Journal of Electrostatics 69 (2011) 456–460

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Contact charging between surfaces of identical insulating materials in asymmetric geometries

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ARTICLE INFO

Article history:
Received 8 October 2010
Received in revised form
28 April 2011
Accepted 9 May 2011
Available online 12 June 2011

Keyword:
Triboelectric charging

ABSTRACT

The charging that occurs when a pair of insulating surfaces of identical chemical composition are rubbed (i.e. triboelectric charging) remains poorly understood. It is believed that asymmetry in contact plays an important role in this charging. To study this phenomenon, we have developed an experimental methodology that asymmetrically rubs two surfaces by contacting a rotating cylinder with a stationary cylinder – the rubbing is asymmetric in that the contacting area is much greater on the rotating cylinder than on the stationary cylinder. We find that the charge transfer occurs with a spatial distribution of charge, in terms of magnitude and polarity, on the contacted area. The direction of the average charge transfer is material dependent: for Teflon–Teflon contact, the surface with the larger contacting area charges positively, but for Nylon–Nylon contact the surface with the larger contacting area charges negatively. This difference is interpreted as being due to a negatively-charged species transferred in the case of Teflon (electrons or negative ions), but a positively-charged species transferred in the case of Nylon (positive ions).

1. Introduction

Triboelectric charging plays an important role in various types of granular systems [1] ranging from dust storms [2] to volcanic plumes [3] to fluidized beds [4]. This charging generates electric fields, which have been detected in dust storms [5] and other granular flows [6]. A fundamental understanding of the charging mechanism remains unclear – the particles have the same chemical composition, and the symmetry inherent in contact between two surfaces of the identical material would seem to preclude a driving force for charge transfer. However, it has been pointed out that this symmetry can by broken by the way the surfaces rub [7], particle size differences [8,9], statistical variations in material properties [10], and external electric fields [11].

In this paper we focus on the role of asymmetric rubbing on triboelectric charging between identical insulators, which we believe is closely related to the role of particle size differences for granular systems. While our eventual goal is to understand triboelectric charging in granular systems, it is easier to perform controlled experiments on the charging of bulk materials in order to understand the effects of parameters such as material composition and contact area. In our methodology, two surfaces are asymmetrically rubbed against each other by contacting a rotating cylinder with a stationary cylinder.

2. Experimental method

We asymmetrically rub two cylindrically-shaped insulating materials by placing the cylinders at right angles with respect to one another, and rotating one of the cylinders, as shown schematically in Fig. 1. The cylinders touch each other at a point. However, the rubbing is asymmetric in that the rotating cylinder is contacted along its entire circumference (as the rotation angle, θ, goes from 0 to 2π), while the stationary cylinder is contacted at only a single point. To quantify the charge transferred during this rubbing process, a surface potential probe held near the rotating cylinder measures the “local surface potential”, $\Phi(\theta,n)$, at the position θ on the cylinder after a number, n, of rotations (Fig. 1b). The “average surface potential” after n rotations, $\Phi(n)$, for the rotating cylinder is the average of these local surface potentials over the circumference of the cylinder (i.e., $\phi(n) = \dfrac{1}{2\pi}\displaystyle\int_0^{2\pi} \varphi(\vartheta, n)\mathrm{d}\vartheta$); in practice, this integral is evaluated numerically with $\Delta\theta = \pi/5$.

Details of our experimental apparatus are as follows. The cylinders used are thin-walled tubes (inner diameter 3/4″, wall thickness 1/16″), which are fitted over a metal rod to provide mechanical stability; for experiments involving contact of identical materials, a single tube is cut into two pieces to ensure that the two

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doi:10.1016/j.elstat.2011.05.003

cylinders are composed of *truly identical* materials. At the beginning of each experiment, each cylinder is neutralized by a combination of methanol washing and drying with ionized air (Model 7901, Exair, Inc.). The stationary cylinder is pressed against the rotating cylinder using a spring-loaded metal fixture, and the latter is rotated at a constant rate using a stepper motor. The local surface potential at the position directly below the probe is measured as a function of time using a non-contacting electrostatic voltmeter (Model 370, Trek, Inc.) positioned 2 mm above the surface of the rotating cylinder; the probe senses an area on the cylinder of ~1 cm^2 (determined by the probe size of 6 mm × 6 mm), which is wider than the contact area on the cylinder (the contact area is in principle a line with infinitesimal width, since the two cylinders contact at a point). The rotation angle of the cylinder as a function of time, $\theta(t)$, is tracked using a digital encoder (Model E8P, US Digital). From $\Phi(t)$ and $\theta(t)$, the local surface potential is obtained as a function of position, $\Phi(\theta,n)$. A data acquisition system consisting of a GPIB interface, a digital card (National Instruments, USB-6008), and Labview software is used to record the measurements.

