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A coaxial probe with a vertically split outer sensor for charge and dimensional measurement of a passing object

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ABSTRACT

A coaxial induction probe with a vertically split outer sensor for simultaneously measuring the charge, distance, and size of a passing object is presented. When a charged sphere passed the probe, current signals of different shape induced to all the sensors. The signals were integrated, and Gaussian curves were fitted. The amplitudes and widths of the fitted curves were used to calibrate the set-up. The experimental calibration was done by using frictionally charged spheres of different sizes. Spheres with unknown size, distance, and charge were measured using the calibrated sensor. However, the speed of the object needed to be known. The results from computer simulations, calibrations, and use in measurements are presented.

1. Introduction

In industry, triboelectric charging causes many undesirable effects. These effects include adhesion on the surfaces [1,2], electrostatic discharges (ESD) [3,4], and dust explosions [5,6]. On the other hand, many useful applications, such as electrostatic powder coating, paint spraying or electrostatic precipitation, are based on controlled movement of charged particles [7]. Since many parameters, such as material properties and environmental conditions, affect the charging processes, a good method for measuring the charge is necessary. Reliable data would also enable the development of the theory behind charging. One of the most widely used method for measuring the electric charge of solid particles is the Faraday cup [8–10] which is also suitable for measuring the charge of electron and ion beams [11–13]. In cases where only the net charge is of interest, Faraday cups are valuable and reliable instruments. However in some applications, for instance when charge density is of interest, the size of the object is also important to know. Also, for moving particles, the particle position and speed can be essential parameters.

A coaxial induction probe for measuring the charge, size, and distance of a passing object was previously presented, with promising results [14,15]. The probe was not only used to measure these properties for frictionally charged spheres, but also to measure the charge-to-mass ratio of fluidized powders in a fluidized bed system. This was possible since the signals arising from a charged object were similar to the signals caused by a bubble in a charged powder. According to recent computer simulations, the probe could be further improved by modifying geometry of the coaxial sensor. In this work, we present both simulational and experimental results obtained by using the new probe geometry to measure passing charged spheres. Machida et al. [16] developed a tomography system based on induced currents caused by a charged particle. Similarly to this study, also they had a probe attached to a metal pipe wall. However, the location of the passing charge was measured using several sensors in different positions. In the present study, this method was not used in order to ensure that the measured signals arose from the same object. This is relevant when using a larger pipe with several charged objects. In this case it is not essential to detect all of them but only a portion.

2. Methods

2.1. Simulations

The previous probe consisted of a circular inner sensor (radius 1 mm) surrounded by a ring-shaped outer sensor (outer radius 3 mm, thickness 1 mm), separated from each other with an insulator. The probe was placed at the inner surface of a steel pipe filled

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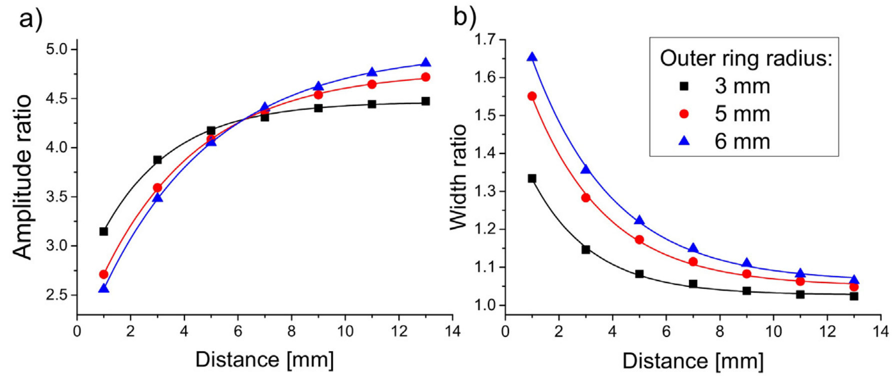

Fig. 1. (a) The signal amplitude ratio and (b) the signal width ratio as a function of the distance from the probe for outer rings of different sizes.

with air so that its tip had the same curvature as the pipe wall. As a charged object passed the probe, two current signals were induced to the sensors. To determine the induced charge, the signals were integrated over time. It was noticed that the shape of integrals were quite similar to Gaussian profile so Gaussian curves were fitted to the data to reduce noise. The amplitudes (A_o and A_i for outer and inner probe respectively) and widths (W_o and W_i) of the fitted curves were recorded. The amplitude ratio A_o/A_i and width ratio W_o/W_i were also calculated. Calibration equations were experimentally determined and used in measurements for these parameters as functions of charge, size, and distance of the passing object [15].

