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Effects of particle size and its size distribution on the forces and particle configurations during the particle size measurement using the interactive force apparatus

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This paper describes the effects of particle size and its distribution on size measurements by means of interactive force apparatus. The apparatus was proposed for particle size measurement in our research group. The advantage of this apparatus is that size measurement using the apparatus is a direct measurement, not depending on the concentration and optical transparency of the solution. Moreover, the measurement can be conducted in both the aqueous solution and organic solvent. Other common apparatuses for size measurements using laser source (i.e., the dynamic light scattering and laser diffraction) are difficult to measure the size of particles in the solution of high particle concentration and/or low transparency accurately, due to multi-scattering of light in the sample solution or solvent. However, the appropriate experimental conditions for particle size measurement using the interactive force apparatus have not been fully determined. In the present study, (a) appropriate particle size range and (b) particle size distribution were determined by calculating (a) the forces acting on fine particles and (b) the potential energies of a cluster under the electric field.

Key words: particle size, particle size distribution, forces on particles, particle configuration, interactive force apparatus

1. INTRODUCTION

It is important to manipulate the degree of dispersion and coagulation of nano-particles in various medium (e.g. aqueous solution and organic solvent) for the many process industries. Therefore, there is a need for understanding the dispersion and coagulation of nano-particles in the medium. There are many techniques for evaluating the dispersion and coagulation of nano-particles, i.e. size measurement turbidity measurement, contact angle measurement, zeta potential measurement, force measurement as well as combination of these techniques. However, these methods usually are not suitable for evaluating the dispersion and coagulation of particles in sample solutions of high concentration or the solution with no optical transparency. On the other hand, these kinds of solutions are commonly used in the many industrial procedures, such as separation of fine particles, deposition of fine particles on fibers.

There are many techniques for particle size measurement. The techniques can be divided in two categories, i.e. measurement in dry condition and measurement in wet condition. In dry condition, the microscopic studies based on optical microscopy, SEM and TEM are the most common techniques for size measurement of particles. In wet condition, the techniques using laser source (i.e. the dynamic light scattering and laser diffraction) are the most common techniques for size measurement of particles. Although these techniques have several advantages, they have some drawbacks. The techniques in dry condition are not applicable for measuring the size of particles in solutions. On the other hand, the techniques in wet condition are not suitable for estimating the size of particles in sample solutions of high concentration or the solution with no optical transparency.

The interactive force apparatus[1] was proposed as an apparatus for particle size measurement. The apparatus is a direct measurement technique, not depending on the concentration and optical transparency of the solution. Moreover, the measurement can be conducted in both the aqueous solution and organic solvent. However, the appropriate experimental conditions for particle size measurement were not fully determined. In the present study, (a) appropriate particle size range and (b) particle size distribution were determined by calculating (a) forces acting on fine particles and (b) potential energies of a cluster under the electric field.

2. FORCES ACTING ON FINE PARTICLES UNDER THE ELECTRIC FIELD

Adhesion forces between fine particles were calculated in order to evaluate the dominant force under the electric field. The van der Waals force (F_{vw}), the electrostatic force (F_e) and the dielectric force (F_{di}) were calculated by using Eqs. 1 - 3.

$$F_{vw} = -\frac{Ad}{12h^2} \qquad (1)$$

$$F_e = -\frac{\pi\sigma_1\sigma_2 d^2}{\varepsilon_0\varepsilon_{r_m}} \qquad (2)$$

$$F_{di} = -\frac{1}{4\pi\varepsilon_0\varepsilon_{r_m}}\frac{6(PV/3)^2}{r^4} \qquad (3)$$

where A is Hamaker constant, d is particle size, h is separation distance between two particles, σ_1 and σ_2 are surface charge densities, ε_0 and ε_{r_m} are the permittivity of free space and relative permittivity of medium, P is the polarization of dielectric material given in Eq. 4, V is the volume of particle .

$$P = (\varepsilon_r - 1)\varepsilon_0 E \qquad (4)$$

where ε_r is the relative permittivity of material. Here the polarization is assumed to be located on the center of spherical particle. The intensity of polarization of spherical particle is PV / 3. Table 1 shows the particle properties and input parameters for calculating coagulation force between two particles.

Table 1 Particle properties and input parameters for calculating coagulation force between two particles

Hamaker constant of silica (in aqueous solution), A/J	3.81 x 10^{-20}
Particle separation distance, z_0/nm	4.00 x 10^{-10}
Dielectric coefficient of free space, ε_0/Fm^{-1}	8.85 x 10^{-12}
Surface charge density of particle, σ_1, σ_2 /Cm^{-1}	2.65 x 10^{-6}
Relative permittivity of water, ε_{rm}(−)	80.4
Relative permittivity of silica, ε_r(−)	3.78
Volume of particle, V/m^3	1.00 x 10^{-6}

3. POTENTIAL ENERGIES OF A CLUSTER UNDER THE ELECTRIC FIELD

Potential energies of a cluster composed of fine particles were calculated in order to evaluate the formation of cluster under the electric field. In the present study, investigation of the formation of linear and triangular configurations composed of magnetic particles[2] was modified. In order to investigate the formation of these structures composed of dielectric particles under the electric field, a case where three particles in contact with each other at their surfaces was considered. The dielectric moments of the three particles is assumed to be aligned with the electric field direction. One of the three particles is denoted by i and the others are denoted by j. Two particles j have the same diameters d_j . The influence of the diameter d_i of particle i on potential energies of the linear ($u_{lin}^{(p)}$) and triangular ($u_{tri}^{(p)}$) configurations was evaluated by using Eqs. 5 and 6 derived from the Eqs. developed by Aoshima and Satoh[2] with the assumption that there is no steric layer around the surface of particles.

