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Contact electrification of a novel dual-material probe with charged particulate flow

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ABSTRACT

A novel dual-material collision electrostatic probe was developed and calibrated in an ejector-funnel setup, which produced charged particulate flow with different magnitudes and polarities of charge density on the particles. The charged particles then collided with the dual-material probe tip, with the transferred charges/currents recorded by electrometers. Experiments were conducted to examine the effects of particle charge density, solid flux, particle collision velocity and angle during the charge transfer process between particles and the probe tip surfaces. A semi-empirical transferred current model which quantifies the effect of the above parameters is proposed, building on the linkage of transferred current measured by the probe and the charge density on the particles.

1. Introduction

Electrostatic charges are a common problem in commercial powder handling processes. Serious electrostatic charges may cause reactor shutdown or even explosions, so effective measurement techniques are needed to monitor electrostatic charges.

The fundamental electrical quantities associated with the charged particles are electrostatic charge, current (charge transfer rate), and voltage (electric potential difference). Electrical charges in flowing solids systems are usually expressed as a charge density (C/m^3, C/kg) or current density (A/m^3, A/kg) [1]. The charge density on particles is crucial in determining the magnitude of electrostatic forces [2]. In the particle pipe flow/pneumatic conveying, ring-shaped electrostatic sensors are often used to measure the solid flow rate/particle velocity [3–5]. Matsusaka et al. [6] proposed a method to measure the mass flow rate and charge density on particles simultaneously by utilizing two short pipes made of materials with substantially different work functions (energy required to remove an electron from the surface).

In fluidized beds, collision probes made of highly conductive materials are often used to measure the charge or current induced and transferred to the probe tip by charged particles. Ciborowski and Wlodarski [7] developed an electrode made of platinum wire (0.5 mm diameter), ending in a "smallish" (~5 mm diameter based on a photograph of the experimental setup) ball, tethered inside the fluidized bed by a silk thread and connected to an electrometer to measure the electrical potential in a glass fluidization column of 0.06 m diameter and 0.555 m height. Fujino et al. [8] adopted a similar approach by inserting into the fluidized bed a spherical brass terminal of 6.0 mm diameter, tethered by a nylon thread and connected to an electrometer. A grounded brass distributor plate served as the reference electrode. Park et al. [9] and Chen et al. [10,11] mounted collision ball probes to measure charges induced and transferred by particles surrounding rising bubbles in a two-dimensional fluidized bed. Moughrabiah et al. [12] and Wang et al. [13] installed collision probes at various heights along their columns to measure the charge distribution inside fluidized beds. Previous collision probes cannot directly give particle charge density, because the current or voltage signals from a collision probe reflect not only the particle charge density, but also the local hydrodynamic properties. Thus a new measurement device is needed to monitor in-situ particle charge density levels in fluidized bed reactors, so as to prevent charge buildup in the reactor and associated wall sheeting and possible accidents.

2. Background of the new probe

Unlike the two short pipes proposed by Matsusaka et al. [6], which are not suited for local and online measurements of charge density in fluidized beds, the probes which are often used in fluidized beds can supply both local and real-time information. Therefore a novel dual-material electrostatic collision probe was designed and fabricated based on the same principle as Matsusaka et al. [6] for the measurement of charge densities in bubbling fluidized beds. While the two short pipes were used in pneumatic transportation, i.e., in dilute phase flow, the fluidized bed where the new dual-material probe is to be used consists of a more

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complex two-phase flow including bubbles and a dense phase. Therefore, the probe needs to be tested and calibrated for both dilute phase and dense phase gas–solid flows.

In this paper, the charging behavior of the ejector-funnel setup is first quantified in order to generate different charge densities on the particles in magnitude and polarity; then factors that affect charge transfer between charged particles and the probe are investigated; finally, a charge transfer calibration equation is developed to correlate the charge transfer rate and particle charge density.

3. Theory for charge transfer between two materials

Contact electrification occurs when two materials are brought into contact and then separated; as a result, charge is transferred causing one material to be charged positively and the other negatively. Contact electrification is related to the potential difference between two bodies in contact [14]. The traditional condenser model gives the transferred charge caused by collisions between particles and a metal surface. The complete details of this model can be found in Matsusaka et al. [15]. The total potential difference, V, is given by:

$$V = V_c - V_e - V_b + V_{ex} \tag{1}$$

where V_c is the potential difference based on the work functions, V_e and V_b are the potential differences due to the image charge and the space charge, respectively, and V_{ex} is the potential difference arising from other electrical field.

