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The deposition morphology of Brownian particles onto a spherical collector

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Abstract

The deposition morphology of particles onto a spherical collector is investigated by applying the Brownian dynamics simulation method in the present paper. The effect of various types of the total interaction energy curves of DLVO theory, and of the shadow area cast by those deposited particles, on the particles' collection efficiencies are examined. The simulation results show that the collection efficiency is always higher when the particle's Brownian motion behavior is taken into consideration. As the deposition location moves closer to the front stagnation point of the collector, the dendrites formed by those Brownian particles also contain more particles. The present simulation method successfully describes the amount of particles collected as well as the morphology of the deposits in a detailed step-by-step manner.

Keywords: Deposition; Morphology; Brownian particle; DLVO theory; Filtration

1. Introduction

The importance of knowing the morphology of particle deposits is obvious in determining the collection efficiency of a fixed bed granular filter. Since the formation and growth of particle deposits changes the surface characteristics of individual collectors continuously in a deep bed filter, hence the extent of particle deposition profoundly affects the rate of particle retention and makes the filtration process become time dependent. Tien et al. [1] and Wang et al. [2] had outlined a direct approach for analyzing the deposition morphology of particles from a flowing suspension to a collector. In their approach, the particle deposition was examined by tracking the trajectories of individual particles as they move toward the collector. Beizaie et al. [3] then executed this approach successfully with the establishment of a comprehensive simulation procedure. In their simulation, Wang et al. [2] had considered the deposition process as an interplay of two basic concepts, the shadow effect caused by those deposited particles and the random distribution of particles in the suspension, which are intrinsic to all particles in a suspension flowing past a collector. The results of their study provide not only the deposition rate of entire filtration period but also relevant information on the geometry of the deposits formed time dependently. The simulation procedure can be found in detail elsewhere ([4], see Chapter 8 of Tien Chi's book) and will be adopted in the present paper.

The trajectory equations formulated by Wang et al. [2] and Beizaie et al. [3], which take into account the hydrodynamic and electrokinetic forces, were proven to be able to describe the deposition morphology of colloidal particles onto the collector surfaces. Since the Brownian diffusion force was not considered in those earlier works, the force balance equations established by their trajectory analyses were deterministic. However, if the Brownian diffusion forces are the dominant force of the deposition process, the deterministic calculation of particle trajectory is no longer possible. Inclusion of these Brownian random forces in the Lagrangian type force balance equation leads to a Langevin type equation, which was solved successfully by Kanaoka et al. [5] in their simulation model of aerosol filtration. Their Brownian dynamics simulation method was proved useful when the inertia and long-range forces (i.e. van der Waals attraction and electrical double layer repulsion) are of the same order of the Brownian diffusion force [6,7]. Applying with this dynamics method, a stochastic procedure was established successfully in our previous papers to simulate the initial deposition rates of Brownian particles onto a spherical collector [8] and in the con-

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stricted tube model [9], respectively. The results obtained by those papers showed that the height of the primary maximum and the depth of the secondary minimum in the total interaction energy curve of DLVO theory [10] play important roles in determining the collection efficiency of Brownian particles at low Reynolds numbers.

In addition to considering the Brownian diffusion effect, the concept of the control window located far upstream from the collector will be adopted in the present paper, too. This control window can be considered as the place where the approaching particles originate singularly and randomly (see Fig. 1) [2,3]. In other words, the probability of finding a particle's location within this control window is the same as in any other locations within the window. By knowing the initial positions of those particles within the control window and the flow field around the collector, one can then determine the particle deposition morphology by integrating the trajectory equation and the collection efficiency of the collector consequently. The simulation results obtained by Beizaie et al. [3] and Ramarao et al. [7] indicate that the deposition process consists of three stages: the clean collector stage, the dendrite growth stage and the final individual dendrites joined stage. Depending upon the size of the control window (i.e. the original number of particles), they also found that the number of dendrites formed will remain the same at the final stage, which implies that the collection efficiency is a time dependent function and will remain unchanged when the final stage of filtration is achieved. Moreover, the lengths of these three stages were found to be dependent on the relative particle to collector size, the flow field around the collector and the electrostatic forces of the DLVO theory.

