Powder Technology 329 (2018) 65–75

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Perspectives

A perspective on electrostatics in gas-solid fluidized beds: Challenges and future research needs

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ARTICLE INFO

Article history:
Received 2 November 2017
Received in revised form 20 January 2018
Accepted 23 January 2018
Available online 03 February 2018

Keywords:
Fluidization
Electrostatics
Hydrodynamics
Triboelectric charging
Application
Simulation

ABSTRACT

This paper provides a perspective on the current knowledge and potential areas of future research related to electrostatics in fluidized beds. Aspects addressed include characterization techniques, charge generation and dissipation mechanisms, interplay between the electrostatics and hydrodynamics, charge control methods, applications of tribo-electrostatic fluidization systems, and computational simulations which account for electrostatic charges. This is a complex research field involving fluid mechanics, powders and electrical physics, with potential rewards in terms of safety, process monitoring and new applications.

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1. Introduction

Gas-solid fluidized beds are characterized by intense solids mixing, uniform temperature profiles, and efficient heat transfer. These features have made fluidization widely used in many physical and chemical processes dealing with particulate systems. Fluidization of solid particles, by its nature, involves intense and frequent collisions of solid particles with each other and with vessel walls, causing tribo-electrification. Although tribo-electrification is a ubiquitous phenomenon, known for centuries, current understanding of the underlying mechanisms is still limited. Intrinsic complexity of particle motion and contacts in fluidized beds results in complex charge generation and dissipation phenomena, far from being well understood. Due to the electrostatic interactions, charged particles in fluidized beds are prone to aggregation by adhering to vessel walls (wall sheeting) [1] and/or to other particles, leading to formation of agglomerates [2]. In addition, the electrostatic charges on particles and vessel walls, as well as high-voltage electrical fields arising from them, can affect the motion of particles and fluids, interfering with sensors and bed internals, leading to malfunction of instruments and operation [3]. Due to these effects, electrostatic charges in commercial gas-solid fluidized bed facilities, especially in fluidized bed polymerization reactors, cause several operational problems such as the formation of undesired byproducts [4], production losses [1], and problematic product handling [5]. Moreover, unintentional charge accumulation and resultant hazardous discharges can cause sparks, fires, and even explosions, affecting process performance and endangering the operators [6–8]. On the other hand, the tribo-charging propensity of fluidized beds and its impact on the particle motion has been exploited in some industrial processes such as powder coating [9] and coal beneficiation. Electrostatic fields have also been proven to be effective in modifying hydrodynamics of bubbling fluidized beds [10–12] and in enhancing fluidization of nanoparticles [13–18].

Hendrickson [1] reviewed electrostatics phenomena in gas phase polymerization fluidized bed reactors, with a focus on commercial issues, particularly wall sheeting, and mitigation techniques. Basic concepts of contact charging and charge transfer, as well as powder charging mechanisms, were reviewed by Matsusaka et al. [19]. Mehrani et al. [20] recently reviewed advances in the fundamental understanding of triboelectric charging, methods to measure particle charge, and attempts to elucidate particle charging processes in fluidized beds. Fotovat et al. [21] also reviewed characterization techniques of electrostatics in fluidized beds, charge generation and distribution mechanisms, interplay between electrostatic and hydrodynamics, charge control methods, applications, and computational simulations of fluidized beds involving charged particles.

This paper provides an outlook of the measurement, characterization, control, applications, and simulation of electrostatics in fluidized beds, highlighting areas needing further research and development for advanced and effective control and exploitation of electrostatics in commercial fluidized beds.

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https://doi.org/10.1016/j.powtec.2018.01.069
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2. When does electrostatics play an important role in fluidized beds?

While electrostatic charges are generated in a wide range of fluidized bed systems, they only play an important role when the resulting electrical forces are appreciable relative to the weight-minus-buoyancy of at least some of the particles. Table 1 summarizes operating conditions and particle properties which are likely to result in electrostatics being important. In particular, electrostatics are most likely to influence hydrodynamic behavior when:

- At least some of the particles are relatively small, e.g. ≤100 μm
- Particle dielectric constants are intermediate in magnitude ($\varepsilon_p > 2$), such that particles are able to gain and retain electrical charges.
- Superficial gas velocities are high enough to cause vigorous particle motion.
- Relative humidity is low, e.g. ≤10%
- Pressure is high, e.g. ≥3 bar
- Temperature is low, e.g. ≤50 °C
- The difference between work functions of the column wall and particles is large, and the wall surface-area-to-reactor-volume ratio is high.

