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Granular flow and dielectrophoresis: The effect of electrostatic forces on adhesion and flow of dielectric granular materials

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ABSTRACT

Electrostatic forces can significantly alter flow properties of granular materials and can adversely affect many industrial particulate processes in unpredictable ways. We investigate here the effect of higher order dielectric electrostatic forces, which are created by non-uniform electric fields, on the agglomeration, adhesion and flow of several granular materials, including pharmaceutical powders. We find that materials can adhere consistently and reproducibly to a metallic rod in a sufficiently strong electric field, which can be produced by either a DC source or tribocharged surfaces. These results provide a simple way to characterize material susceptibility to electrostatic agglomeration. The effect of applied non-uniform fields on the flow of grains falling from a cylindrical hopper is studied and found to significantly reduce the particle flow rate. The effects of humidity, particle size, coatings, and the grounding of equipment are also tested. Finally, contrary to common intuition, we find that grounding a metallic surface can actually exacerbate particle adhesion and agglomeration.

1. Introduction

Electrostatic forces can profoundly impact the flow of granular materials in ways that can be either beneficial or detrimental to industrial operations. Several industries have developed techniques to utilize electrostatic phenomena — for example, the coating [1], separations [2,3], and xerography [4] industries all use electrostatics to control particle behaviors efficiently and reliably. In other industries, however, electrostatics can cause serious problems, including dangerous dust explosions [5–7]. Electrostatic agglomeration and segregation are especially troublesome for the pharmaceutical industry, where the poorly understood nature of electrostatic phenomena can severely hamper pharmaceutical powder handling operations, causing jamming, undesirably high variability of active component concentration in tablets [7], and spontaneous demixing of powder blends [8].

In spite of the industrial importance of electrostatic phenomena, these effects have not been examined as thoroughly as other aspects of granular flow. Several researchers have studied the charging of grains in fluidized or pneumatically conveyed systems [6,9,10], while others have observed a rich range of particle behaviors caused by electrostatics, including agglomeration [10,11], segregation [8,12] and complex pattern formation [11,13]. Recent inroads have also been made regarding the effects of localized charges on particle interactions [14,15].

In the present paper, we examine a specific aspect of electrostatics on granular behaviors, namely the effect that non-uniform electric fields can have on the flow and agglomeration of powdered materials. We focus on non-uniform fields because these fields lead to net forces on insulating materials [16], and we find that these forces both play a complex role on granular flow and can be used to assess the tendency of grains to flow smoothly or to jam under common conditions.

The tendency of insulating particles to be attracted to regions of high electric field strength is referred to as dielectrophoresis (DEP), and has been extensively studied by Pohl [17] and others. This effect is caused by the difference in forces acting on opposite sides of polarized particles in non-uniform electric fields. Almost all materials become polarized when placed in an electric field, and in a uniform field the forces acting on both sides of a particle are balanced, therefore the particle feels no net force. However, in a non-uniform field one side of a polarized particle is subjected to a stronger electric field than the other (cf. [18]), and experiences a net force in the direction of the converging field [17]. The direction of the field (whether positive or negative charges are present) does not affect the motion of the particles; only the direction of increasing field intensity determines the direction of the force. In the simplest case, where the electric field is steady and only a single spherical particle is present, the DEP force is given by

$$F = 2\pi R^3 \frac{\varepsilon_1(\varepsilon_2 - \varepsilon_1)\nabla(E)^2}{\varepsilon_2 + 2\varepsilon_1}, \quad (1)$$

where R is the particle radius, E is the electric field and ε_1 and ε_2 are the dielectric constants of the particle and the surrounding medium respectively [17].

DEP forces have already been utilized for the manipulation of small scale particles and have become especially useful for biomedical

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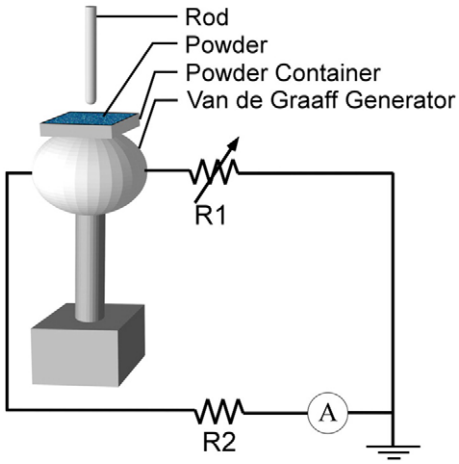

Fig. 1. Schematic of the voltage-controlled Van de Graaff generator with powder container on its top surface. The circuit used to control the voltage of the VDG is also displayed. By moving the wire nearer or farther from the VDG the resistance can be raised or lowered.

applications. They have been exploited for both the separation of living and dead cells [19], as well as cancerous cells from healthy ones [20]. DEP has been studied also for its ability to separate micro and nano-sized particles based on the particles' sizes or compositions [21,22]. The ability to manipulate individual particles on these small scales has also attracted attention. These forces can be employed to stretch, squeeze, rupture cell walls, or fuse cells together by applying force [23]. DEP has also been used to manipulate individual DNA molecules allowing them to be anchored to an electrode surface, stretched and then severed at specific locations [24].