The obtained Gaussian width ratio data was suffered from high standard deviations and therefore could not be used for the calculations. The charged objects were required to pass the probe symmetrically, as otherwise the calculations yielded false results. As the lateral displacement from the probe axis increased, the signal amplitudes decreased, since more electric field lines coupled with the grounded metal pipe walls. However, relatively less electric field lines coupled with the inner sensor, thus increasing the amplitude ratio A_o/A_i. On the other hand, the width ratio W_o/W_i decreased.

The computer simulations in the present study were made using finite element software COMSOL Multiphysics 4.3b. Charged spheres with various sizes were set to pass the probe inside a metal pipe, with different distances from the probe. Tetrahedral mesh was used. The mesh size around the tip of the probe was set to "extremely fine" and around the sphere to "finer", as the software's built-in parameter sets were called. As a result, the element size was approximately 0.1 mm for the probe tip, and 2 mm for the sphere. The electric field **E** at the probe tip was calculated using equations

$$\nabla \cdot (\epsilon_0 \epsilon_r)\mathbf{E} = \rho \quad (1)$$

and

$$\mathbf{E} = -\nabla V, \quad (2)$$

where ρ is charge density, ϵ_0 is permittivity, ϵ_r is relative permittivity, and V is potential. The induced charge was calculated by first calculating the surface charge density σ from equation

$$\mathbf{E} = \frac{\sigma}{\epsilon_0 \epsilon_r}\hat{u}_n, \quad (3)$$

where $\hat{u}_n$ is the unit normal vector. The surface charge density σ was then integrated over the surface of the sensors. Relative permittivities were set to 10^4 for the probe and the metal pipe, 3.0 for the sphere, 2.1 for the insulators, and unity for air which filled the pipe. No special boundary conditions were applied to the insulator part of the probe.

Increasing the radius of the outer ring increased the ranges of ratios A_o/A_i and W_o/W_i. This is illustrated in Fig. 1(a) and (b), where three outer rings with different radii (3 mm, 5 mm and 6 mm) are compared. According to the simulation results, increasing the outer ring radius improves the probe sensitivity to changes in the size, distance and charge of the passing object, which enables more accurate calculations and a wider detection range. Asymmetrically passing objects could be taken into account by vertically splitting the outer ring into two adjacent parts. If the object has displacement to the right for instance, the signal amplitude ratio $A_o^R/A_o^L > 1$ since more field lines would couple with the outer right sensor. For a symmetrically passing object, $A_o^R/A_o^L = 1$.

2.2. Experimental methods

2.2.1. The experimental set-up

A new coaxial probe with a two-piece outer sensor was built based on the simulations from brass. The tip of the probe consisted of a disc-shaped inner sensor (radius 2 mm) which was surrounded by a 2 mm wide, vertically split outer sensor ring (outer radius 10 mm). The sensors were separated from each other by non-conducting epoxy. As illustrated in Fig. 2, the outer ring was split vertically into two adjacent parts and separated by a 1 mm wide insulator in the upper and lower parts of the ring. There was also an insulator around the outer probe. The probe was attached to a metal pipe with an inner diameter of 100 mm and height of 1.0 m, in order to use the probe later in measurements in a fluidized bed device. The curvature of the probe tip was matched with the curvature of the pipe wall.

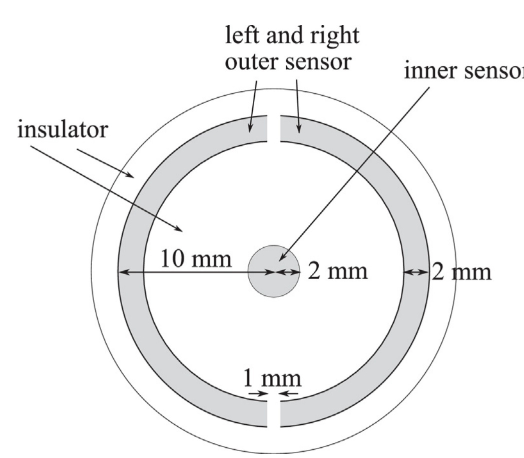

Fig. 2. The tip of the coaxial probe with a vertically split outer ring sensor.