Experiments were performed under ambient and environmentally-controlled conditions. In the latter case, the charging of the insulators was carried out in a vacuum chamber (Laco Technologies). The chamber was first evacuated by a mechanical roughing pump, with a base pressure of 50 mTorr, then backfilled with dry nitrogen (N_2) gas. The chamber was held at a constant pressure, by setting the input N_2 flow rate and adjusting the needle valve to the vacuum pump; a Convectron pressure gauge (Model 275, Granville-Phillips) was used to monitor the pressure. To rotate the cylinder in vacuum, a ferrofluidic feedthrough (FerroTech) was employed. An electrical feedthrough was used to provide power to the electrostatic voltmeter probe inside the chamber. A grounded stainless steel mesh surrounded the apparatus inside the chamber to act as a Faraday cage and shield the measurements from outside electrical noise.

3. Results

3.1. Contact between different materials

To test our methodology, asymmetric rubbing experiments were initially performed between two *different* materials, Teflon (PTFE) and Nylon (Nylon 6,6) in an N_2 environment ($P = 250$ Torr). We examined both a rotating Nylon cylinder contacting a stationary Teflon cylinder, and a rotating Teflon cylinder contacting a stationary Nylon cylinder (recall that our methodology measures the surface potential only on the rotating cylinder). Results for $\Phi(n)$ are shown in Fig. 2. For the Nylon cylinder rotating against a stationary Teflon cylinder (Fig. 2a), $\Phi(n)$ increases in the positive direction with time, reaching a steady-state value of +50 V after 200 rotations. In contrast, for the Teflon cylinder rotating against a stationary Nylon cylinder, $\Phi(n)$ increases in the negative direction with time, and reaches a steady-state value of −600 V after 200 rotations (Fig. 2b). These results are in general agreement with the

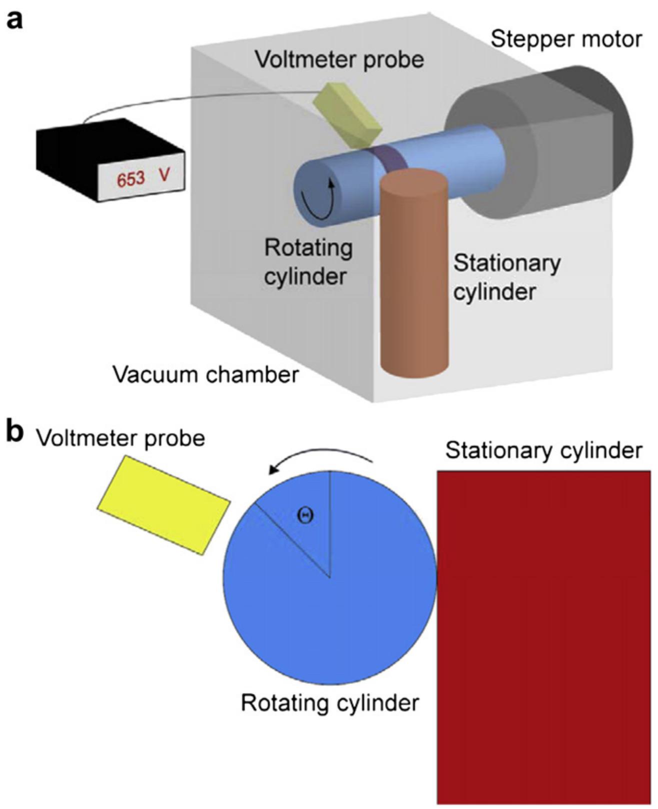

Fig. 1. (a) A schematic illustration of the experimental apparatus that asymmetrically rubs two insulating cylinders by rotating one of the tubes with a stepper motor. The charge on the rotating cylinder is measured by an electrostatic voltmeter. The apparatus is sealed inside a vacuum chamber to control the environment. (b) Schematic of the spatial charge distribution on the rotating cylinder measured by the electrostatic voltmeter probe. The charge is measured as a function of angular position, as the cylinder rotates, with a resolution of $\theta = 2°$.

