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Characterization of electrostatic sensors for flow measurement of particulate solids in square-shaped pneumatic conveying pipelines

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Abstract

Theoretical analysis of an electrostatic sensor with square-shaped electrodes for installation on a pneumatic conveying pipeline is reported in this paper. In comparison with ring-shaped ones, the square-shaped electrodes are more difficult to analyze because of the four sharp corners. Based on a mathematical model of the electrostatic sensor, induced charge on the electrode and hence the induced current are derived. Sensitivity distribution and frequency response of the sensor are consequently identified. Additionally, effects of the geometric dimensions and attributes of charged particles on the characteristics of the sensor are investigated. Experimental work was performed on a purpose-built particle flow test rig in order to verify the modeling results. Suggestions on the improvement of the electrostatic sensor design are also given.

Keywords: Electrostatic sensor; Square-shaped pipeline; Pneumatic conveying; Charge induction

1. Introduction

Solids particles always carry a certain amount of electrostatic charge during transportation in pneumatic conveying pipelines due to collisions between particles, impacts between particles and pipe wall and friction between particles and air stream. Since the charge on the particles carries certain information of the flow in the pipelines, electrostatic sensors in the form of a conductive electrode in conjunction with signal conditioning electronics are used to measure the flow parameters. This method has obvious advantages over other techniques because of its simplicity in electrode and circuit design, cost-effectiveness and robustness. Various electrostatic sensors have been successfully used to measure velocity [1–3], concentration [4,5], mass flow rate [4,6,7] of solids and particle size [8,9].

Properties of electrostatic sensors with ring-shaped electrodes as well as their applications to pneumatic conveyance have been well studied in the past [1,2,5]. However, very little research has been undertaken on electrostatic sensors for square-shaped pipe sections which are seen in some industrial processes such as fluidized beds [10]. Murnane et al. [11] studied briefly the electrical field due to a point charge in a square pipe using simplified analytic representation to deduce the induced charge density on the electrostatic sensor. In this paper, we present in detail both theoretical analysis and experimental studies of square-shaped electrostatic sensors, particularly sensor characteristics such as spatial sensitivity, signal bandwidth, and their dependence on sensor geometry.

Yan et al. [1] studied the characteristics of ring-shaped electrostatic sensors by combining analytical modeling and experimental investigations. A similar approach is adopted here to investigate in detail the characteristics of square-shaped electrostatic sensors. Based on an approximate mathematical model, induced charge on the inner surface of the electrode is derived when charged particles pass through the electrode. Furthermore, characteristics of square-shaped electrostatic sensors are discussed through both theoretical and experimental analysis.

2. Modeling and inference

2.1. Modeling of a square-shaped electrostatic sensor

A basic physical model together with an approximate mathematical model of an electrostatic sensor for installation on a

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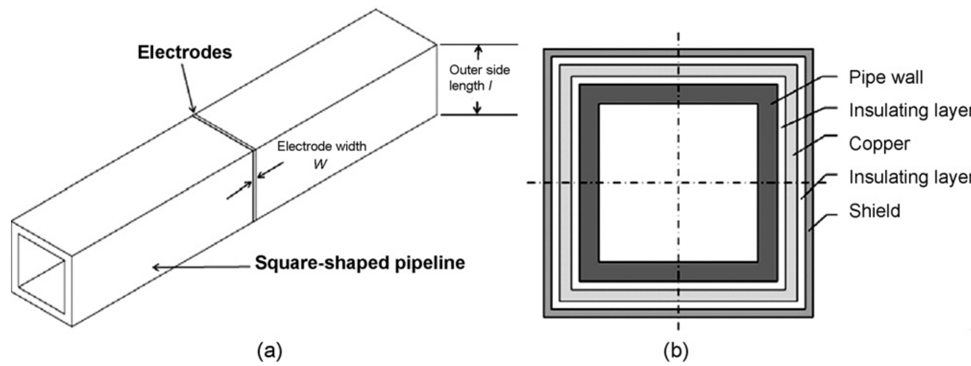

Fig. 1. Physical construction of the electrostatic sensor: (a) sensors' structure and (b) cross-section.

square-shaped pneumatic conveying pipeline is established. The modeling of the electrostatic sensor aims at obtaining the total induced charge on the inner surface of the electrode due to the passage of a known point charge. Some assumptions are intentionally made here to reduce modeling complexity. However, the model of the sensor is still accurate enough to reveal the intrinsic characteristics of the square-shaped electrostatic sensors.

