Numerical Analysis and Experiments on the Electromechanical Behavior of Wired-Shape Conducting Particles

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This paper presents the numerical analysis and experiments on the electromechanical behavior of conducting wired-shape particles. We investigate the effects of particle ending profiles and orientation on the initial motion prior to the particle liftoff. The boundary element method was used to analyze the electric field, force and torque on the particles. The experimental results show that the particles mostly began their motion at either end. When the sharp tip was separated from the electrode, the initial motion almost exclusively took place at the sharp end. On the other hand, the probability was slightly higher for the motion at the rounded end when the sharp tip was close to the electrode. The numerical calculation clarifies that the electrostatic and gravitational torques contribute to such liftoff behavior.

***Index Terms*— electrostatic, force, insulation systems, electromechanics, particle, torque.**

I. Introduction

It is well known that the presence of particles, particularly conducting ones, is a main cause of the insulation failures [1]. Particles may lower discharge onset voltage of the system. The corona onset and breakdown in the presence of particles were investigated theoretically or experimentally [2, 3]. Conducting particles are charged by a contact with an electrode and may move between electrodes [4]. Particle movement can magnify the undesirable field intensification.

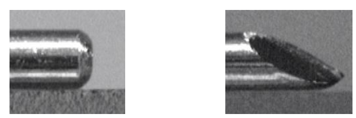
This paper presents numerical and experimental studies on the behavior of wired-shape particles under a uniform electric field in air. The particles exhibit complicated behavior under electric field [5]. The dependency of particle motion on the end profiles was found in an experiment [6]. Still, the role of the particle end and orientation has not been fully clarified. Our objective is to employ a numerical method to investigate fundamentals related to the initial motion of the particles and compare the results with particle behavior in experiments. As the motion behavior is closely related to the liftoff electric field, this study complements the prediction of particle liftoff prediction in insulation systems.

II. METHODS

Particles were 0.5mm diameter and 4 mm long aluminum wires (AL-01135, Nilaco). Their ends were either sharp or rounded by a sandpaper. Fig. 1 shows the ending profiles, whose tips are identified hereafter as rounded (R), sharp (S1) with a tip angle ≈ 35°, and S2 with a smaller tip angle ≈ 27°. For example, an R-R particle has two rounded ends, and an R-S1 particle has a rounded end and an S1 sharp end.

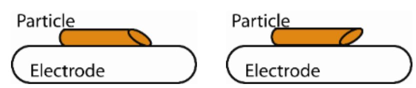
A. Configuration

We consider the configuration of a particle lying on a grounded electrode under an external electric field. For a particle with one sharp end, Fig. 2 shows two orientations of particle treated in this work. That is, the tip is either close to the electrode surface in Fig. 2a or well separated from the surface in Fig. 2b.



(a) (b)

Fig. 1. Ending profiles of the particles: (a) rounded end and (b) sharp end.



(a) (b)

Fig. 2. Orientation of the sharp tip for an R-S particle: (a) tip close to electrode surface and (b) tip well separated from electrode surface.

B. Numerical Analysis

We used the boundary element method (BEM), a numerical field calculation method, to analyze the electric field on the particles. The BEM is based on the relationship between potential ϕ and the normal outward component E_n of the electric field on the boundary of a domain. For potential ϕ_i at point i in domain Ω enclosed by boundary Γ,

$$C_i\phi_i = \int_\Gamma \psi(\mathbf{r},\mathbf{r}_\Gamma)E_n \,\mathrm{d}\Gamma + \int_\Gamma \frac{\partial \psi(\mathbf{r},\mathbf{r}_\Gamma)}{\partial n}\phi \,\mathrm{d}\Gamma - \mathbf{E}_0(\mathbf{r}-\mathbf{r}_0) \tag{1}$$

where $\mathbf{r}$ is the position of i, $\mathbf{r}_\Gamma$ is the position on boundary Γ, $\mathbf{r}_\Gamma$ is the reference point of zero potential, ψ is the fundamental solution, and C_i is a constant. We omitted the upper electrode by using a condition of an applied vertical electric field $\mathbf{E}_0$ in (1). The presence of the lower electrode was treated by using image elements. The calculation was carried out by using an in-house program for calculation flexibility and for post-processing. The numbers of elements were between 5000–7000 for all cases.

After the electric field calculation, we determined the electrostatic force $\mathbf{F}_E$ on a particle. $\mathbf{F}_E$ acts in the upward direction, tending to lift the particle from the lower electrode. The liftoff electric field E_L can then be determined from the balance between $\mathbf{F}_E$ and downward gravitational force $\mathbf{F}_G$.

