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Invited paper

A novel dual-material probe for in situ measurement of particle charge densities in gas–solid fluidized beds

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ABSTRACT

Particle charge density is vitally important for monitoring electrostatic charges and understanding particle charging behavior in fluidized beds. In this paper, a dual-material probe was tested in a gas–solid fluidized bed for measuring the charge density of fluidized particles. The experiments were conducted in a two-dimensional fluidized bed with both single bubble injection and freely bubbling, at various particle charge densities and superficial gas velocities. Uniformly sized glass beads were used to eliminate complicating factors at this early stage of probe development. Peak currents, extracted from dynamic signals, were decoupled to determine charge densities of bed particles, which were found to be qualitatively and quantitatively consistent with charge densities directly measured by Faraday cup from the freely bubbling fluidized bed. The current signals were also decoupled to estimate bubble rise velocities, which were found to be in reasonable agreement with those obtained directly by analyzing video images.

Introduction

Electrostatic charging commonly arises in particle handling processes. In pneumatic conveying, charges are mainly generated from collisions between particles and pipe inner walls. The charge signals from electrostatic sensors in pneumatic conveying system depend on the properties of the particulate flow. Extensive work has been undertaken to use electrostatic sensors (for example, ring-shaped metal electrodes) to measure solids flow rates, particle concentrations, and particle velocities (Gajewski, 2008; Yan, Byrne, Woodhead, & Coulthard, 1995). Electrostatic signals from pneumatic conveying systems have received considerable attention, but electrostatic signals from fluidized beds have not been studied intensively.

Electrostatic charges in gas–solid fluidized bed reactors, resulting from a balance between charge generation and dissipation, can significantly affect reactor performance. For example, charges in polyolefin reactors can cause particles to adhere to the reactor wall, then melt and fuse together to form “sheets”. Significant reactor wall sheeting can, in turn, lead to loss of product, plugging of the discharge system or even loss of fluidization. There are significant economic incentives to prevent the formation of wall sheets (Hendrickson, 2006). However, determination of the cause of sheeting with metallocene catalysts has been hampered by the lack of suitable instrumentation. Most sheeting incidents with metallocene catalysts have occurred with little or no advanced indication by any of the previously used process instruments, including conventional static probes (Hagerty et al., 2005). Moreover, the development of high-activity catalysts combined with advanced reaction technologies has created a growing need to monitor the electrostatic behavior of particles. This requires the development of reliable and accurate measurement techniques which can provide transient local particle charge density, as well as charge density distribution across a spectrum of fluidized particle sizes (Bi, 2011).

There are two major techniques for measuring particle charge density in gas–solid flow systems: (a) Faraday cup (direct method), and (b) electrostatic probes (indirect method). The former yields charge density directly, but it is an offline measurement tool, not suitable for in situ monitoring of industrial reactors. Moreover, additional charge generation or dissipation during particle sampling may affect the measurement accuracy. The collision probe is one type of electrostatic probe, widely used by industry, especially in polyolefin processes. These probes are made of highly conductive materials, generally inserted along the axis of the bed and connected to electrometers to measure the electrostatic charge buildup inside the fluidized beds. Collision probes receive charges,

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Notation

a_i	fitted constant in Eq. (7), dimensionless
A_p	probe tip surface area, m^2
b_i	fitted constant in Eq. (7), C s^2/(kg m^2)
c_i	fitted constant in Eq. (7), C/kg
C_min	minimum charge, C
D_B	bubble size/diameter, m
D_s	particle diameter, m
E	electrical field, V/m
I	total current, A
$\bar{I}$	average current, A
m	mass of particles, kg
Q	total charge on particles, C
Q_s	surface charge density, C/m^2
p	permittivity defined in Eq. (16), dimensionless
q_m	charge density or specific charge on particles, C/kg
t	time, s
U_p	average particle velocity, m/s
U_g	superficial gas velocity, m/s
U_B	average bubble rise velocity, m/s
U_mf	minimum fluidization velocity, m/s
W_s	mass flow rate of particles striking probe surface, kg/s