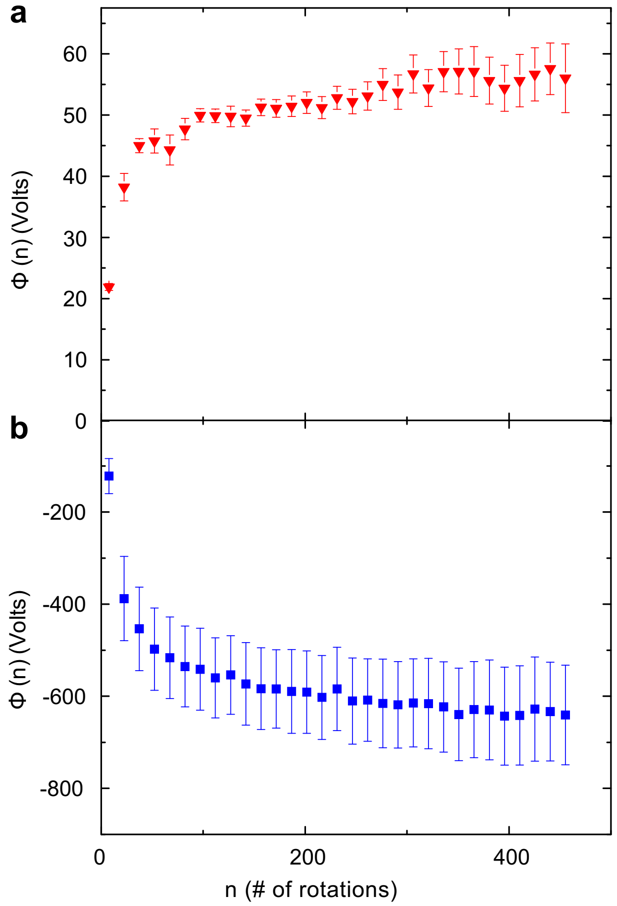

Fig. 2. The average surface potential, $\Phi(n)$, for (a) a rotating Nylon cylinder contacting a stationary Teflon cylinder and (b) a rotating Teflon cylinder contacting a stationary Nylon cylinder where n is the number of rotations. All trials were conducted in a controlled N_2 environment ($P = 250$ Torr). The results represent an average of $m = 9$ trials and error bars indicate the standard error $\frac{\sigma}{\sqrt{m}}$, where σ is the standard deviation.

triboelectric series, which predict that Nylon charges positively and Teflon charges negatively when the two surfaces contact one another.

Results for $\Phi(\theta,n)$, the local surface potential, are shown in Fig. 3 as a function of θ for the case of a rotating Teflon cylinder in contact with a stationary Nylon cylinder. While $\Phi(n)$ is negative (Fig. 3a), $\Phi(\theta,n)$ varies significantly with θ, and is even positive at some θ (Fig. 3b). Similarly, for the rotating Nylon cylinder in contact with a stationary Teflon cylinder, $\Phi(n)$ is positive (Fig. 4a), but $\Phi(\theta,n)$ varies significantly with θ and is negative at some θ (Fig. 4b).

3.2. Contact between identical materials

Similar asymmetric rubbing experiments were carried out for *identical* materials. Fig. 5a shows $\Phi(n)$ for a rotating Teflon cylinder contacting a stationary Teflon cylinder in a N_2 environment ($P = 250$ Torr). The rotating Teflon cylinder charges positively. For comparison, results were obtained under ambient conditions and showed that the charging is qualitatively the same, but smaller in magnitude than in the N_2 environment. Experiments were also carried out for a rotating Nylon cylinder contacting a stationary Nylon in a N_2 environment ($P = 250$ Torr) (Fig. 5b). In this case, the rotating cylinder charges *negatively* – opposite to the result found for Teflon. A similar difference in the triboelectric charging behavior between Teflon–Teflon and Nylon–Nylon has been reported by Lowell and Truskott [12].

