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Influence of particle electrification on AC-based capacitance measurement and its elimination

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ABSTRACT

Based on the variations of equivalent electrical permittivity with different phase concentrations in two-phase or multiphase flow, the capacitance sensor has been successfully used for the phase concentration measurement due to its advantages of non-invasion, low-cost, high reliability and non-radiation. However, solid particles are charged due to the collisions between particles and pipe wall in gas–solid flow system. The charge carried by solid particles will induce a certain amount of charge on the electrode of capacitance sensor, which causes an additional output in the capacitance measurement circuit. Hence, the particle electrification causes errors in capacitance measurements, and even leads to the failure of the measurement system for solid concentration and tomography system based on capacitance sensor. In this paper, the influence of particle electrification on the AC-based capacitance measurement circuit is theoretically and experimentally investigated based on a capacitance sensor with helical surface-plate electrodes. The results indicated that the capacitance signal and the electrostatic induction signal have different frequency band ranges. The influence of charge on capacitance measurements can be eliminated by rationally designing the capacitance measurement circuit, and further accurate and reliable capacitance measurement can be achieved.

1. Introduction

Capacitance method has been successfully used for the phase concentration measurement in two-phase flow due to its advantages of non-invasion, low-cost, high reliability and non-radiation [1–10]. Two-phase flow with different constituent contents has different equivalent electrical permittivity. When the flow passes through the sensitive space of a capacitance sensor, the capacitance between the metal electrodes of the sensor will change, and thus the phase concentration can be derived. However, the sensitivity distribution of the capacitance senor is inhomogeneous in space. As a consequence, the phase concentration measurement is easily affected by the flow pattern. So many trials have been carried out to optimize and develop a suitable capacitance sensor with homogeneous sensitivity distribution. Six types of sensor structures were explored by Abouelwafa and Kendall [6]. Various sensors with different structures were also tested under different flow conditions [1–5,7–10]. Results proved that capacitance sensor with helical surface-plate electrodes have the best linearity for concentration measurement. More importantly, optimized capacitance sensor can obtain a homogenous sensitivity distribution and be used for the accurate particle concentration measurement regardless of the inhomogeneous particle concentration distribution. Capacitance sensor can be widely applied to gas–liquid and gas–solid flow

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measurement [7–10]. In addition, capacitance sensing method has been used for tomography technique and it comes into being electrical capacitance tomography (ECT). The medium distribution image can be reconstructed by using suitable data processing algorithms based on ECT and further can be used for the flow visualization and flow pattern identification [11–14].

Regardless of the capacitance sensor structure, one key issue of the capacitance sensor's application is the accurate capacitance measurement. Presently, the most suitable approaches for capacitance measurements are charge/discharge circuit and AC-based circuit because of their good stray-immunity [15]. As for the gas–solid two-phase flow, particle electrification is an inherent phenomenon caused by the collisions between particles and pipe wall in gas–solid flow system [16,17]. Charge carried by particles induces a certain amount of charge on the detection electrode of the capacitance sensor when passing it, which causes an additional output in the capacitance measurement circuit. This makes the errors in capacitance measurements, and even leads to the malfunction and damage of measurement circuit. To analyze and eliminate the influence of particle electrification on capacitance measurement, the capacitance measurement circuit should be taken into account. Zhang et al. [18] discussed the influence of electrostatic charge distribution on the capacitance measurements of ECT based on a switch capacitance configuration. The uneven electrostatic charge distribution in pneumatic pipe was regarded as the source of the capacitance measurement errors. Gao et al. [19] investigated the electrostatic effect on AC-based ECT by simulations and experiments. Although the work proved the fact that particle charge has influences on the capacitance measurement, further study is still essential to eliminate the influences.

In this paper, the influence of particle electrification on AC-based capacitance measurement circuit output is firstly analyzed from the aspects of electric field theory and circuit analysis based on a capacitance sensor with helical electrodes. Experiments are then carried out on a belt conveyor rig. The output signals from the measurement circuit are analyzed in detail, and further a modified AC-based capacitance measurement circuit is proposed to eliminate the influences.