Greek letters

α_i	fitted parameter in Eq. (9), kg/m
β_i	fitted parameter in Eq. (9), C s^2/(kg m^2)
γ_i	fitted parameter in Eq. (9), C/kg
δ	lower boundary of the ratio of the current peaks from two materials in Eq. (6), dimensionless
Π_r	relative permittivity or dielectric constant, dimensionless
Π_o	permittivity of vacuum, 8.854×10^{-12} F/m
ε	local voidage, dimensionless
ε_mf	voidage at minimum fluidization, dimensionless
ρ_p	particle density, kg/m^3
λ	maximum tolerable time difference between current peaks from the two materials in Eq. (5), s
φ	coefficient in Eqs. (1) and (2), dimensionless
ω	upper boundary of the ratio of the current peaks from two materials in Eq. (6), dimensionless
$\Delta\tau_\mathrm{B}$	time for a single bubble to pass the probe, s

Subscripts

1	Ni
2	TiN
B	bubble
sd	standard deviation
tran	transfer
ind	induction
max	maximum
min	minimum

both transferred from particles colliding with the probe tip and induced when the particles pass by (Park, Bi, Grace, & Chen, 2002). However, they cannot give direct charge density information, and signals are difficult to interpret.

Table 1 lists the measurement techniques used to determine particle charge density in laboratory gas–solid fluidized beds. Collision probes have rarely been employed for this purpose because the current or voltage signals received from them not only reflect the particle charge density in the bed, but also local dynamic properties, such as bubble size and velocity. Charge density and hydrodynamic information are both embedded in the transient charge signals derived from electrostatic probes in fluidized bed reactors. Effects of changes in hydrodynamic behavior by altering pressure, superficial gas velocity, initial bed height, and distributor on bed electrification have been investigated (Liu, Bi, & Grace, 2010; Yao, Bi, & Park, 2002; Zhou, Ren, Wang, Yang, & Dong, 2013). To determine the charge density using collision probes, one needs to decouple hydrodynamic information from charge variations. A. H. Chen, Bi, and Grace (2003) proposed a method to extract particle charge density from charge signals by a single material ball probe, based on single bubble injection experiments with known bubble volumes. Bi, Chen, and Grace (2007) further suggested that the standard deviation, normalized by the average current, could mainly reflect the local hydrodynamics, assuming that the particle charge density term would be canceled out during normalization. A novel dynamic probe should, in principle, be able to determine both charge density and hydrodynamic properties in freely bubbling fluidized beds.

Instead of using single dynamic collision probe, charge density and local hydrodynamics may also be obtained from two sets of signals from two collision probes located in close proximity. A dual-material probe featuring two sensors of significantly different work functions was thus developed recently by the authors (He, Bi, & Grace, 2014) and calibrated in idealized homogenous particle flow systems to examine the effects of particle charge density, particle–probe surface contact angle, particle velocity, and particle concentration in a calibration device. This paper presents experimental results obtained from a two-dimensional bubbling fluidized bed to demonstrate the capability of the proposed novel dual-material probe to measure the particle charge density in bubbling fluidized beds.

Experimental

Probe

In a previous paper (He et al., 2014), dual-material probes were prepared to facilitate simultaneous measurements of local electrostatic charge density of particles and hydrodynamic properties in gas-fluidized beds. Titanium nitride (TiN) and nickel (Ni) were selected as the probe materials because of their large difference in work functions (TiN: 2.9 eV vs. Ni: 5.0–5.4 eV), relatively high hardness, low cost, and availability. Results obtained when continuous streams of particles were directed onto the surface of the probes showed that the largest differences between currents transferred to/from the two probe materials occurred when the charged particles struck the probe at right angles. Therefore, for the current study, a new dual-material probe was designed to allow charged particles to directly strike downward-facing tips, as shown in Fig. 1. A Teflon tube maintained a high electrical resistance to the ground, while a brass tube enclosing the Teflon tube reduced background electric noise by eliminating disturbances due to buildup of charges on the column walls. As in the previous work (He et al., 2014), two square pieces (TiN and Ni), each 6 mm × 6 mm in cross-section and 1 mm thick, were connected to coaxial cables. The charge signals from these two tips were amplified by two electrometers (Model 5010B, Kistler, USA) and logged into a computer by a data acquisition card (PCIe-6321, National Instrument, USA) and Labview software, with a sampling frequency of either 100 or 500 Hz.

Motor-pulley setup

A motor-pulley system was built to check the induced charges on the dual-material probe, as shown in Fig. 2. A DC compact gear