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Estimation of the interior permeability of polymer-flocculated sludge flocs

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Abstract

This study estimates the polymer-flocculated waste activated sludge floc interior permeability by observing the motion of individual flocs moving vertically towards an impermeable flat plate. The fluid flow fields surrounding and inside the flocs were modeled numerically and served as the basis for calculating the hydrodynamic drag force. Experimental data correspond to the numerical solutions regardless of the floc Reynolds number. According to our results, polymer flocculation produces large flocs with the same global interior structure as the original sludge flocs. The permeability range for flocs was also estimated based on the floc size investigated.

Keywords: Polymer flocculation; Permeability; Sedimentation; Settling experiments; Drag calculation

1. Introduction

Floc size and density significantly influence the performance of flocculation processes. The free-settling test has been widely employed to estimate these two factors (Tambo and Watanabe, 1979; Mitani et al., 1983; Li and Ganczarczyk, 1989; Lee, 1994). Based on the relationship between floc size and density, flocs have been proposed to be highly porous fractal-like aggregates comprised of numerous primary particles (Li and Ganczarczyk, 1989, 1990; Lee et al., 1996).

Information regarding the hydrodynamic drag force exerted on a highly porous sphere is necessary when considering its motion. This also applies to sedimentation or centrifugation of sludge flocs (Wu et al., 1998). A non-porous sphere moving through an infinite Newtonian fluid would experience a hydrodynamic resistance of F_S, as is well documented in the literature (Happel and Brenner, 1983). However, the correlations of drag force for a *porous* sphere ($F_{f,S} < F_S$) remain under-researched. Wu and Lee (1998a,b, 1999) numerically elucidated the fluid flow field and associated hydrodynamic drag force exerted on a highly porous sphere moving in a Newtonian fluid pool. In addition to flowing around the sphere, the fluid also flowed through the interior of the sphere.

Wu et al. (1998) observed the motion of waste activated sludge flocs moving towards an impermeable plate. According to the relationship between floc velocity and gap between the floc and the plate, Wu et al. estimated the permeability of the floc interior by comparing the settling data with analytical solutions of Payatakes and Dassios (1987) and Burganos et al.

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(1992). The basic concept is simple: the response of a porous floc subjected to a (mild) hydrodynamic environment change should differ from that of a nonporous object of the same size and overall weight. Floc interior permeability can be estimated by comparing the two responses. Experimental data for the response of a highly porous object subjected to a hydrodynamic environment change could provide insights into flow processes involving flocs. However, little information is available in the pertinent literature.

Polymer conditioning has long been used to pretreat slurries to increase their settleability and the corresponding filterability (Chu and Lee, 2000). Charge neutralization and interparticle bridging are the two main mechanisms involved in flocculation of the constituent particles into large flocs (Hunter, 1989). When the former dominates, the polymer dose at which the particle surface charge is neutralized and the maximum settling velocity and/or minimum resistance to filtration are strongly correlated (Hemme and Ay, 1994). This investigation elucidates the hydrodynamic response of flocs of waste activated sludge moving toward an impermeable plate, focusing on the effects of polymer flocculation. The permeability of the sludge flocs is also estimated based on the experimental results.

2. Experimental

A waste activated sludge sample was taken from the wastewater treatment plant of the Neili Bread Plant, Presidental Enterprise Co., Taoyuan, Taiwan, and was tested within 2 h of sampling. The chemical oxygen demand (COD), suspended solids (SS) and turbidity data for the supernatant drawn from the sludge were determined using EPA Taiwan standard methods. The results read as follows: 5.6 mg/l (COD), 7.1 mg/l (SS) and 1.39 NTU (turbidity). The weight percentage of the sludge sample was 0.7% (w/w).

Cationic polyelectrolyte, known as polymer T-3052, was obtained from Kai-Guan Inc., Taiwan. The polymer T-3052 is a polyacrylamide with an average molecular weight of 10^7, and a charge density of 20%. The mixing unit was a baffled mixing chamber with a stirrer. The weighed powder was first suspended in distilled water. Diluted polymer solution was then gradually poured into the mixing vessel which was stirred at 200 ppm for 5 min followed by 50 rev./min for another 20 min.

