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The role of fluid turbulence on contact electrification of suspended particles

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ABSTRACT

A probabilistic version of a well-known phenomenological model for contact electrification is used to examine the effect of fluid turbulence on charge development for suspended particles as a function of the particle Stokes number. The distribution of particle collisions and particle charge appear to approach asymptotic states for high values of the Kolmogorov-scale Stokes numbers, exhibiting approximately normal distributions. The influence on particle contact electrification of differences in initial charge carrier density and in particle size are examined.

1. Introduction

Contact electrification is the transfer of charge that occurs when two particles collide with each other or when a particle collides with or rolls along a surface [35]. This phenomenon of charge transfer is usually called *contact electrification* when it occurs as a result of particle collisions and it is called *triboelectric charging* (or tribocharging) when it occurs due to frictional contact between materials that slide or roll relative to each other. Contact electrification of particulates in a turbulent flow occurs widely in both industrial and natural processes. Contact electrification in various process industries, such as coal mining, sawmills, grain mills and storage facilities, is known to lead to dangerous explosions of dust clouds [14]. Contact electrification is responsible for development of electric field gradients leading to formation of lightning in sandstorms [31,57,59] and volcanic eruptions [8,51]. Contact electrification due to dust storms plays a particularly important role on dusty planets, such as Mars, where it is responsible for the strong ambient charging of dust particles [15,18,21]. A leading theory for development of electric charge within thunderstorms is that it is caused by contact electrification due to collision of ice particles within the storm cell [23,46]. Similarly, contact electrification of ice particles in planetary ring systems, such as that of Saturn, lead to particle charging that influences the structure of the rings and their interaction with the planetary atmosphere [22,25]. A theoretical study by Ref. [11] proposed contact electrification of micrometer-scale particles in a turbulent environment as being responsible for formation of lightning in the solar nebula, which is important for formation of the small mm-scale chondrules that serve as the building blocks of the planetary system.

There has been a great deal of recent research on fundamental issues associated with particle contact electrification. Despite its importance to a large range of problems, many fundamental aspects of contact electrification remain unresolved. Even the most basic question of what exactly is transferred between the two colliding materials that gives rise to the charge differential is at present not entirely clear, and may in fact differ for different types of contact electrification processes. The problem is not a lack of explanations for the electrification process, but instead too many plausible explanations. Material particles, ions and electrons have all been proposed as possible charge carriers [4,29,36,54,56]. A traditional view of contact electrification is represented by the triboelectric series, which empirically orders materials to indicate the direction of charge transfer during contact electrification. However, the triboelectric series is not always reproducible [20,32], and order within the series can sometimes be reversed, such as following ultraviolet irradiation [26]. Contact electrification has also frequently been observed between chemically identical insulator particles [27,33,47]. Material inhomogeneity, asymmetric

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contact, electron band gap defects, and local polarization have all been used to explain the charging mechanism [3,28,29,33,39].

Despite on-going research on the fundamental physics of contact electrification, reasonable phenomenological models of particle charge exchange exist with which one might proceed to investigate other issues associated with the phenomenon [2,13,27,58]. Following this line of thought, the current paper examines the influence of the surrounding turbulent flow field on the particle electrification process. We note that contact electrification examples, such as those discussed in the first paragraph of this section, take place in a wide variety of fluid flow environments, ranging from normal earth atmosphere to the low-pressure Martian atmosphere to the near-vacuum conditions of Saturn's rings, and for particle sizes ranging from about 1 μm to 1 cm. The degree of interaction between the colliding particles and the fluid in which they are suspended can be characterized by a dimensionless parameter called the Stokes number, St, which is defined as the ratio of the characteristic time scale τ_p for particle drift relative to the fluid and the fluid time scale τ_f. For sufficiently small particles the Stokes drag law can be used to write the particle time scale as $\tau_p = m/3\pi\mu d$, where m and d are the particle mass and diameter, respectively, and μ is the fluid viscosity. The fluid time scale is typically taken to be the fluid convective time, given by the ratio $\tau_f = L/U$ of the characteristic fluid length scale L to the fluid velocity scale U. For small values of St, the particles are in an *orthokinetic* regime in which they move with the local fluid velocity and the collisions between particles are primarily due to the local fluid shear flow [45]. For values of St close to unity, the particles are in an *accelerative-correlated* regime and particles will drift considerably relative to the fluid. For heavy particles at sufficiently high concentration in a turbulent fluid, the drift induced by centrifugal force causes particles to cluster in high-concentration sheets lying in-between the turbulent eddy structures [5,16,19,48]. For St much larger than unity, the particles are in an *accelerative-independent* regime in which particle inertia is sufficiently large that particle motion is only slightly influenced by the fluid forces [1].