The capacitance C is given by [16]

$$C = \frac{\Delta q}{V} = \frac{\prod_0 \prod_r A}{z_0} \tag{2}$$

where C is the capacitance between the two bodies (probe and particles), V is the total potential difference between probe and particles, Δq is the transferred charge during contact time interval Δt, Π_0 is the permittivity of vacuum, Π_r is the relative permittivity of air, A is the contact area between the probe metal surface and particle, and z_0 is the critical gap between the bodies.

The electric current generated from continuous collisions is given by

$$I = -\frac{W_s}{m_p} \Delta q. \tag{3}$$

This current is mainly transferred current, with the negative sign accounting for its direction.

4. Probe design and fabrication

A dual-material probe consisting of two materials of significantly different work functions has been developed. Titanium nitride (TiN) and nickel (Ni) were selected as the materials for their large difference in work functions and their high hardnesses, as shown in Table 1. Fig. 1 illustrates the schematic design of the probe: the probe tip contains two 6 × 6 mm metal pieces, each attached to a coaxial cable. A Teflon tube of 19 mm outer diameter prevents charge leakage and maintains a high resistance to the ground. A metal shield, grounded during measurement, was used to reduce background electrical noise from the column walls. For dual-material probes, it is especially important that the metal mesh of the two coaxial cables should not contact the tip. This prevents charge leakage and eliminates interference between the two current signals. In addition, electrical wires should be as short as possible to minimize noise. Initial tests showed that the charge measured by the probe with no contact with particles was close to the baseline, which was two orders of magnitude smaller than when the probe surface was struck by charged particles.

5. Experimental equipment and measurement techniques

5.1. Ejector-funnel setup and particles

The probe was calibrated using an ejector-funnel setup, as shown in Fig. 2a. For dilute phase flow experiments, the Plexiglas funnel was removed. The glass beads were fed through a glass funnel, evenly dispersed into an ejector (RAV375H, AIR-VAC), and then passed through a 90° elbow-type fitting and a straight pipe. Four combinations of polyvinyl chloride (PVC, 25 mm long and 24 mm ID), stainless steel (SS, 22 mm long and 26 mm ID) and aluminum (Al, 23 mm long and 25 mm ID) were selected for the 90° elbow and pipe, as shown in Fig. 2b. For dense phase flow experiments, the Plexiglas funnel collected the charged particles from the ejector, and then dropped them onto the probe surface.

Glass beads belonging to Geldart Group B were used for all tests, with a volume weighted mean diameter of 624 μm, determined by a Malvern Mastersizer 2000. According to Cross [17], electron energies in an insulator are a function of position, surface impurities and local atomic structure, as well as the chemical properties of the material. Therefore, the work function of insulator should be determined experimentally. The work function, dielectric constant and resistivity of silicon dioxide (the major component of glass) and different types of glass are provided in Table 1. Before each test, the glass beads were washed with ethanol and water, and then dried overnight to eliminate impurities and dust. All experiments were undertaken at room temperature of 19–23 °C; with environmental relative humidity of 27–52%.

5.2. Charge density

The total net charge, Δq (C), on particles after they pass through the ejector-funnel setup, was measured by an electrically insulated Faraday cup, connected to an electrometer (Keithley Model 6514). The Faraday cup contains two copper cylinders, an inner cup and an outer cup, with a height of 250 mm and inner diameters of 150 mm and 200 mm, respectively. The charge density, q_m (C/kg), of particles was obtained by

Table 1
Electrical properties and hardness of different materials used in the experiments [4,27–35].

Materials	Glass	Titanium nitride (TiN)	Nickel (Ni)	Stainless steel (SS)	Polyvinyl chloride (PVC)	Aluminum (Al)
Work function, ev	Silicon dioxide: 5.0	2.9	5.04–5.35 [27] 4.96–5.03 [28]	4.4	4.85 [29] 5.13 [30]	4.06–4.26 [27] 3.38–4.08 [28]
Hardness, kg/mm^2	560	2300	1340	N/A	N/A	N/A
Dielectric constant	Silicon dioxide: 3.78 Iron-sealing glass: 8.41	N/A	N/A	N/A	3.2	N/A
Conductivity, S/m or volume resistivity, Ω·cm	Iron-sealing glass: 1E^{10} Ω·cm Soda-borosilicate: 7E^7 Ω·cm Silicon dioxide: >1E^{19} Ω·cm	3–7E^7 S/m	1.43E^7 S/m [27] 6.9E^{-6} Ω·cm [28]	1.45E^6 S/m [31] 90E^{-6} Ω·cm [28]	1E^{14} Ω·cm	3.5E^7 S/m [32] 2.62E^{-6} Ω·cm [28]