2.1.1. Basic physical model

Fig. 1 shows the physical model of an electrostatic sensor for the velocity measurement of pneumatically conveyed solids in square-shaped pipelines. Fig. 1(a) illustrates the construction of sensors; the screen layer is removed for clarity of illustration, whilst Fig. 1(b) shows the cross section of the sensor. In this study, the square-shaped electrodes are embedded in the pipe wall via insulators, as shown in Fig. 1(b). Charge is induced on the inner surface of the electrode when charged particles travel through it. To simplify the analysis, suppose the induced charge on the surface of the electrode is measured by ideal external electronics. Meanwhile, a particle carrying charge q is regarded as an impulse input when passing axially through the electrode at a constant speed. Consequently, the impulse response of the electrostatic sensor is inferred.

2.1.2. Approximate mathematical model

A mathematical coordinate system of the electrostatic sensor is shown in Fig. 2. The modeling of the electrostatic sensor is achieved under the following assumptions:

(a) A charged particle is regarded as an ideal point charge (P), regardless of its geometric dimensions.
(b) Point charge P is considered to merely have axial velocity, free of radial speed.
(c) The thickness of the electrode is neglected.
(d) Influence of the insulating layers and shield on the distribution of electric field in the sensing area is negligible.

From a mathematical point of view, in the coordinate system (Fig. 2), the dash median of the sensor electrode lies on the plane uov. N stands for the projection of point charge P on plane uov, whilst Q is on the crossing line of planes $u = l/2$ and $s = 0$.

2.2. Inference of induced charge

The electric field strength at point Q is given by

$$E = \frac{q}{4\pi\varepsilon_0 |PQ|^2} \tag{1}$$

The normal electric field strength on the electrode surface is expressed as

$$E_\perp = E \sin\theta \cos\phi \tag{2}$$

where

$$\sin\theta = \frac{|NQ|}{|PQ|}, \quad \cos\phi = \frac{|Q_x - N_x|}{|NQ|} \tag{3}$$

for the rectangular plane $u = l/2$ of the electrode.

Thus

$$E_\perp = E\frac{|NQ|}{|PQ|}\frac{|Q_x - N_x|}{|NQ|} = E\frac{|Q_x - N_x|}{|PQ|} = \frac{q(u-x)}{4\pi\varepsilon_0 |PQ|^3} \tag{4}$$

where

$$|NQ| = \sqrt{(u-x)^2 + (v-y)^2},$$
$$|PQ| = \sqrt{|NQ|^2 + z^2} = \sqrt{(u-x)^2 + (v-y)^2 + z^2} \tag{5}$$

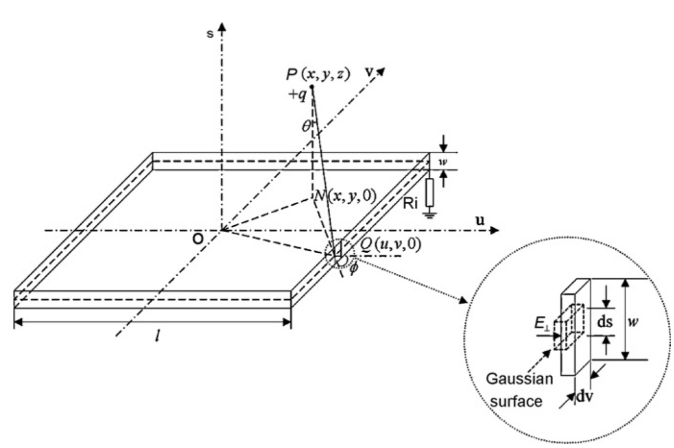

Fig. 2. Mathematical coordinate system for the modelling of the electrostatic sensor.