2. Mathematical model of capacitance sensor and circuit analysis

2.1. Sensor structure

The structure of the capacitance sensor with double helical surface-plate electrodes is schematically shown in Fig. 1. Double electrodes are mounted on a dielectric pipe to form a capacitor. They are covered in a metal shield to isolate external electromagnetic interference. R_1 and R_2 denote the inner and outer radius of the dielectric pipe, respectively. R_3 is the inner radius of the shield. α is the angle of the helical electrode. L is the pitch of the helical surface-plate electrode. Moreover, the number of the electrode twisting turns along the pipe surface is denoted by n. In this paper, the helical electrodes and shield are made of red copper and brass, respectively. The material of the dielectric pipe is plexiglass. Other structural parameters are as follows: $R_1 = 25$ mm, $R_2 = 30$ mm, $R_3 = 38$ mm, $\alpha = 120°$, $L = 120$ mm, $n = 0.5$.

2.2. Mathematical model

In an AC-based capacitance measurement circuit, the frequency of excitation signal, which imposes electrical field in the measurement domain, is of the order of 1 MHz. The corresponding wavelength of electromagnetic radiation is 300 m, exceeding the sensor size by several orders in magnitude (usually less than 1 m). So the electric potential distribution inside the sensor can be described by the electrostatic field theory [12]. According to Gauss' law, the electric flux density $\boldsymbol{D}(x,y,z)$ meets the following equation:

$$\nabla \boldsymbol{D}(x,y,z) = \rho(x,y,z) \tag{1}$$

where ∇ is the divergence operator and $\rho(x,y,z)$ is the volume charge density.

$\boldsymbol{D}(x, y, z)$ can be rewritten as

$$\boldsymbol{D}(x,y,z) = \varepsilon(x,y,z)\boldsymbol{E}(x,y,z) = -\varepsilon(x,y,z)\nabla\varphi(x,y,z) \tag{2}$$

where $\varepsilon(x,y,x)$ is the spatial permittivity distribution, $\boldsymbol{E}(x,y,z)$ is the electric field intensity distribution and $\varphi(x,y,z)$ is the electric potential distribution.

Assuming that there is no electrostatic charge in the pipe, the voltage excited to the electrode 1 is V_E, and the electrode 2 acts as detection electrode at virtual earth potential, the electric field within the sensor can be described by Possion's equation and the Dirichlet boundary conditions [12]:

$$\begin{cases} \nabla(\varepsilon(x,y,z)\nabla\varphi(x,y,z)) = 0 \\ \varphi(x,y,z)|_{(x,y,z)\in\Gamma_{E1}} = V_E \\ \varphi(x,y,z)|_{(x,y,z)\in\Gamma_{E2}} = 0 \\ \varphi(x,y,z)|_{(x,y,z)\in\Gamma_S} = 0 \end{cases} \tag{3}$$

where Γ_{E1}, Γ_{E2} and Γ_S denotes the boundaries of the electrode 1, electrode 2 and the shield. The charge induced on the surface of the electrode 2 (S) can be calculated by

$$Q = \int_S \boldsymbol{D}(x,y,x)d\boldsymbol{S} \tag{4}$$

At present, the analytical solution of the model cannot be directly obtained. It is usually solved by using finite element method. After calculating the induced charge on electrode 2, the capacitance of the sensor (C) can be acquired:

$$C = \left|\frac{Q}{V_E}\right| \tag{5}$$

Capacitance is a physical quantity to reflect the ability of a capacitor to store electrostatic charge. It is only related to the geometric structure of the sensor (electrode shape and size, type and distribution of the dielectric medium). Fig. 2 shows the linear relationship between the induced charge on the electrode 2 and the excitation voltage on the electrode 1 by simulation when the pipe is empty, indicating that the capacitance is constant.