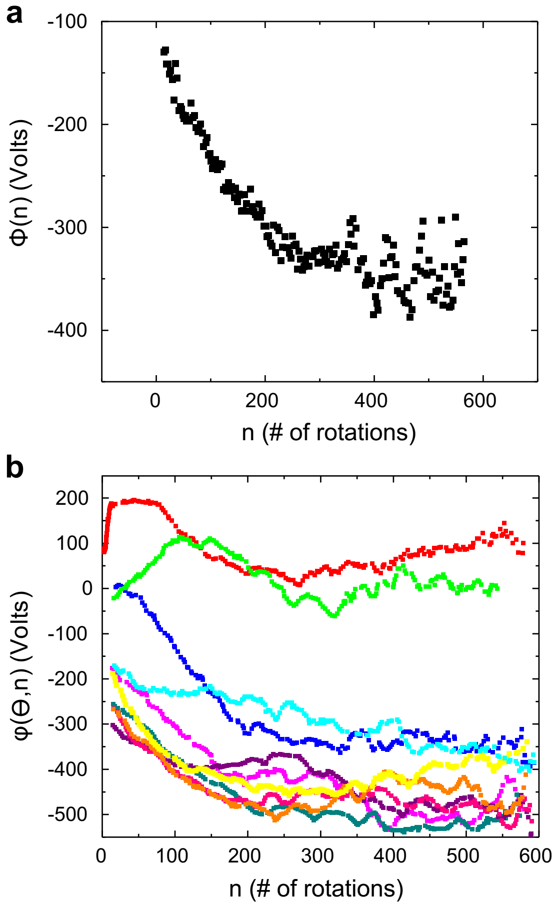

Fig. 3. Results for (a) the average surface potential, $\Phi(n)$, and (b) the local surface potential, $\Phi(\theta,n)$, for a rotating Teflon cylinder contacting a stationary Nylon cylinder (each color corresponds to a different θ; these θ are equally spaced in $\pi/5$ increments between 0 and 2π). Data is for 1 trial.

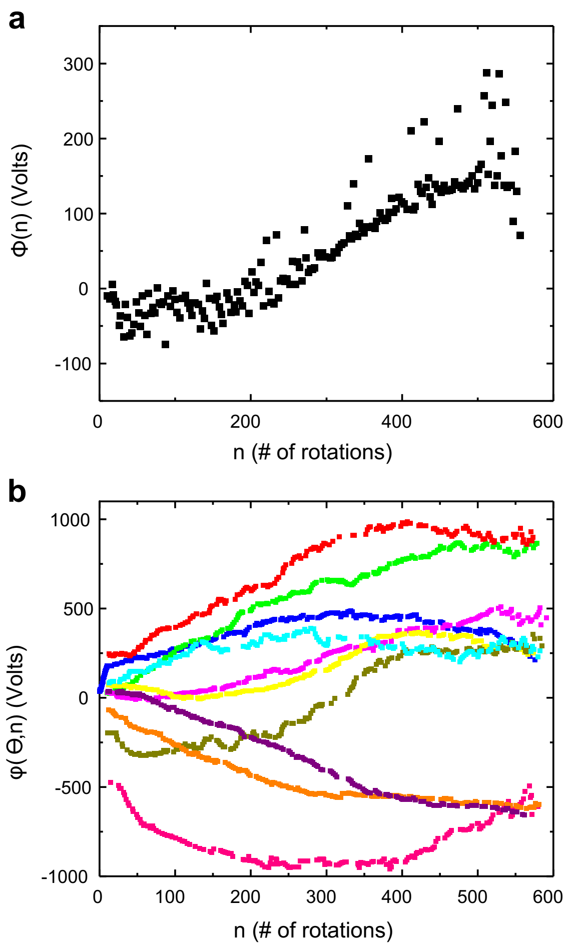

Fig. 4. Results for (a) the average surface potential, $\Phi(n)$, and (b) the local surface potential, $\Phi(\theta,n)$, for a rotating Nylon cylinder contacting a stationary Teflon cylinder (each color corresponds to a different θ; these θ are equally spaced in $\pi/5$ increments between 0 and 2π). Data is for 1 trial.

Fig. 6a shows $\Phi(\theta,n = 200)$, the local surface potential after 200 rotations, for a rotating Teflon cylinder in contact with a stationary Teflon cylinder. While $\Phi(n = 200)$ is positive (see Fig. 5a), $\Phi(\theta,n = 200)$ varies significantly with θ, and is negative at some θ. Similar variations in the local surface potential are reproduced on different trials (Fig. 6b and c).