By using the same simulation procedure established by Beizaie et al. [3] and Ramarao et al. [7] and Langevin type trajectory equation, the deposition morphology of Brownian particles onto a spherical collector will be investigated in the present paper. In these simulations, the effects of the various shapes of the total interaction energy curves of DLVO theory and the shadow effect are also considered. Distinguished deposition morphology is found between those particles with and without considering the Brownian diffusion behavior.

2. Theoretical formulation

As shown in Fig. 1, assume that there is a square 2b by 2b dimension control window, whose center is perpendicularly located on the y-axis far upstream from the collector. This control window can be considered as the spatial domain through which particles originate singularly and randomly. The distribution of the initial positions of each approaching particle is assigned by the random number software of IMSL [11] in the present simulation. With the specification of the flow field around the collector, the particle's deposition trajectory by integrating the Langevin type equation can be simulated. From the trajectory of a given particle, one can then determine whether this particle will be deposited onto the surfaces of a collector or onto the previously deposited particle.

Let S be the area of the control window, the number of particles passing through this control window for a time t is

$$M = SU_\infty C_\infty t \tag{1}$$

where U_∞ and C_∞ are the approach velocity and concentrations of the suspension.

If m is the number of particles collected as a function of M, then

$$m = \int_0^t SU_\infty C_\infty \eta \, \mathrm{d}t \tag{2}$$

From Eqs. (1) and (2), one can express the collection efficiency of the collector as

$$\eta = \frac{\mathrm{d}m}{\mathrm{d}M} \tag{3}$$

On the other hand, if the collector is assumed to be spherical in shape, the extent of particle deposition is expressed by the single collector efficiency η_s which can be written as

$$\eta_s = \frac{1}{\pi r_f^2 U_\infty C_\infty}\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{S}{\pi r_f^2}\frac{\mathrm{d}m}{\mathrm{d}M} = \frac{\mathrm{d}m}{\mathrm{d}M^*},$$
$$\text{with } M^* = M(r_f^2/S) \tag{4}$$

where r_f is the radius of the spherical collector. In the present paper, the relationship between m and M^* will be investigated

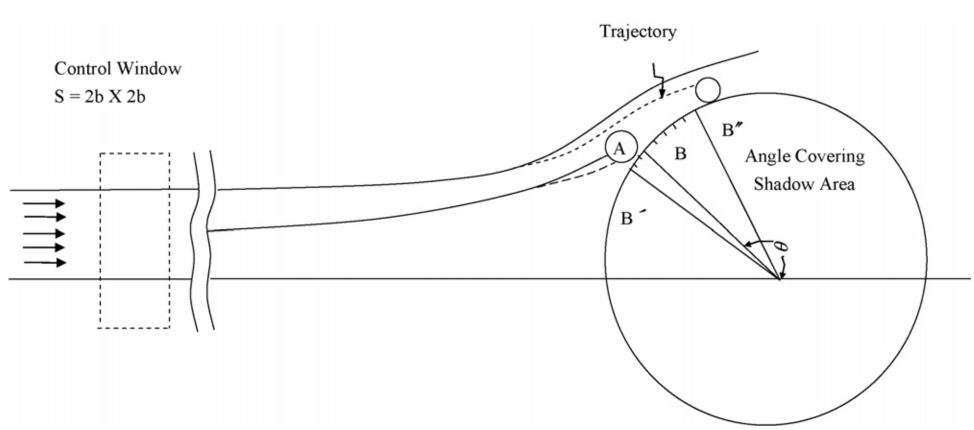

Fig. 1. The schematic diagram of the control window for simulating deposition of Brownian particles onto a spherical collector, in which the concept of shadow area is illustrated.