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# Use of triboelectric probes for on-line monitoring of liquid concentration in wet gas–solid fluidized beds

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**Abstract**

The objective of this study was to validate the effectiveness of a novel method employing triboelectric probes for accurate on-line solid moisture measurements in fluidized beds. Liquid injections were conducted in a fluid bed of glass beads and the resulting solid moisture was monitored during the whole drying stage by acquiring triboelectric signals generated from several locations inside the bed. For various superficial gas velocities and amounts of injected liquid, the bed drying end point and the fraction of sprayed liquid involved in the formation of slow-vaporizing stable agglomerates were estimated performing fast signal analysis by means of the $W$ statistic.


*Keywords:* Fluidization; Drying; Vaporization; Agglomeration; Triboelectric probes; $W$ statistic; Liquid jet

## 1. Introduction

In many industrial applications where a liquid is injected into a bed of fluidized particles, it is essential to accurately monitor the evolution of the solid moisture. In the pharmaceutical, agriculture and food industries, high product quality is often dependant on the capability of detecting the bed drying end point to prevent product over-drying. In agglomerators, polyolefin reactors and fluid cokers, as well as in dewatering processes of sludges, slurries and waste streams, inappropriate moisture levels can severely reduce the bed fluidity and lead to the formation of undesired agglomerates. Furthermore, several studies have shown that in industrial processes such as fluid catalytic cracking, fluid coking, and gas-phase polymerization, uniform and rapid distribution of injected liquid droplets on solid particles can yield better results by promoting a fast vaporization of the liquid phase or minimizing the fraction of liquid that is involved in agglomerate formation (House et al., 2004).

Most of the methods that are commonly employed to infer the solid moisture in industrial driers make use of indirect measurements by monitoring either the temperature or the humidity of the inlet and outlet gas streams. However, as clearly pointed out by Mujumdar (1995), indirect measurements of the solid moisture content, resulting in a low-efficiency control of the drying process, are detrimental to the dried product quality, and direct, on-line measurements of the solid moisture are highly advisable.

Until now, most of the studies conducted on accurate, direct moisture measurement in particulate systems have addressed the problem of measuring moisture in soils. Some of these techniques employ capacitance probes, which measure the electrical capacitance between two electrodes inserted in the soil, whose apparent dielectric constant is affected by the presence of interstitial water (Starr and Paltineanu, 2003). Capacitance probes are simple to set up and offer the advantage of providing instantaneous measurements of the soil water content. On the other hand, the measured capacitance is characterized by a high sensitivity to the solids holdup, especially near the electrode surface, which makes this technique unsuitable for fluidized beds. The soil moisture has also been measured by time domain reflectometry,

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which relates the soil water content to the velocity of an electrical pulse sent to and then reflected by a probe placed in the soil (Evett, 2003a). Since this technique measures the soil permittivity, which depends not only on moisture but also on solid holdup, it is not applicable in fluid bed dryers. Microwave spectrometry measures soil microwave absorbance at frequencies of 1–2 and 9–10 GHz, at which water strongly absorbs microwaves (Webster, 1999). It has the inconvenience of being affected by solid holdup, nature of solid material, and temperature, while soil microwave reflectance requires the use of complex algorithms (Thakur and Holmes, 2004; Walker et al., 2004). Soil moisture can be measured by neutron moderation using high-energy neutrons, which are slowed down by collisions with nuclei of atoms in the soil (Evett, 2003b). The neutron energy loss is mainly related to collisions with hydrogen atoms so that the presence of compounds such as alcohols, for instance, affects the water content measurement. Besides this limitation, neutron moderation has the disadvantage of requiring a radioactive source of fast neutrons and is affected by solid holdup. Techniques employing magnetic resonance detect a loss in frequency power when subjecting hydrogen atoms of water molecules to electromagnetic radiation of the appropriate frequency (Webster, 1999). As for neutron moderation, the presence in the soil of compounds other than water containing hydrogen atoms reduces the measurement accuracy.

On-line granule water content measurements have been performed in a fluidized bed granulator by using a near-infrared reflectance method detecting water with three wavelengths (Rantanen et al., 2000). The NIR set-up used in this study, however, required a continuous air blowing system over a sight glass, through which the fiber-optic probes could access the granulator and measure the reflectance spectra of the bed solids. In industrial fluid bed driers NIR spectrometry requires the installation of sophisticated, expensive and rather cumbersome probes inside the fluidized bed.

Currently no reliable method is available to directly measure the solid moisture and detect the drying end point in fluidized beds. The first objective of the present study was, therefore, to develop an accurate measurement method for continuous real-time monitoring of the solid drying process.

After testing and assessing several sensors and techniques for their efficiency and accuracy, including thermocouples, static and dynamic pressure transducers, and liquid vapor concentration measurements, an innovative method for accurate instantaneous measurement of solid moisture, based on triboelectrification, was developed. When a metal surface is exposed to fluidized particles that randomly impact on it, a transfer of electrical charge, referred to as frictional electrification or triboelectric charging, occurs between the solid particles and the conductive surface. If the metallic material is connected to the ground, the triboelectric effect produces a current whose intensity and fluctuations are influenced by several factors, such as concentration, size, surface roughness and velocity of the impinging particles (Da Silva et al., 2003), geometric characteristics of the particle-metallic surface collisions, material work functions, and eventual preexisting charge and moisture of the particles (Moore, 1974).

Triboelectric currents have been used to characterize interactions between gas–liquid jets and fluidized beds. By inserting triboelectric probes into the liquid spray region, Hulet et al. (2003) were able to examine the stability of gas–liquid jets interacting with a draft tube. Dawe et al. (2004) employed triboelectric signal measurements to evaluate angle of expansion and penetration depth of gas–liquid sprays. In the present study, for the first time, triboelectric probes were used to detect the local moisture of fluidized solids during liquid injections and the following bed drying stage.

## 2. Experimental set-up and conditions

The experimental set-up used in the present work consists of a 2.8 m tall fluidized bed with a rectangular cross-section of 0.15 m $\times$ 1.22 m. A bank of six sonic nozzles controlled the fluidization air velocity, which was varied from 0.15 to 0.65 m/s. The fluidized solid particles were monosize, spherical glass beads with a Sauter-mean diameter of 175 μm and an apparent particle density of 2500 $kg/m^3$. In all the experiments performed, the bed was operated at the same initial temperature of 19.5 °C and the fixed bed height was maintained at about 0.87 m so that the total mass of bed solids was approximately 240 kg.

The fluid bed was equipped with a spray nozzle having a tip diameter of 0.16 mm, which was horizontally mounted in the bed about 60 cm above the perforated plate distributor. The injecting liquid flow rate was stabilized by using a regulator connected to a pressurized nitrogen cylinder.

Preliminary studies conducted with solutions of water and propanol determined the effect of the water content of the injected liquid on triboelectric signals, showing that a higher water content results in a larger mean triboelectric current. The wettability and agglomerating tendency of glass beads with different liquids, were investigated in a previous work by McDougall et al. (2005), which showed that pure propanol is extremely likely to form agglomerates with glass beads while pure water does not have any tendency towards agglomeration when a perfect spray nozzle is used. To better simulate the liquid–solid interaction occurring in industrial processes, the experiments conducted in the present study were carried out injecting 30 wt% propanol-water solutions, although the addition of propanol to water reduced the signal intensity.

The triboelectric current measurements were performed with seven horizontal stainless steel rods inserted into the fluidized bed in the locations shown in Fig. 1. Each probe was covered by a thin Teflon insulating tube except for the two 3 mm-long ends, one end to permit tribocharging