A glass cylinder (6 cm in diameter and 50 cm in height), sectioned on a side with an attached plane view glass, was employed for the floc-settling test (Wu et al., 1998). Meanwhile, a JAI 950 camera fitted with a close-up lens was used to record the floc motion. The parallax problem was not serious in this investigation owing to the use of flat optical glass for observation. A

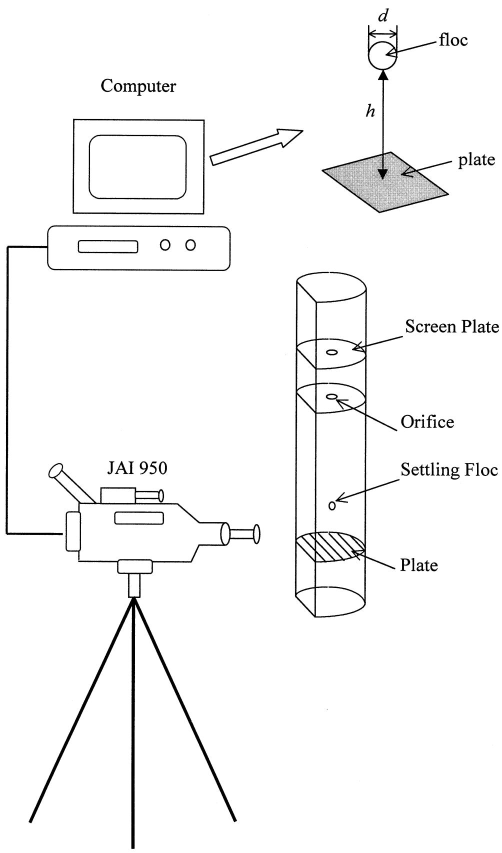

Fig. 1. The settling floc onto the plate.

flat plate was installed at the centerline of the settling column. The floc was released carefully from the top of the column toward the plate. The floc diameter was estimated based on the equivalent circle with the same projection area as the floc. By defining the mass center, the distance between the floc center and the flat plate was recorded by analyzing the image using the software Inspector (Matrox). The projection area of the floc and the vertical distance could be calculated based on the image analysis. The ultimate error for length measurement was determined from the optical resolution of the camera system, and was estimated to within 1%. From the distance vs. time data the floc moving speed can be found through numerical differentiation and data smoothing. The maximum error in velocity estimation was below 2%.

Assume that a spherical floc of diameter d is released from the far top end and moves freely downward towards a bottom flat plate. If the floc Reynolds number is not very large (< 100), the transient effect can be safely neglected and the process can be assumed to be a pseudo-steady state.

Fig. 1 schematically represents the flow process. The sphere is assumed to have an interior permeability of k

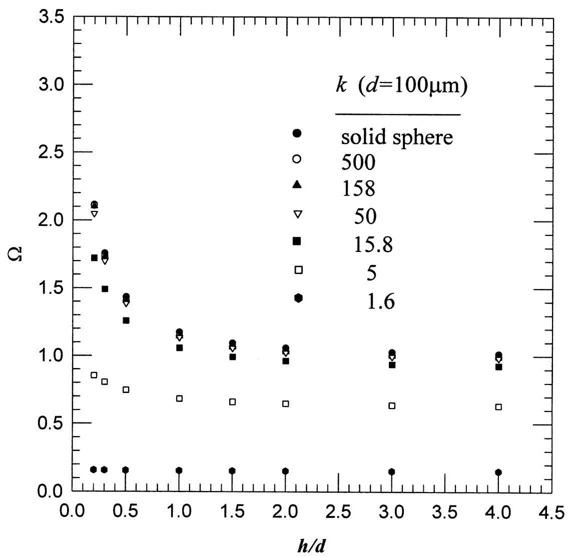

Fig. 2. Ω vs. d/h plot at $Re = 30$.

(m^2). The governing equation for the fluid velocity in the porous sphere, including the viscous effect, is the combined Darcy–Brinkman's law. Meanwhile, the governing equations for the surrounding Newtonian fluid field are the steady-state Navier–Stokes equations. The general-purpose computational fluid dynamics program FIDAP 7.5 (FDI Inc., USA) was used to solve the governing equations. Fig. 2 displays the calculated Ω vs. h/d relationship (where h is the distance between the floc and the plate) at some k values and $Re = 30$. Ω represents the ratio of the drag force actually experienced by the floc to the force calculated by correlations based on impermeable spheres. This parameter thus incorporates the effects of advection flow in the interior of the floc, its non-spherical shape, and other imperfections (Note: all calculations presented herein are for spherical particles, and the following discussions neglect the shape effect.) Under the circumstances considered, the sum of the gravity force, the buoyancy force and the drag force is zero, and thus at any point during the travel of the floc, the following equality holds:

$$F_{\text{gravity}} - F_{\text{buoyancy}} = F_{\text{drag}} = \Omega F_s. \quad (1)$$

