Negative Dielectrophoresis 를 이용한 미세 입자의 유전율 측정

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Estimation of Dielectric Constant of Small Particles Using Negative Dielectrophoresis

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Abstract

The dielectric constants of small particles are estimated using negative dielectrophoresis(DEP). A pair of cylindrical electrodes is proposed to produce a non-uniform electric field that levitates a dielectric particle. Measuring the height of the levitated particle, we can calculate the effective polarizability, and estimate the dielectric constant of the particle using a non-linear regression method. By determining dielectric constant of polystyrene and polychloromethylstyrene particle, the proposed electrode structure and method show the possibility to measure the dielectric constants of dielectric particles.

Introduction

There are several methods to measure the dielectric constants of small dielectric particles or biological cells, including the suspension method [1], the micropipette method [2] and the DEP method [3]-[7]. In the suspension method, only the average values of the particles dielectric constant can be found because many particles are required for the good sensitivity. Although the dielectric constant is measured directly for individual cells in micropipette method, the analysis of the method is complex due to the leakage current. In non-uniform electric field, dielectric particles or cells move toward the region of the strongest electric field or that of the weakest field, depending on the sign of the effective polarizability at the working frequency. The former is called the positive DEP and the latter the negative DEP. The DEP force levitates a dielectric particle or biological cell stably with or without control. The dielectric constant can be estimated from the levitation height and the theoretical formulas.

T. B. Jones et al. has contributed to the determination of dielectric constant using the the DEP method and reported several electrode geometries for the negative DEP [4]-[9]. But the structures of these electrodes are complex and locks any explicit expression for the stable levitating point.

In this paper, we measure dielectric constants of dielectric particles using the negative DEP method. A pair of cylindrical electrodes is proposed to generate the non-uniform field. With the effective polarizability for the theoretical model and the estimated effective polarizability from analysis and experiments, particle dielectric constants are determined by non-linear regression.

Analysis

Fig. 1 shows the proposed electrode structure. When voltage is applied to the electrodes, the negative DEP force applied to the particle, F_{dep}, balances the gravitational and buoyant force. The time-averaged DEP force is determined by the effective polarizability, χ_{eff} and the gradient of the square of the electric field as shown in Eq. (1).

$$\langle \mathbf{F} \rangle = \frac{1}{4} v \chi_{eff} \nabla |\mathbf{E}|^2 , \tag{1}$$

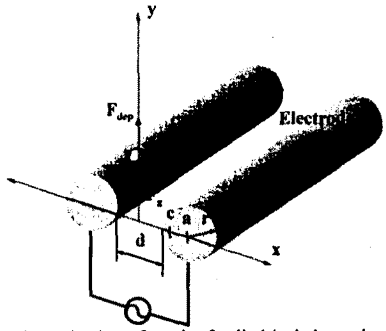

Fig. 1. Schematic view of a pair of cylindrical electrodes

where v is the volume of the particle, and $\mathbf{E}$ is the intensity of the electric field. The effective polarizability is the function of the conductivities and permittivities of the spherical dielectric particle and medium [10]. The particle is stably levitated at the minimal point of the potential energy. The potential energy of the system, U, is the sum of two terms

$$U = U_e + U_g , \tag{2}$$

where $U_e = -\frac{1}{4} v \chi_{eff} |\mathbf{E}|^2$,

and $U_g = v(\gamma_2 - \gamma_1) g y$,

and where γ_2 and γ_1 are the densities of the particle and the medium respectively, and g is the gravitational constant. The electric field in figure 1 is expressed as

$$\mathbf{E} = -\frac{cV}{\ln\left|\frac{a+r-c}{a+r+c}\right|}\left(\frac{x^2-c^2-y^2}{\left((x-c)^2+y^2\right)\left((x+c)^2+y^2\right)}\mathbf{i} + \frac{2xy}{\left((x-c)^2+y^2\right)\left((x+c)^2+y^2\right)}\mathbf{j}\right), \qquad (3)$$

