elements generation and analysis in which the generated mesh elements covered everywhere around the domain which includes the whole reference pipe-section which is not necessary in tomography, which requires only cross-sectional distribution of the flowing or process materials.

One of the problems of tomographic imaging of multiphase flow is the good quality of the resulted charge distribution within the measurement domain [20]. In order to improve the qualities of the electrodynamic tomography images, various efforts have been made, among which is the work of Machida and Kaminoyama [6], in which they proposed more sensors to obtain better tomography image. The implications of more sensors in a system are high cost, design sophistication and possible weaken of the test points. Too many protruded sensors around a test point may make the test point to be a potential point of system failure, due to the dynamism of normal industrial environment. Other efforts were also made to improve the quality of the tomography images using Neural Network [21] and Fuzzy logic [22], with no specific solution to problem of charge distribution. In this paper tomography images of particles moving through a pipeline were reconstructed by the use of the 4 and 16 electrodynamic sensor array. In the reconstruction of the images, a two dimensional induced charge model for each of the 4 and 16 arrays of electrostatic sensors that are installed around a pneumatic conveying pipeline were made. The system equation derived in [11] is used to develop the electric charge spatial sensitivity matrices for the 4 and 16 sensors' systems as well as the sensitivity maps of their problem domains. The maps were developed to demonstrate the sensitivity of the sensors to the charges carried by the moving particles. The matrices were used to reconstruct the concentration profile of the moving particles by applying the Pro-Rata Distribution Method (PRDM) detailed in [23]. The objective of the paper is to explore the possibility of using fewer sensors for determination of the concentration profile of moving solid particles across the conveying pipeline's cross-section, which could be applied in the relevant industries.

2. Methodology

2.1. The sensor configuration

The schematic diagrams of the sensor configurations used in the modeling of the two systems are shown in Fig. 1, which is for the 4 sensor system, where the electrodynamic sensors are installed equally spaced on the circumference of a pipeline cross-section. Similar configurations was also used for the 16 sensor system. The electrode protrudes through the outer surface of the pipe cross-section and flushes along the inner surface.

2.2. Discretization of the sensing domain into finite elements

The FEM requires the subdivision of the problem domain into many subdivisions, and each subdivision is called a finite-element or computational mesh [24,25]. In this paper, the Matlab program was developed and used to mesh the sensing zone into triangular-shaped elements. The elements are the image pixels of the tomography imaging system. The developed program also installed and spaced the electrode sensors equally around the circumference of the pipe. Fig. 2 shows the schematic diagram of the 4 sensors' system, showing the meshed domain with the 4 sensors installed. Fig. 2 also shows one of the meshed elements being exaggerated and a reference sensor with their central Cartesian coordinates respectively.

2.3. The mathematical modeling

The modeling of the system equation involved a formulation of the relationship between the electrostatic fields due to the charges in each finite-element as sensed by the installed sensors as shown in Fig. 2. According to Green et al. [26], the presence of charge/s at

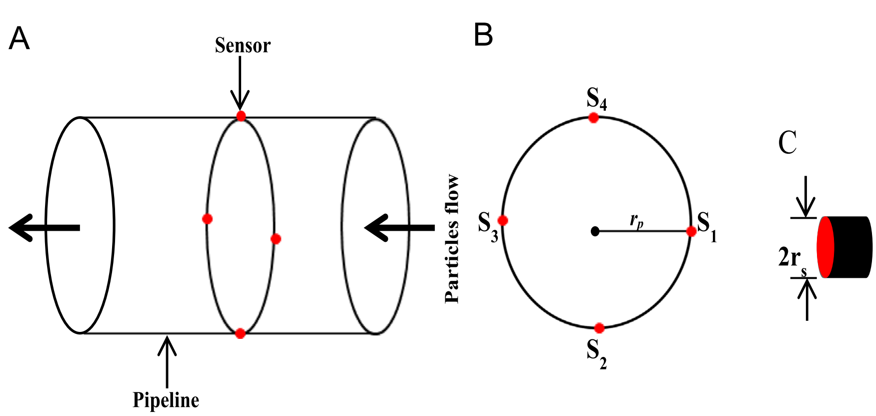

Fig. 1. (A) Pipeline with the sensors installed at a point around the circumference. (B) Pipe cross-section with the 4 sensors installed. (C) Pin electrode of the electrodynamic sensor.