The gravity and the buoyancy force remain unchanged for a given sphere. Consequently, the product ΩF_s remains constant as the sphere travels towards the plate. Since Ω increases with a shrinking gap, the sphere must lower its speed to reduce the corresponding F_s (a linear function of the terminal velocity). When the sphere is far from the plate, its settling velocity can be taken as that in an infinitely large pool (i.e. a constant). The corresponding terminal velocity is V_t, and the corresponding drag force is $\Omega_0 F_s$. Meanwhile, when the floc approaches the plate, the velocity decreases to V, and the drag force becomes $\Omega_0 F_{s1}$. Consequently, rewriting Eq. (1) as $\Omega F_{s1} = \Omega_0 F_s$, and knowing that $F_s = 3\pi d\mu V_t$ and $F_{s1} = 3\pi d\mu V$, produces (Wu et al., 1998):

$$V_t/V = \Omega/\Omega_0 \quad (2)$$

By measuring V as the floc travels towards the flat plate and the terminal velocity V_t, the ratio Ω_0/Ω can be obtained based on Eq. (2). In using Eq. (2) the pseudo-steady state assumption is adopted.

3. Results and discussion

3.1. Hydrodynamic response

Figs. 3 and 4 illustrate the microphotographs of a floc moving toward a flat plate at polymer dose = 20 and 30 ppm, respectively. The corresponding terminal velocities in an infinitely large pool (V_t) were measured as 1.32 and 4.78 mm/s, respectively. The flocs were apparently not perfectly spherical. Their diameters were estimated as 622 and 1709 μm, corresponding to the Reynolds numbers of 0.82 (Fig. 3) and 8.16 (Fig. 4). The latter case significantly exceeded the creeping flow limit ($Re \ll 1$).

In Fig. 3a where the floc is 1.43 mm (h) away from the flat plate, the local velocity (V) is 1.319 mm/s, closely corresponding to the terminal velocity measured in an infinitely large medium. In Fig. 3b, after 0.84 s, the gap shrinks to 0.48 mm. The floc velocity decreases to 0.87 mm/s, indicating the involvement of plate effects. In Fig. 3c, the floc nearly touches the plate while the moving speed is further reduced to 0.28 mm/s. The measurement of the gap between the floc and the plate vs. time data produce the relationship of V/V_t (hence Ω_0/Ω in Fig. 2) and h/d.

Fig. 4a–c illustrates the corresponding photographs at dose = 30 ppm, higher than that of Fig. 3. The floc

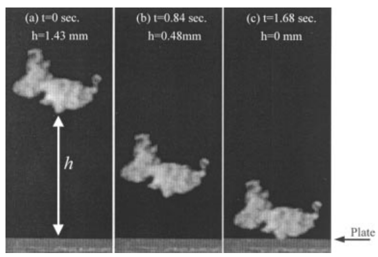

Fig. 3. Microphotographs of a floc moving toward a flat plate at polymer dose = 20 ppm. $d = 622$ μm, $V_t = 1.32$ mm/s, $Re_t = 0.82$.

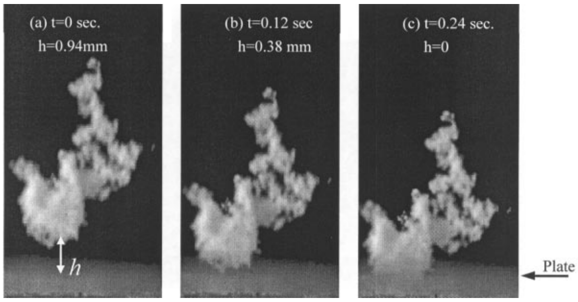

Fig. 4. Microphotographs of a floc moving toward a flat plate at polymer dose = 30 ppm. $d = 1710$ μm, $V_t = 4.78$ mm/s, $Re_t = 8.2$.

size appears greater, indicating the action of the polymer flocculation. Furthermore, polymer flocculation produces rather irregular flocs.

3.2. V/V_t vs. d/h curves

Figs. 5 and 6 present some V/V_t vs. d/h curves for original sludge flocs and flocs at a polymer dose of 20 ppm, respectively. The ratio of V/V_t decreases as the gap falls below a critical value. This critical gap decreases with increasing Re due to inertia effects (Wu et al., 1998). Furthermore, the application of polymer into the suspension did not markedly shift the curves, indicating that the floc interior was no looser following flocculation. This observation does not correlate with that of Guan (1999) who conducted light-scattering experiments.