We can determine electrostatic torque $\mathbf{T}_E$ about point **c** from the following integration on particle surface S:

$$\mathbf{T}_E = \oint_S \mathbf{r}_c \times \mathbf{f}_E \, ds \quad (2)$$

where $\mathbf{r}_c$ is a vector from **c** to the point of integration. We calculate $\mathbf{T}_E$ and gravitational torque $\mathbf{T}_G$ about the left and right ends, and the total torque $\mathbf{T}_{TOT}$ is then obtained from $\mathbf{T}_{TOT} = \mathbf{T}_E + \mathbf{T}_G$.

C. Experiments

Experiments used a parallel electrode system of 10 mm gap. DC high voltage of positive or negative polarity was applied to the upper electrode. The particle motion was recorded by frame rates up to 1000 fps. To examine the particle motion induced by the critical electric field for the lift-off condition, we increased the voltage magnitude gradually by 0.5 kV/s until the particle began to move. Separated experiments were also carried out by applying a fixed voltage magnitude to compare the behavior under the same electric field strength.

III. RESULTS AND DISCUSSION

A. Electric Field

Fig. 3 presents distribution of electric field E_n on the R-S1 particle. (E_n is normalized by the applied electric field.) The R-R particle has the smallest value of the field maximum, whereas the R-S2 particle has the highest field maximum when the sharp tip is separated from the lower electrode. The electric field in Fig. 3 is highly nonuniform at the upper tip, which contributes the large electrostatic force on the particle. The unsymmetrical distribution of electric field between the left and right halves of the R-S1 particle implies a rotating behavior of particle from the lying orientation. At the time that a particle begins to rotate, the surface force acts at the center of the rotation, and has no contribution to the torque. However, we must consider the gravitational torque, which depends on the tip profile and orientation.

Fig. 3. Electric field E_n, normalized by the applied field, on the surface of R-S1 particle having the sharp tip separated from the electrode.

B. Initial motion

Based on the recorded particle motion, we classify the particle behavior as the initial motion at (a) rounded end, (b) sharp end and (c) both ends, i.e., parallel liftoff, as illustrated schematically in Fig. 4. Table 1 summarizes the probability of each kind of the initial motion for the R-S1 particle when the applied voltage was gradually increased until the particle moved. The table clearly shows that the probability of initial motion at both ends was very small when the ending profiles were different. When the sharp tip was close to the electrode, the probability that the rounded end moved first was slightly higher. On the other hand, when the tip was well separated from the electrode, the particles raised the sharp end first in almost all tests.

We calculate the torque on the R-S1 and R-S2 particles by taking the rounded (left) and sharp (right) ends of the contact line between the particle and the electrode as the center of rotation. The torque magnitude is referred to be positive if it rotates the opposite ending point upward from the electrode. Fig. 5 shows the calculated total torque T_{TOT} for each orientation when applied field is 7 kV/cm, approximately the liftoff field in experiments. The torque is larger about the sharp end than about the rounded end when the sharp tip is close to the electrode. On the contrary, when the sharp tip is separated from the electrode, the torque about the rounded end becomes remarkably stronger. Therefore, the calculation results can be used to explain the observed particle motion.

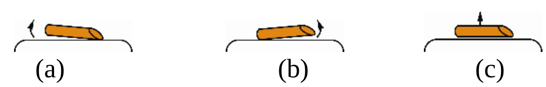


Fig. 4. Schematic illustration of initial motion of particle at (a) rounded end, (b) sharp end and (c) both ends.

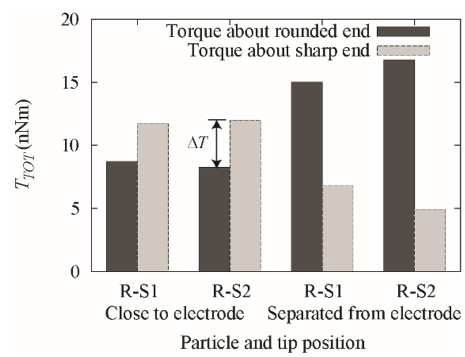


Fig. 5. Total torques T_{TOT} on the particles with one sharp tip under 7 kV/cm electric field.

TABLE I
INITIAL MOTION OF THE R-S1 PARTICLE AT THE CRITICAL LIFTING FIELD

Orientation	Probability of initial motion (%)		
	Rounded end	Sharp end	Both ends
Fig. 2a	53	40	7
Fig. 2b	3	97	0

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