where $c^2 = a^2 - r^2$,
where r is the radius of the electrode, a is the center position of the electrode, c is the position of the equivalent line charge and V is the applied voltage [11]. As the structure of the electrodes is axisymmetric, the minimal point of the potential energy can be obtained by the equation, $\frac{\partial U}{\partial y} = 0$. The stable height of the levitated particle is determined by

$$-\frac{D}{B}y = A\left(c^2 + y^2\right)^3, \qquad (4)$$

where

$$A = \frac{\left(\ln\left|\frac{a+r-c}{a+r+c}\right|\right)^2}{c^2},\quad B = (\gamma_2 - \gamma_1)g,\quad D = V^2\chi_{eff}.$$

The constant A depends only upon the geometry of the electrodes. B involves the effect of the difference between the particle and the medium densities. D depends on the effect of the applied voltage and the electric parameters of the medium and the particle. The intersection of the curve and the line in the equation (4) is a minimum or a maximum of the potential energy. Depending on B and D, the number of the intersection point is one, two or zero. The levitation height(critical levitation height), when the number is one, is important. The critical levitating point is defined in the Eq. (5):

$$y_p = \frac{c}{\sqrt{5}}. \qquad (5)$$

When the number of intersections is two, the levitation height larger than the critical levitation height is a stable levitation height. While the other is an unstable equilibrium. The parameters, A, B, and D, must be carefully chosen so that the levitating point is higher than the critical levitating point. When the height of the levitated dielectric particle is measured at an applied AC voltage, the effective polarizability at the frequency can be calculated using Eq. (4).

When a spherical particle is suspended in a medium, the effective polarizability can be expressed as

$$\chi_{eff} = \varepsilon_1\left(3\frac{\varepsilon_r - 1}{\varepsilon_r + 2} - \frac{9(\varepsilon_r - \sigma_r)}{(\varepsilon_r + 2)(\sigma_r + 2)\left(1 + \omega^2\tau^2\right)}\right), \qquad (6)$$

where $\varepsilon_r = \frac{\varepsilon_2}{\varepsilon_1}$, $\sigma_r = \frac{\sigma_2}{\sigma_1}$, $\tau = \frac{\varepsilon_2 + 2\varepsilon_1}{\sigma_2 + 2\sigma_1}$,

and $\omega = 2\pi f$,

and where ε_1 and ε_2 are the permittivity of the medium and particle, respectively, σ_1 and σ_2 are the conductivity of the medium and particle, respectively, and ω is angular frequency [10]. From the data of the effective polarizability in the experiment and the theoretical expression in Eq. (6), the dielectric constant can be estimated using non-linear regression method. The sum of squares of the error is defined as

$$S = \sum_i \left(\chi_{eff,i}^{\exp} - \chi_{eff,i}^{theory}\right)^2. \qquad (7)$$

$\chi_{eff,i}^{\exp}$ means the experimented value of effective polarizability from the levitation height and Eq. (4). $\chi_{eff,i}^{theory}$ is the theoretical value from Eq. (6). Minimizing the summation of Eq. (7) gives the conductivity and dielectric constant of the dielectric particle. The Levenberg-Marquart method is used for the non-linear regression.

Experiments and Results

The electrode gap, d, in Fig. 1 is designed to have 95μm. The narrow gap greatly reduce the capacity of power supply. The levitation height is measured over the frequency range of 1-1000Hz and at two voltage values, 120V and 140V. Polystyrene particle(φ = 100μm) in corn oil(ε = 3.1, σ = 5.0x10^{-11}[S/m]) is levitated between the electrodes(φ = 2mm) as shown in Fig. 2.

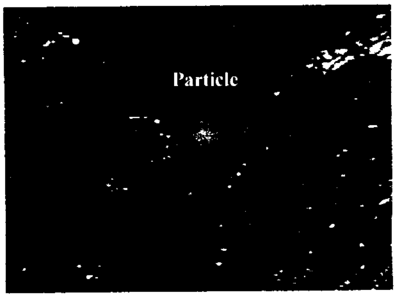

Fig. 2. Photograph of the levitated polystyrene particle

Fig. 3 shows the experimental results obtained with spherical polystyrene particle. As the maximum variation of the height of each experiment is nearly 5μm, causing an error of ± 1% error in the effective polarizability. It is negligible in the estimation of the permittivity. The higher levitation height is obtained at higher voltage. Fig. 4 shows the experimental results of a spherical polychloro-methylstyrene. It shows the similar results to that of a polystyrene particle.