Data fitting between experimental data and numerical results yields estimates of the β value, which is

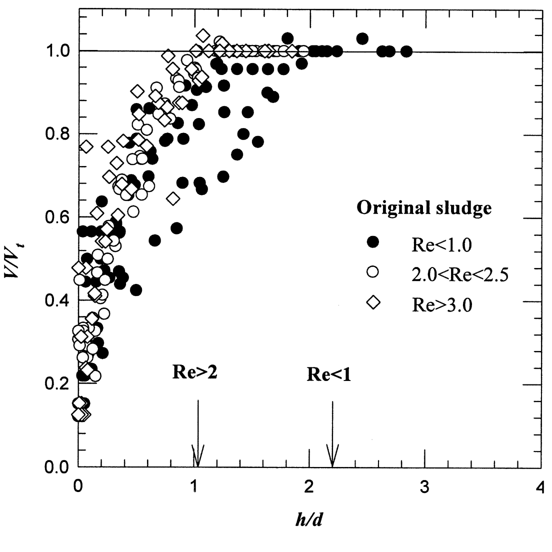

Fig. 5. V/V_t vs. d/h curves. Original sludge.

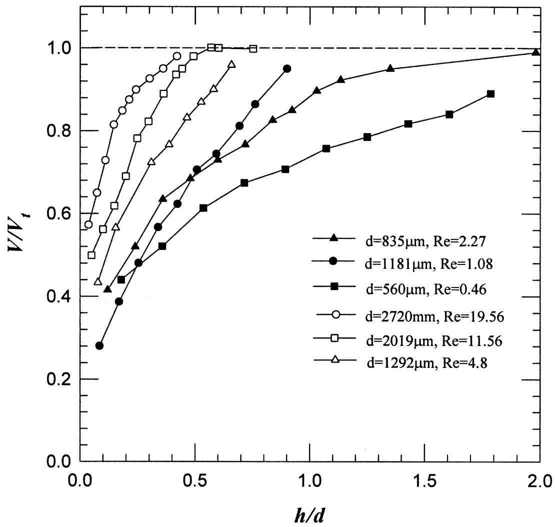

Fig. 6. V/V_t vs. d/h curves. Polymer dose = 30 ppm.

defined as $d_f/k^{0.5}$. The β values for waste activated sludge flocculated at 0 (original), 20 and 30 ppm are all approximately 1.6–5. Restated, at the same floc size, the β values for polymer-flocculated activated sludge resemble those of the original sludge. The permeability ranges from 2.5×10^{-9} to 8×10^{-7} m^2 for original sludge flocs of size 150–800 μm. For the polymer-flocculated sludge, the range is 3×10^{-9}–7×10^{-7} m^2 for flocs of size 560–2719 μm. These estimates compare to the experimental results of Wu et al. (1998). Polymer-flocculated sludge flocs are usually larger than those found in original sludge, thus exhibiting a relatively greater permeability. Nevertheless, the dimensionless permeabilities for the present original and flocculated sludges are actually similar.

3.3. Hydrodynamic permeability

Lee (1999) proposed that the simplest picture of a floc can be viewed as a fractal of fractals (but of different dimensions), namely, a multi-fractal. Later Biggs et al. (1999) also suggested a similar scheme for their polystyrene latex aggregates. A floc is composed of smaller aggregates, which are themselves formed from tiny principle particles. Therefore, small channels exist within the aggregates, while large channels cover the whole floc. Meanwhile, fluid tends to flow along the path of least resistance. Restated, fluid faces difficulties flowing through small channels while the observed drag reduction is mainly attributed to the existence of large channels. Thus, the permeability measured herein is for the global structure of the multifractal. If all details of the floc structure are considered, the flow resistance should increase. The free-settling test is generally used to estimate floc density. However, since the floc density is averaged over the whole floc, the free-settling test will usually underestimate the true floc density.

Guan (1999) employed a light-scattering technique to measure the fractal dimensions of sludge flocs, and indicated that polymer flocculation reduced the fractal dimension. Restated, the flocs became looser following flocculation. However, this work suggests rather that the global structure of flocs was not changed significantly when subjected to polymer flocculation. The flocs continued to exhibit a larger permeability after flocculation simply because of growing floc size.

4. Conclusions

This work estimated the interior permeability of waste activated sludge flocs when subjected to cationic polymer flocculation. The analysis was based on observation of the motion of individual flocs moving vertically towards an impermeable flat plate. The fluid flow fields surrounding and within the floc were modeled numerically, and the hydrodynamic drag force was calculated on this basis. The experimental data correlate with the numerical solutions regardless of the floc Reynolds number. Polymer flocculation created large flocs that retained the same global interior structure as the original sludge flocs. The large floc size still allows easy fluid flow-through. For original sludge flocs ranging in size from 150–800 μm, the permeability ranged from 2.5×10^{-9} to 8×10^{-7} m^2, while for the polymer-flocculated sludge, the range was 3×10^{-9}–7×10^{-7} m^2 for floc sizes ranging from 560 to 2719 μm.

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