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Study on the spatial filtering and sensitivity characteristic of inserted electrostatic sensors for the measurement of gas–solid two-phase flow parameters

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ABSTRACT

A velocity measuring method using an inserted electrostatic sensor with spatial filtering effects is obtained using the point charge mathematical model established in this paper. Employing the established mathematical model helps determine the spatial filtering and spatial sensitivity characteristics of the probe. The spatial sensitivity distribution is obtained by simulating the point charge mathematical model, and when the point charge is near the probe ($a>0$), the sensitivity of the probe is higher and the spatial sensitivity of the probe has symmetry. The relation between the probe length L inserted into a pipe and the charge induced on the probe can also be obtained using simulation, where the longer the probe length L is, the larger the signal amplitude is. However, the signal amplitude is almost invariant when the probe length L is larger than the radius of the pipe. Experiments prove that the spatial filtering and sensitivity characteristics of the probe are consistent with the simulation results. When the free fall velocity of particles is the same, the probe has a low-pass characteristic for the measured signals. It is proven that the fluid velocity measurement method using spatial filtering effects can completely measure the fluid velocity using the spatial filtering characteristic experiments of the probe. The spatial filtering measurement velocity method is also feasible when measuring continuous objects.

1. Introduction

Gas–solid two-phase flow is extensively used in life and industrial processes; therefore, increasing the efficiency and accuracy of methods for measuring gas–solid two-phase flow parameters and controlling the flow are good for the environment. There are two main methods for measuring gas–solid two-phase flow parameters using electrostatic induction theory: a non-contact sensor and a sensor inserted into the pipe. The usual shape of non-contact electrostatic sensors is a ring, and currently, researchers aiming to measure the solid phase velocity [5–6] and mass flow rate of gas–solid two-phase flow [7–8] are conducting studies on ring electrostatic sensors [1–4]. Ring electrostatic sensors are more complicated to install than inserted sensors. The inserted probe can easily be installed in the pipe, and the parameters of gas-solid two-phase flow can be measured online. Signal acquisition methods for the inserted probe include the direct current measurement method and the alternating current measurement method. The direct current measurement method and the alternating current measurement method employ direct current theory and alternating current theory, respectively, to measure the fluid parameters using electrostatic inducement theory [9]. During the measurement of the parameters of a gas–solid two-phase flow, some factors interfere with the measurement of the particles' charge [10], such as particle materials, the fluid velocity and particles that attach to the pipe walls. The alternating current method has more advantages than the direct current method, such as a better anti-interference characteristic and a greater measurement range, and it obtains the real measured signal and excludes the effects of interference signals.

When the diameters of pipes are slightly large, it is more difficult to fit the ring probe on the pipes; therefore, the inserted electrostatic sensor is easier to install than the ring probe for pipes with large diameters. When the diameters of the conveying pipes increase, the inserted probe can easily measure the fluid parameters by increasing the probe depth L. Thus, the measurement method using an inserted sensor provides a simple and effective way to measure flow parameters in pipes with larger diameter. The radius of the electrostatic sensor inserted into the pipe is R, and the probe schematic diagram is shown in Fig. 1.

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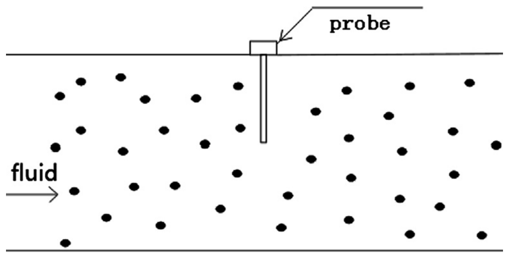

Fig. 1. Schematic diagram of an inserted probe.

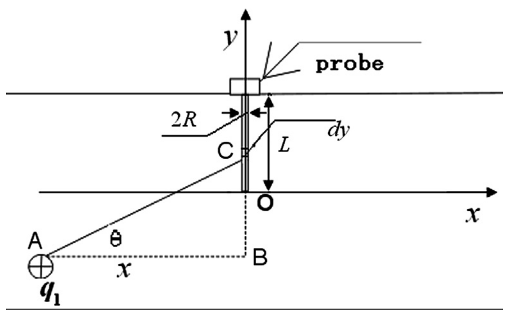

Fig. 2. Schematic diagram of a point charge.