$$\frac{u_{\mathrm{lin}}^{(p)}}{kT\lambda_0} = -2\left(\frac{d_i d_j}{d_0^2}\right)^3\left(\frac{d_0^3}{\left(\frac{d_i+d_j}{2}\right)^3}+\frac{d_0^3}{\left(\frac{d_i+d_j}{2}+d_j\right)^3}\right)-2\left(\frac{d_j}{d_0^2}\right)^3\frac{d_0^3}{{d_j}^3} \qquad (5)$$

$$\frac{u_{\mathrm{tri}}^{(p)}}{kT\lambda_0} = 2\left(\frac{d_i d_j}{d_0^2}\right)^3\frac{d_0^3}{\left(\frac{d_i+d_j}{2}\right)^3}\left(1-3\frac{4\left(\frac{d_i+d_j}{2}\right)^2-{d_j}^2}{4\left(\frac{d_i+d_j}{2}\right)^2}\right)+\left(\frac{d_j}{d_0^2}\right)^3\frac{d_0^3}{{d_j}^3} \qquad (6)$$

where k is the Boltzmann's constant, T is the absolute temperature, λ_0 is the dimensionless parameters for the particles with the mean diameter d_0.

4. RESULTS AND DISCUSSION

4.1 Forces acting on fine particles under the electric field

Adhesion forces between fine particles were calculated in order to evaluate the dominant force under the electric field. Figure 1 shows the calculated values of the van der Waals force (F_{vw}), the electrostatic force (F_e) and the dielectric force (F_{di}). It should be noted that the van der Waals force is stronger than the dielectric force where (1) d is less than 10000 nm under the electric field of smaller than 1x10^8 V/m, and (2) d is less than 1000 nm under the electric field of 1x10^9 V/m. Particle size should be lower than 1000 nm to prevent artificial coagulation based on dielectric force when the applied electric field is higher than 1x10^9 V/m for the measurement. Therefore, the van der Waals force is the dominant adhesion force between fine particles within the calculated range. The interactive force measurement should be conducted within the range in order to measure the size of fine particles, where the much less effect of the electric field acts on the coagulation of fine particles than the van der Waals force.

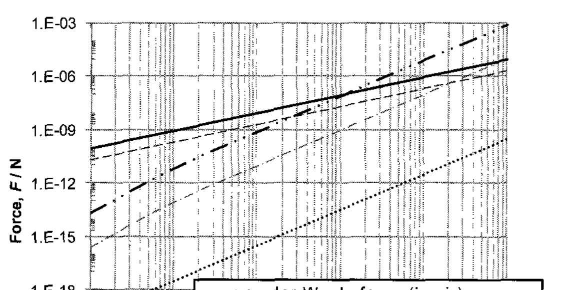

Fig. 1 Adhesion forces between two particles under the electric field under the electric field of 1.00 x 10^9 V/m.

4.2 Potential energies of a cluster

Potential energies of linear and triangular formation as a function of particle diameter are shown in Fig. 2. It should be noted that potential energy of the linear and triangular configurations intersect at d_i / d_0 = 2.6. Therefore, the linear configuration is more stable than the triangular configuration where d_i / d_0 is less than 2.6. If the particle size distribution was Gaussian distribution of variance σ^2 = 0.2, 0.4, 0.8 and 1.6, possibility of triangular formation under the electric field were 0.01%, 0.45%, 3.2% and 9.6%, respectively. Therefore, triangular formation is negligible i.e., the linear configuration is dominant when the Gaussian distribution of variance $\sigma^2 \leq 0.4$.

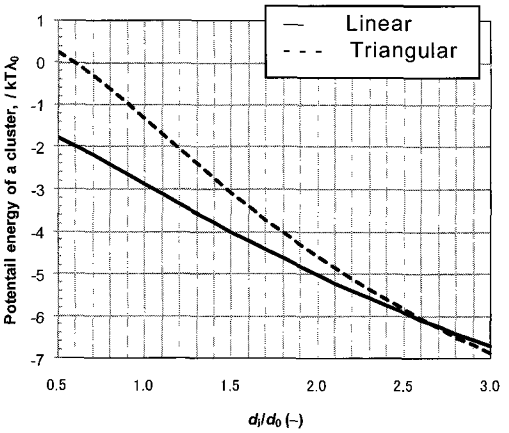

Fig. 2 Potential energies of linear and triangular formation as a function of particle diameter d_i / d_0.

5. CONCLUSIONS

In the present study, (a) appropriate particle size range and (b) particle size distribution were determined by calculating (a) forces acting on fine particles and (b) potential energies of a cluster under the electric field. According to the calculations, the appropriate conditions for measuring measures the size of fine particles by using interactive force apparatus were proposed as follows:

(1) The particle size is in the range within 1 nm – 100 μm where much less effect of the electric field acts on the coagulation of fine particles than the van der Waals force under the electric field of smaller than 1×10^8 V/m.
(2) The particle size distribution is the Gaussian distribution of variance $\sigma^2 \leq 0.4$ when the linear configuration is dominant over the triangular configuration.

References

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