Other researchers have investigated DEP forces as a possible method to separate large particles (larger than 90 μm) from suspensions in non-conducting fluids. These researchers were able to collect significant concentrations of particles by simply applying a large potential to a wire running through a cylindrical container of insulating fluid and solid particles [25,26]. Lin and Benguigui [27] have investigated the ability of large electric fields and matrices of dielectric fibers to filter fine solid particles from liquids or mixtures of other particles. These dielectric matrices can be easily cleaned and reused, unlike other filters, simply by removing the electric field and therefore the forces binding the particles to the matrix.

We are interested here in powder handling operations that are intrinsic to the processing and manufacture of pharmaceuticals and fine chemicals. In many of these operations, strong electric fields are commonly encountered, leading to dangerous discharges as well as flow interruptions [28]. We investigate the influence of DEP on the flow of granular materials, with a mind to both improving industrial particle handling operations and developing techniques to characterize the susceptibility of given powders to electrostatic problems.

To this end, we determine the strength of DEP forces and effects of DEP on granular behaviors in two prototypical granular systems: first, nearby a grounded metal rod in a strong electric field (where electric field gradients, and hence DEP forces, can be very strong), and second in flow from a cylindrical hopper (where the geometry is very simple, and we can investigate the effects of DEP on flowing materials). We investigate the effects of particle size and composition as well as environmental humidity on DEP effects, and we evaluate the utility of two commonly used methods to control electrostatic forces: material modification and equipment grounding. We begin by describing the experimental system; then we present results, and finally we draw conclusions.

2. Experimental

We use a commercial Van de Graaff generator (VDG) to generate controllable electric fields. The voltage of the VDG was controlled by constructing a voltage divider, as shown schematically in Fig. 1. As indicated, by varying the rheostat shown (R1 in Fig.1), we were able to drain current from the VDG, which we found permitted us good control over the generator voltage. We measured the voltage by monitoring the current through a known resistor (R2 in Fig. 1) using an electrometer (either a Keithley Instruments 610CR or a Trek 217, in ammeter mode). R2 is a large (20 GΩ) resistor, which is used to step-down the voltage as current passes through the resistor to the ammeter. A finely tipped grounded wire acting as a corona source was used as the variable resistor. We found that by moving the wire tip nearer or farther from the VDG, the voltage of the VDG measured with the electrometer, could be reproducibly controlled. Through this approach, the voltage of the VDG could be controlled to within 300 V when its voltage was set to 20 kV, or to about 1.5%. At lower voltages, the VDG's voltage could be more accurately controlled.

For our first experiment, a powder container ($13\times13\times1$ cm) was constructed from plastic (either Teflon or acrylic) and filled with a powder of interest (described in further detail shortly). The container was symmetrically placed in contact with the top of the VDG (as depicted in Fig. 1). A grounded metal rod (1.2 cm in diameter) was attached to a moveable jig centered on the powder container, which allowed the rod to be smoothly moved up or down. At the start of the experiment the rod was immersed in the powder to a depth of 6 mm. The VDG was then activated and the voltage was allowed to reach a steady value, which usually occurred within about 1 s, at which time the rod was smoothly and rapidly raised from the bed of grains. Any material adhered to the rod was collected and weighed. In this way, we were able to evaluate a powder's tendency to adhere due to DEP forces in a reproducible and controllable way.

Powders used in this study, consist of white art sand (average diameter 300 ± 90 μm), glass beads of various sizes, and several pharmaceutically relevant powders including granulated lactose (110 ± 45 μm, Foremost, 316/Fast-Flo) and microcrystalline cellulose (140 ± 100 μm, FMC Biopolymer, Ph102). The average diameter of the particles was determined using a Beckman Coulter LS 13 320 dynamic light scattering apparatus.

To ensure that the powder was not significantly charged during the filling of the powder container or while the VDG was on, the charge of the powder was measured using a Faraday cup. The container was filled with powder, placed on the VDG for 30 s and then emptied into the Faraday cup and the net charge measured. The charges produced in this manner were small, and are listed in Table 1. The difference in measured charge produced by filling the container and then emptying it after 30 s

Table 1
Comparing the DEP and electrostatic forces acting on particles with either the charge that the particles developed after being placed and then emptied from the powder container or with their maximum possible charge amount.

Material	DEP force (N)	Charge per particle (nC)		Measured charge		Maximum charge	
		Measured charge	Maximum charge	Image force (N)	Electric field (N)	Image force (N)	Electric field (N)
Cellulose	1×10^{-6}	1.3×10^{-6}	2×10^{-3}	8×10^{-13}	2×10^{-9}	1×10^{-6}	2×10^{-6}
White sand	5×10^{-6}	5.0×10^{-5}	8×10^{-3}	3×10^{-10}	7×10^{-8}	6×10^{-6}	1×10^{-5}
Glass beads (150 μm)	1×10^{-7}	3.2×10^{-6}	1×10^{-3}	4×10^{-12}	4×10^{-9}	1×10^{-6}	3×10^{-6}
Lactose	6×10^{-7}	3.4×10^{-7}	2×10^{-3}	9×10^{-14}	5×10^{-10}	8×10^{-7}	1×10^{-6}