4. Discussion

Before discussing our results, we point out that it is still unclear what is being transferred between surfaces during triboelectric charging – i.e., negatively-charged electrons or positively- or negatively-charged ions. Evidence in favor of electrons is that charge transfer in metal-insulator systems correlates with the work function of the metal [13], and triboelectrically charged surfaces have been found to initiate electrochemical reactions [14]. Evidence in favor of ions is that surface modification can alter the types of transferrable ions and lead to predictable changes in triboelectric charging [15], and that the degree of charging has been related to the zeta potential of the material [16,17]. Overall, it is possible that the species transferred (i.e. electrons or ions) can depend on the material and the conditions – triboelectric charging may sometimes be due to electrons being transferred, and other times due to ions being transferred. In addition, when surfaces are rubbed, abrasion and subsequent material transfer from one surface to the

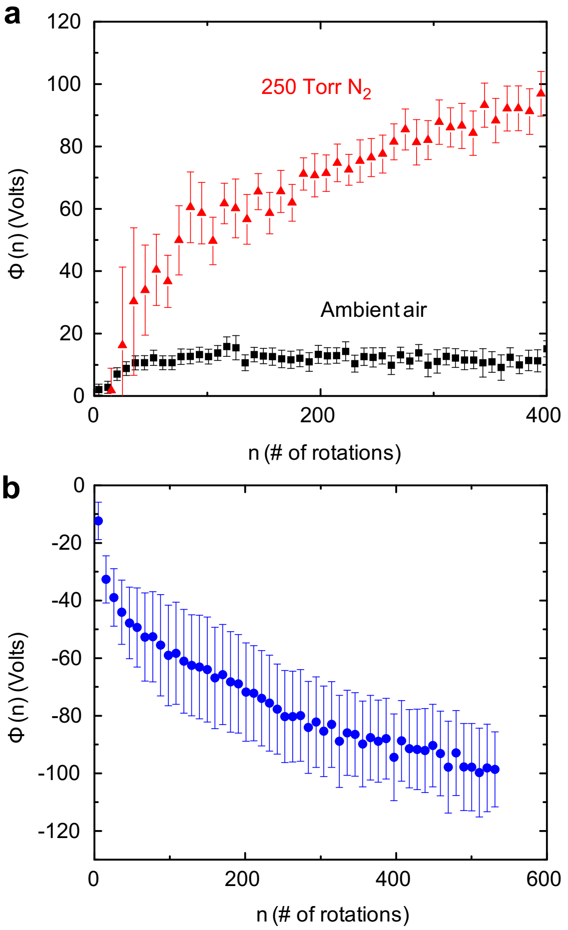

Fig. 5. The average surface potential, $\Phi(n)$, for (a) a rotating Teflon cylinder contacting a stationary Teflon cylinder at ambient conditions and in a controlled N_2 atmosphere ($P = 250$ Torr), and (b) a rotating Nylon cylinder contacting a stationary Nylon cylinder in a controlled N_2 atmosphere ($P = 250$ Torr) where n is the number of rotations. These results represent an average of $m = 9$ trials for Teflon and $m = 8$ trials for Nylon. Error bars indicate the standard error, $\frac{\sigma}{\sqrt{m}}$.

other can occur, providing another means for charge transfer between surfaces.

First, we address the large variations in the local surface potential Φ with position θ (see Figs. 3b, 4b and 6a, b, and c). Our results indicate that the surface charges inhomogeneously, both in terms of magnitude and polarity (i.e. some areas charge negatively while others charge positively). Similar results were found by Lowell and Akande [18], and subsequently by others [19,20], using completely different experimental procedures and materials. Lowell and Akande showed that the same variations occurred from trial to trial, suggesting local variations of some properties inherent in the material surface (rather than by a mechanism associated with the charging process such as charge migration or discharge) [18]. We have similarly measured spatial variations in the charge from different trials (see Fig. 6b and c), which suggests the same explanation in terms of variation in some properties of the surface. The nature of these variations in surface properties is not known.

We now address our results for charge transfer between asymmetrically rubbed surfaces of identical materials. Lowell and Truskott presented a theory to explain the effect of asymmetric rubbing on charge transfer [7]. This theory is based on nonequilibrium distributions of 'charged species' – in the Lowell-Truskott paper, the charged species were taken to be electrons, but it can be generalized such that the charged species could also be ions [21]. The idea behind their theory is that charged species may be trapped in high energy states (i.e., not at equilibrium), and contact with another surface allows these trapped species to relax to lower energy states *on the other surface*; this is a 'one-way' transfer, in that after the species relax to lower energy states they will not transfer again. The number of trapped species available to transfer from a given surface is proportional to the contacting area on that surface – in the context of asymmetric rubbing, this implies that more species transfer off of the surface with the larger contacting area than off of the surface with the lower contacting area, which leads to net transfer of the charged species from the surface with the larger contacting area to the surface with the lower contacting area. If the charged species are negative (electrons or negative ions), then the surface with the larger area of contact will charge positively, and if the charged species are positive (positive ions), then the

