Frictional Flow and Developer Charge

Suresh Ahuja, Physicist. 1192 Gatestone Circle, Webster, NY 14580

Abstract

Intimate contact between the surfaces takes place by normal and tangential forces (friction). Lattice- Boltzmann and DEM methods have been used to analyze frictional flow, particle collisions and solving Navier- Stokes' equations.

Any collision between toner and developer can result in charge exchange that depends on dielectric relaxation. Charge transport processes in disordered complex media are accompanied by anomalously slow relaxation for which usually a broad distribution of relaxation times is adopted. To account for those properties of the environment, a standard kinetic approach in description of the system is addressed either in the framework of continuous-time random walks or fractional diffusion. A model can be constructed which assumes collisions between toner particle being elastic-plastic and an elastic carrier particle. Charge transfer takes place during each collision and the collision frequency is derived from particulate flow of cohesive particles. Charge to mass is analyzed for dependence on toner particle size, charge mobility, dielectric relaxation and yield stress (modulus) of toner and carrier surfaces. Model predictions are compared with experimental results.

Introduction

Charge exchange between surfaces has been modeled as taking place by electron transfer, ion transfer, mass transfer and acid base transfer[1]. For the three-dimensional polymer structure, carrier transport occurs not only along the chains, but also between the neighbor chains (intermolecular transport). It is generally believed that this intermolecular transport occurs via a hopping or tunneling mechanism dependent on molecular separation distances such that better packing of polymer chains and elimination of grain boundary defects enhance inter-chain transfer rate. Intimate contact between the surfaces takes place by normal and tangential forces (friction).

Electron or Ion Transfer in Contact Electrification

Mechanism of contact electrification has been investigated as electron transfer and ion transfer for many decades. A popular design tool in consideration of electron transfer has been work function and triboelectric series. If differences in a single physical property, such as the electron work function, were responsible for all instances of contact electrification, one could use the relative values of that property to arrange all materials into a single triboelectric series. There are some sets of materials, however, that form a cyclic triboelectric series[2]. Most researchers have assumed that the contact electrification of insulators also involves the transfer of electrons but experimental observations appear to contradict this view. The contact electrification of insulators does not correlate with bulk electronic properties, such as the dielectric constant, or atomic properties, such as ionization energy, electron affinity, or electronegativity[3]. The electron-transfer model is energetically plausible only for materials with no band gap (metals) or small band gaps (semiconductors).

Stability and reliability of toner charge is ensured through tha addition of external additives. Certain additives caused the toner to acquire a negative charge, whereas others caused it to acquire a positive charge upon contact electrification. Eelectron donors or acceptors such as electron-rich aromatic compounds or electron-poor quinones are not effective charge-control agents. Dyes that contain a large organic cation and a small inorganic anion yield a positively charged toner, whereas dyes that contain a large organic anion and a small inorganic cation yield a negatively charged toner[4].

In an assumption that the potential energy of a mobile anion (or cation) between two surfaces at different electrical potentials is given by the sum of three terms: two short-range interactions (one for each surface, with potential-energy curves shaped like a Lennard–Jones potential or Morse potential) plus a long range Coulombic interaction. In the hypothetical geometry in which the two surfaces are in van der Waals contact, an ion between the surfaces experiences a single potential well. As the two materials separate, the potential-energy surface evolves into an asymmetric double-well potential. The energy of the mobile ion is generally lower when it is close to its covalently bound counterion because of the favorable Coulombic interaction in that location.

Consider the behavior of a single anion during the separation of the two materials. When the two surfaces are in contact, the ion will move within its single potential well. When the surfaces are a small distance apart, and the doublewell potential has a sufficiently small barrier, the ion can move freely between the two surfaces. At some distance, the potential barrier becomes sufficiently high that it traps the ion kinetically on one surface or the other. The energy required to separate the surfaces, and increase the electrostatic potential between them, is supplied by the mechanical work used to separate the surfaces [5].

The decrease in contact electrification at high humidity is not surprising and probably involves increased surface conductivity. The decrease in contact electrification to nearly zero at 0%RH suggests that water is necessary for the transfer of ions during contact electrification. Contact of two surfaces, each having an adsorbed film of water, yields a "water bridge" between the surfaces. Over this short distance, the entropic (diffusional spreading) tendencies of the ions are comparable to the electrostatic forces, so the mobile ions will distribute themselves across the entire thickness of the water bridge. The high dielectric constant of water reduces the electrostatic cost of separating the mobile ions from their counterions. The final separation of charge occurs when the water bridge splits into individual adsorbed layers of water [6]. Forssberg and his team found correlation between zeta potential and contact electrification for polymers that contain bound ions and mobile counterions as well as correlation between the zeta potentials of several inorganic minerals and the contact electrification of these minerals. [7].