The above operating conditions delineate situations where triboelectrification is most likely to influence the hydrodynamics of most fluidized beds studied in the literature. Nonetheless, it is quite possible that in some cases electrostatics will be pronounced under conditions that are less conservative than those listed above.

3. Characterization of electrostatics in fluidized beds

Detailed characterization of electrostatics in fluidized beds strongly relies on accurate, online, and local measurement techniques. Electrostatic charges can be measured directly using Faraday cups, or indirectly extracted from signals registered by electrostatic probes of three major types: capacitance probes, collision probes, and induction probes/sensors.

By measuring the net charge of a given mass of particles, Faraday cups can directly provide particle mass charge density, i.e. particle charge-to-mass ratio. Faraday cups are generally used offline, measuring the charge density of particles withdrawn from different locations of the fluidized bed. This could be associated with generation of extra charges or dissipation of charges during the handling of particles and variations in environmental factors, such as atmospheric air humidity and electromagnetic noise. These issues could be addressed by reducing the contact area of the sampling units (scooper/spoon/tube) [44], coating them with the same material as the fluidized particles [44], or integrating them into the Faraday cup [26,45–47]. To determine charge distribution of particles in a fluidized bed, an electric field can be employed to separate particles withdrawn from the bed, based on their charge magnitude and polarity, with the resulting portions of particles collected in the pails of a multi-compartment Faraday cup [48,49].

Due to the difficulties associated with particle sampling and utilization of Faraday cups in large-scale industrial processes operating at elevated pressures and temperatures, it is desirable to use electrostatic probes to measure local particle charge densities online. The output of an electrostatic probe is in the form of an induced charge signal [50,51], current signal [52] or voltage signal [53,54] from which the local charge level in a gas-solid fluidized bed is extracted. For example, a capacitance probe inside a fluidized bed connected to an electrometer measures the potential of a section of the bed located between the probe and a grounded reference (reactor wall, metal distributor or another metal probe).

Collision probes, or so-called ball probes, the most commonly used electrostatic probe in industry, receive both charges transferred from particles colliding with the probe surface and charges induced when particles pass the probe [32,55]. The average magnitude of electrical current/potential from collision probes depends on the charge density and velocity of particles colliding with the probe and the collision frequency or particle concentration [19]. Examining electrostatic signals by time-frequency analysis [4,27,56] and by chaotic analysis [57] showed

Table 1
Factors affecting electrostatics in fluidized beds.

Class of parameter	Increasing	Trend with respect to electrostatics	Comment	Reference
Operating conditions	U_g	Bubbling and turbulent flow regimes: ↑ q_m		[22–27]
		Slugging regime: ↔ or ↓ q_m		
	P	↑ particle charging	Pressure increase up to 2500 kPa	[25,28]
	T	↓ Cumulative charge	Temperature increase up to 75 °C	[25,26]
	RH	Dielectric and hydrophilic particles: ↓ q_m		[5,23,29–34]
		Hydrophobic particles: ↔ q_m		[35]
		Electrically conductive particles: ↑ q_m		[36]
Particle properties	ρ_p	↔ Cumulative charge	LLDPE vs. HDPE particles	[28]
	$\overline{d}_p$	Mono-disperse systems: ↑ q_m		[22,34]
		Multi-disperse systems: ↓ q_m		[37]
	Φ_p	↓ q_m	Mono-disperse glass beads	[38]
	ε_p	↑ q_m	Work function is correlated with dielectric constant	[39,40]
		↓ q_e		[41]
	σ_p	↔ q_m		[42]
	W_{PSD}	↑ q_m	Mass charge density increases with increasing the fraction of small particles.	[43]

↑: Increase.
↓: Decrease.
↔: Negligible change.
$\overline{d}_p$: Mean particle size.
P: Pressure.
q_e: Equilibrium particle charge[a].
q_m: Mass charge density (charge-to-mass ratio).
RH: Relative humidity.
T: Temperature.
U_g: Superficial gas velocity.
W_{PSD}: Width of particle size distribution.
ε_p: Dielectric constant of particle.
ρ_p: Particle density.
σ_p: Electrical conductivity of particle.
Φ_p: Particle sphericity.
[a] A charge beyond which a particle no longer gains or loses charge upon impact.

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