The current paper utilizes a probabilistic contact electrification model, together with a hard-sphere discrete element method for particle collisions and a pseudo-spectral method for direct numerical simulation of homogeneous turbulence, to examine the effect of the background turbulence on contact electrification of the particles for different Stokes numbers. The effect of turbulent flow both on the overall rate of contact electrification and on the collision and charge distribution is examined. The computational models used in the research are summarized in Section 2. Results of the paper are presented and discussed in Section 3, including the effect of Stokes number on contact electrification and an examination of contact electrification with bidisperse mixtures of particle size and initial charge carrier density. Conclusions are given in Section 4.

2. Computational methods

2.1. Particle transport

The particle collisions were simulated using the hard-sphere model, as described by Ref. [10]. The hard-sphere model solves the particle impulse equations during collisions to obtain the post-collision particle velocities $\mathbf{v}_n(i+1)$ from the given pre-collision velocities $\mathbf{v}_n(i)$ and restitution coefficient e. For two particles labeled 1 and 2, the restitution coefficient is defined by

$$e_{rest} \equiv \frac{|[\mathbf{v}_1(i+1) - \mathbf{v}_2(i+1)]\cdot\mathbf{n}|}{|[\mathbf{v}_1(i) - \mathbf{v}_2(i)]\cdot\mathbf{n}|}, \quad (1)$$

where $\mathbf{n}$ is the unit normal vector from the centroid of particle 1 to that of particle 2. The hard-sphere model also solves the angular impulse equations to obtain the particle angular rotation rate after the collision. The model uses Coulomb's law of friction for the sliding force and assumes that once a particle stops sliding, there is no later sliding of the particle. During the time period in-between collisions, the simulation method solves the particle momentum and angular momentum equations for the particle velocity and rotation rate, subject to forces and torques induced by the fluid, including viscous drag and torque, Saffman lift [43,44], and Magnus lift [42]. Added mass force, pressure gradient force and Bassett force are negligible based on the parameter values used in the computations. Electrostatic forces (Coulomb and dielectrophoretic forces) were also neglected on the assumption that particle charges were too weak for these forces to be significant in comparison to the fluid drag. The fluid velocity was interpolated from a 128^3 Cartesian grid onto the particle locations with cubic accuracy using the M4′ variation of the B-spline interpolation method developed by Ref. [37].

As two particles collide, the contact force between the particles is transmitted via a flattened contact region, across which the particle surfaces are separated by a small gap of width δ. The gap thickness is on the order of a nanometer, which for micrometer-scale or larger particles is much less than the particle diameter. For spherical particles, the contact region has a circular shape with radius $a(t)$. For non-adhesive particles, the contact region radius starts at a value of zero at the onset of contact, increases during the compression stage of the collision to a maximum value of $a_{\max}$, and then decreases again during the recovery stage of the collision until it vanishes again at the particle detachment point. An expression for the maximum contact region radius can be obtained using the Hertz contact theory as [24,35].

$$a_{\max} = \left(\frac{15 M w_r^2 R^2}{16E}\right)^{1/5}, \quad (2)$$

where $w_r = |[\mathbf{v}_2(i) - \mathbf{v}_1(i)]\cdot\mathbf{n}|$ is the relative radial velocity between two particles labeled '1′ and '2′ prior to the ith collision, and M, R and E are the effective mass, radius and elastic coefficient of the colliding particle pair, defined by

$$\frac{1}{M} \equiv \frac{1}{m_1} + \frac{1}{m_2}, \quad \frac{1}{R} \equiv \frac{1}{r_1} + \frac{1}{r_2}, \quad \frac{1}{E} \equiv \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}. \quad (3)$$

Here m_n, r_n, E_n, and ν_n denote the mass, radius, elastic modulus and Poisson's ratio for particle n, respectively.

2.2. Contact electrification

The phenomenological contact electrification model used in the current study is a stochastic version of the model proposed by Refs. [13] and [28]. The original model assumed that the charge carrier for contact electrification is a set of electrons trapped in high-energy band gaps, which transfer into a low-energy state when transported to a second particle during particle collision. However, it was noted by Ref. [9] that the model is equally valid with ions as the charge carrier (see also [54]). The number of charge carriers at time t is denoted by $N_{H,n}(t)$ on a particle n with diameter d_n. If the initial surface number density of charge carriers is ρ_n, then $N_{H,n}(0) = \pi\, d_n^2 \rho_n$. When a particle collides with another particle, each particle transfers to the other particle all of the charge carriers