Literature [11] introduces the finite-element model for an inserted probe and obtains the sensitivity distribution of the probe. Furthermore, mathematical models for a ring inducement probe have been described in the literature [1,5,12,13]. In this paper, a single particle mathematical model for an inserted probe is established. By simulating the mathematical model, the spatial filtering characteristic and the spatial sensitivity characteristic of the probe are obtained. The spatial filter velocity measurement method for an inserted probe is obtained by analyzing the spatial filtering characteristics (assuming that the induced charge process follows the triangular rule). These characteristics of an inserted probe are verified by experiments, and the fluid velocity measured using the spatial filter method is calibrated with the cross-correlation velocity, measured by the ring probe.

2. The mathematical model of a point charge

There is a sensing zone around the probe. Therefore, when a solid-phase charging particle moves along the pipe, a charge can only be induced on the inserted probe if the particle is located in this zone. When the inserted electrostatic sensor measures the parameters of a gas-solid two-phase flow, this process occurs within the sensing zone X. Thus, mathematical models of the probe are established for the sensing zone X using the electrostatic induction principle. However, the model developed using this method is an approximate 2-D model. The purpose of this paper is to provide a better method and to find a more accurate fluid charging physical model.

The charged particle is considered to be a point charge, with an electric charge q_1. The schematic of this point charge model is shown in Fig. 2. To obtain the spatial filter measurement velocity method using this mathematical model, we assume that q_1 (at point A in Fig. 2) is in the same plane as the probe.

In Fig. 2, L denotes the length of the probe, x denotes the horizontal distance from q_1 to the probe, a denotes the vertical distance from q_1 to the probe, R denotes the radius of the probe, and D denotes the diameter of the pipe. The calculation is performed as follows.

The electric-field intensity E at point C is:

$$E=\frac{q_1}{4\pi\varepsilon_0[(y-a)^2+x^2]} \tag{1}$$

The infinitesimal area element (point C in Fig. 2) ds is:

$$ds=\pi R\,dy \tag{2}$$

The induced charge q on the electrostatic sensor can be calculated using Gauss's Theorem as follows:

$$dq=-\varepsilon_0 E_\perp ds=-\varepsilon_0 E ds\cos\theta=-\frac{x\ q_1\ R\,dy}{4[(y-a)^2+x^2]^{1.5}} \tag{3}$$

By integrating over the variable y, the charge q induced on the probe can be obtained:

$$q=-\int_0^L\frac{x\ q_1\ R\,dy}{4[(y-a)^2+x^2]^{1.5}}$$
$$=-\frac{Rq_1}{4x}\left(\frac{L-a}{[(L-a)^2+x^2]^{0.5}}+\frac{a}{(a^2+x^2)^{0.5}}\right)$$
$$(a\in(L-D,L)) \tag{4}$$

Expression (4) is the point charge mathematical model for an inserted electrostatic sensor.

3. The spatial filtering characteristic of an inserted probe

3.1. The amplitude-frequency response

First, the amplitude-frequency response is obtained and used to determine the spatial filter action based on an idea previously discussed in the literature [14]. As shown in Fig. 8 and Fig. 12, assuming that the inserted electrostatic sensor induced-charge process follows the triangular wave rule, the new amplitude-frequency response and the spatial filter action of the probe can be obtained.

3.1.1. The amplitude-frequency response of a gate function

According to the transfer function inalterability of a system, the point charge mathematical model for the probe can be simplified by setting $a=0$. The amplitude-frequency response can then be obtained using the simplified model.

$a=0$ is substituted into expression (4), and the simplified model is as follows:

$$q=-\frac{Rq_1}{4x}\cdot\frac{L}{\left(L^2+x^2\right)^{0.5}} \tag{5}$$

Provided that the solid particle enters the sensitivity zone X, an induction charge will appear on the inserted probe.

Setting $K=\frac{RL}{4x\left(L^2+x^2\right)^{0.5}}$, we obtain:

$$q=-Kq_1 \tag{6}$$

where K is the proportionality factor.

We set the input point charge q_1:

$$q_1=q_0\delta(t) \tag{7}$$

The time that the point charge spends moving in the sensitivity zone 2X is given by $2X/v$. The equations for a point charge moving in the sensitivity zone 2X determine the gate function [14], shown in Fig. 3.

Applying the Laplace transform to expression (6), the transfer function of the system can be obtained:

$$H(s)=\frac{q(s)}{q_0}=-\frac{K}{s}\left[1-\exp\left(-\frac{2xs}{v}\right)\right] \tag{8}$$