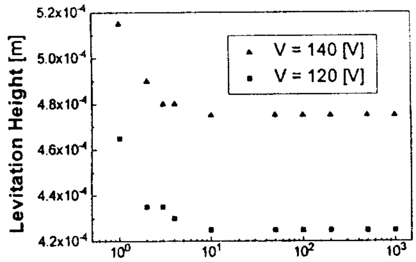

Fig. 3. Levitation height of polystyrene particle

The effective polarizability, χ_{eff}, can be calculated from the experimental height and Eq. (4). The marks in Fig. 5 and Fig. 6 show this effective polarizability. The dielectric constants are determined by non-linear regression method using Eq. (6) and Eq. (7). The estimated dielectric constants and published value are given in table 1. The estimated values of polystyrene particle compare favorably with handbook data [12]. As it is known that the addition of chloride in polymer increases the dielectric constant, it is reasonable that the dielectric constant of polychloromethylstyrene is larger than that of polystyrene.

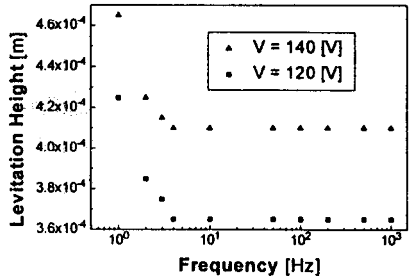

Fig. 4. Levitation height of polychloromethylstyrene particle

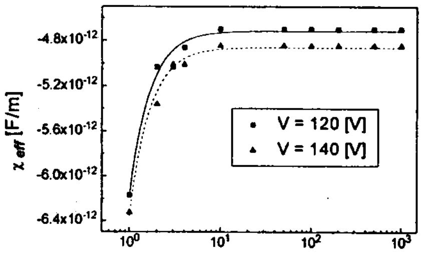

Fig. 5. Plot of the calculated effective polarizability for polystyrene particle

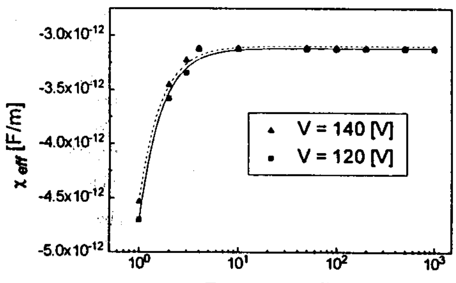

Fig. 6. Plot of the calculated effective polarizability for polychloromethylstyrene particle

Table 1. Estimated values of dielectric constant at T=25℃ (*Handbook of plastics)

Dielectric constant	120[V] d=95[μm]	140[V] d=95[μm]	handbook*
Polystyrene	2.60	2.58	2.5 - 2.7
Polychloro-methylstyrene	2.76	2.76	n.d.

Discussion

In the Fig. 5, the effective polarizability has some difference. It comes from the measuring limit of our experiments. The minimum scale in our experiments is 5μm due to the limit of magnification of our system.

The electric potential energy, U_e, in Eq. (2) is based on the equivalent dipole method. The experimental setup and the size of particles in the experiments, do not satisfy the above assumption. Althogh it could cause some discrepancies from exact values, the dielectric constants of small paticles can be roughly and easily determined.

Conclusion

The dielectric constants of spherical dielectric particles, polystyrene and polychloro-methylstyrene particles, are estimated using negative dielectrophoresis. A simple new electrode structure is proposed to measure the dielectric constants of dielectric particles. The estimated dielectric constants agree with the handbook value. Therefore, using the proposed method, dielectric constant of particles can be measured without any control to levitate particles.

Acknowledgment

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