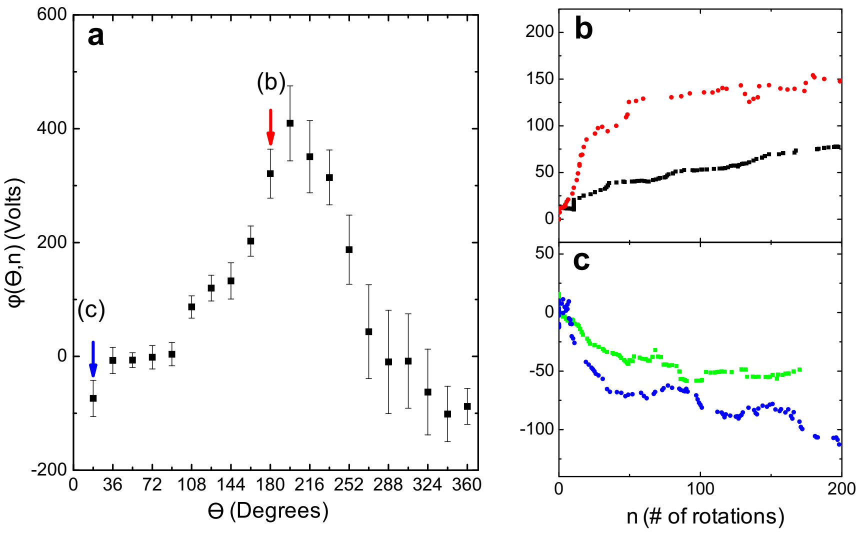

Fig. 6. (a) Local surface potential, $\Phi(\theta,n)$, as a function of angular position, θ, for a rotating Teflon cylinder in contact with a stationary Teflon cylinder. The potential was measured after $n = 200$ rotations and averaged over $m = 4$ trials. The local surface potentials at two angular positions, $\theta = 0°$ and $\theta = 180°$, are shown in (b) and (c), respectively, as a function of number of cylinder rotations. Red and blue data points are from one experimental trial, and black and green data points are from another trial. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

surface with the larger area of contact will charge negatively. In the case of Teflon–Teflon, the rotating cylinder charged positively. Since this surface has a larger area of contact, the result is consistent with negative charged species (electrons or negative ions) being transferred in the charging process. In contrast, in the case of Nylon–Nylon, the rotating cylinder charged negatively, which is consistent with positive charged species (positive ions) being transferred in the charging process.

We have previously shown that the theory put forth by Lowell and Truskott can be used to address electrostatic charging in granular systems [8,9]. Particle size differences play a similar role to asymmetric rubbing, in that the contacting area of a large particle is greater than that for a small particle – this leads to an accumulation of the charged species on the smaller particles. If the charged species are negative, this mechanism would lead to smaller particles charging negatively and larger particles charging positively. We note that the negative charging of smaller particles has been found in experimental studies of granular systems composed of silica, polyethylene, and Mars and Lunar regolith simulants, [22–24] and inferred from the polarity of dipolar electric fields in particle clouds (assuming smaller particles are blown to higher elevations in the particle clouds) [2,5,6]. Our present results, which suggest that positive ions are transferred when one Nylon surface contacts another Nylon surface, lead to the prediction that in granular systems composed of Nylon particles the smaller particles will charge positively. We are planning to carry out experiments to test this prediction.

5. Conclusion

Using asymmetric rubbing experiments, we have shown that when identical materials are contacted such that there is a difference in the contacting area, charge transfer occurs from one surface to the other. While there are spatial variations in the polarity and magnitude of the charge transferred, the average charge transfer is found to be in a single direction for a given material. This direction of charge transfer appears to be material dependent, and the surface that gets contacted over a larger area charges positively in the case of Teflon–Teflon, but negatively in the case of Nylon–Nylon. We suggest that this difference in charging may arise from different types of species being transferred – for Teflon, negatively-charged species are transferred (perhaps electrons), whereas for Nylon positively-charged species are transferred (positive ions).

Acknowledgments

We acknowledge funding from the National Science Foundation (CBET-0852773, DMR-0705191) and American Chemical Society Petroleum Research Fund

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