During flow of toner particles collisions take place between toner particles, toner particles and external additives and between

toner particles and carrier beads. The collisions are both normal and tangential. Tangential collisions involve dynamic friction. Collisions amongst particles or between particles and objects are, in general, not head-on, and thus, shear also has to be taken into account. By considering charge exchange in a single collision and the collision frequency, a rate equation can be derived which considers contact area formed in a single collision [8,9].

$$Q \cong K a_2^{\,3} v^{3/5} k_2^{\,4/5} \times \left(\frac{A_0}{2\pi a_2^{\,2}} \right) \left[1 - \exp\left(\frac{-2\pi a_2^{\,2}}{A_0} \right) ft \right] \quad (1)$$

where K is a rate constant, a_2 is the size of toner particle, v is the velocity of approach, k_2 is the reduced modulus of the toner, A_0 is the surface area of carrier bead, f is the number of toner particles striking a carrier bead per unit time. *K i*s defined as $A^* T^2 \exp(-e\varphi_B / kT)$ with A^* is the effective Richardson constant, T is the temperature, e is the charge on an electron, φ_B is the carrier toner barrier height and k is the Boltzmann's constant.

The velocity of approach is calculated using models of powder flow. Lattice- Boltzmann and DEM methods have been used to analyze frictional flow, particle collisions and solving Navier- Stokes' equations [10]. For laminar flow, velocity of particles in a tube can be calculated to be

$$v = U\left[1 - 2 \quad \left(y^2 / L^2\right)\right] - U_{TS} \quad (2)$$

where U is the average velocity of the particulate flow, y is the distance from the center of the tube, L is the tube radius and U_{TS} is the settling velocity.

Walter John investigated a model of charge transfer where the contact area and the separation of the particle such as toner contacts surface as of a carrier bead and forms a

parallel plate capacitor. The capacitor acquires charge through the application of the contact potential. [11]. The contact charge, Q, is given by

$$Q_c = \frac{\pi \epsilon_0 V_c}{Z} \left[\frac{5}{4} \pi^2 \rho v^2 (k_p + k_s) \right]^{2/5} \times a^2 (1 - e^{-\Delta t/\tau}), \quad (3)$$

where ε_0 is the permittivity, V_C is the contact potential, Z is the effective particle-surface separation, ρ is the density of the particle material, υ is the impact velocity, k_p and k_S, are the mechanical constants of the particle and carrier surface materials, respectively, a is the particle radius, Δt is the duration of the contact, and τ is the charge relaxation time of the particle.

The mechanical constants are given by

$$k = (1 - \nu^2)/(\pi E) \quad (4)$$

where v and E are the Poisson's ratio and Young's modulus.

For particles of insulating materials,

$$Q_c = \frac{2.94 \pi V_c}{ZK\rho_p} \left[\frac{5}{4} \pi^2 \rho (k_p + k_s) \right]^{4/5} v^{3/5} a^3, \quad (5)$$

where p, is the resistivity of the particle material and K is the dielectric constant. Experimentally, it is shown that charge on a particle such as a toner particle increases with increase in particle size, increase in modulus (hardness) of toner particle and increase in velocity of impact [11].

Conclusion

Models of particle- particle and particle- surface interactions are reviewed. Models predict the affects of particle size, modulus, velocity of impact, resistivity and dielectric constant. Limited experiments on particle size (toner size),impact velocity and modulus of particle(toner) are consistent with model predictions.

References

[1] Ahuja, S. K., Review of dynamic contact electrification models, European Conference on Electro photography, Cambridge England, 1976

[2] Harper W. R., Contact and Frictional Electrification, Laplacian, Morgan Hill, 1998.

[3] Wiles, J. A, Grzybowski, B. A..Winkleman, A . Whitesides, G. M. Anal. Chem. 75, 4859(2003).

[4] Diaz, A. F.,J. Adhes., 67, 11191998)

[5] Whitesides G. M. and McCarty, L. S. Angew. Chem. Int. Ed. 47, 2188 – 2207(2008).

[6] Kuo, I.-F.W., Mundy, C. J. Science 303, 658(2004)

[7] Manouchehri, H. R.. Rao, K. H , Forssberg, K. S. E. Part. Sci. Technol. 2001, 19, 23.

[8] Ahuja, S.K., J. Phy. D 9,1305(1976)

[9] Ahuja, S.K., J. Appl. Phy, 47(10),4706-4707(1976)

[10] Kumaran V., J. Fluid Mech. 506, 1 (2004).

[11] John W., Aerosol Science and Technology 23,2-24 (1995)

Acknowledgement

I am very grateful of the support from Xerox Corporation for decades.

Author Biography

Suresh Ahuja received his BS in physics and chemistry from the Punjab University (1959), his MS in Soil Physics from Indian Research Institute (1961) and his PhD in Polymer Physics from Polytechnic Institute of Brooklyn (1967). After working over 37 years at Xerox with several years as Principal Scientist he retired. He hasover twenty(20) patents.. He has published over 60 publications and presentations at international conferences. He is a member of APS, ASME, SOR and IST.