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Effect of double-stage velocity gradients on abatement and morphology characteristics of flocs in a conical fluidized-bed flocculator

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ABSTRACT

A double-stage velocity gradient conical fluidized bed flocculator (DG-FBF) was employed to investigate the issue of floc breakage that occurred in a single-stage velocity gradient conical fluidized bed flocculator (SG-FBF), using 150 mg/L Kaolin clay suspension as the influent and 60 mg/L polymer aluminum chloride as the flocculant dosage. Two kinds of particles with significant differences in effective weight (i.e. silica gel beads and resin beads) were packed into the DG-FBF; these particles separated into two grades along the axial direction due to the fluid shearing force. The back-mixing problem, which lead to floc breakage in the SG-FBF was apparently solved, as confirmed by both the observed flow patterns and the floc size distributions. The two-stage velocity gradient and voidage observed in the DG-FBF created a more suitable environment for growth of the aggregates. The flocs formed in the DG-FBF tended to be denser and presented an advanced self-similarity as evidenced by the results of fractal dimensioning. In addition, the abatement efficiencies of Kaolin suspensions in the DG-FBF increased by about 10% at most of the loading rates investigated (at superficial velocities of 6.7–17.9 mm/s) and became more stable compared with those from the SG-FBF.

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1. Introduction

Collisions of particles bridged with polymer lead to the formation of aggregates or flocs in the flocculation process. However, there is the possibility that flocs may undergo breakage under certain conditions. There is also some evidence that floc breakage at high shear rates may be irreversible to some extent, so that broken flocs do not readily re-aggregate when the shear rate is reduced [1,2]. Therefore, the velocity gradients which determines the shear rate being exerted on the suspended particles is typically controlled to two or three levels to satisfy the collision of the particles first and then to avoid them being broken by over shearing.

Fluidized bed flocculation has been employed as a novel flocculator where the driving force for aggregation of the colloids is created by the random movement of the solid phase [3–5], rather than by the traditional mechanical agitation or hydraulic shearing. Although the considerable efficiency and energy saving capability of the fluidized bed flocculator had been confirmed [3,6], the single packing mode of the solid phase in the previous works resulted in a uniform shear rate being exerted on the colloids or fine particles throughout the bed, which was a disadvantage to the growth of flocs as discussed above.

In a conical fluidized bed, the velocity gradient decreases gradually in the axial direction due to the unique geometry of the bed [2,7], which overcomes the undesirable single velocity gradient throughout the entire bed. However, the abatement efficiency in the conical fluidized bed tends to decrease as the bed height reaches a certain level, even though the flocculation time may be increased. The breakage of the formed flocs might occur as discussed in our previous work, which may result from the over back-mixing in the bed [2]. Therefore, the objective of the present work was to further experimentally evaluate the occurrence of the breakage of the flocs, and then mitigate or eliminate this breakage in the flocculator by establishing a multi-velocity gradient with two different particles. In particular, the hydrodynamic performance and the dynamic characteristics of the flocculator were investigated and their influences on the aggregation of the fine particles were analyzed.

2. Materials and methods

2.1. Experimental set-up and flocculator operation

A conical fluidized bed with a tapered angle of 8° was employed as the fluidized flocculator in this work, as shown in Fig. 1. The unit consisted of four Plexiglas sections from bottom to top: a 200 mm high plenum chamber packed with 2.5 mm plastic beads for

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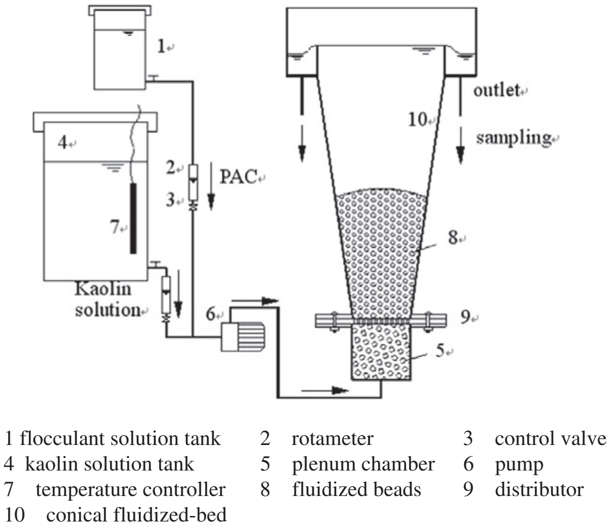

Fig. 1. Conical fluidized bed flocculation-coagulation set-up.

improving the fluid distribution and promoting flocculant mixing; a distributor plate with a series of 1.6 mm holes to provide a 2% opening ratio; a test section; and an expanded section.

Spherical silica gel beads with a mean diameter of 1570 μm and a wet density of 1510 kg/m^3 were used as the solid phase of the single-stage fluidized bed flocculator (SG-FBF) at several pre-selected initial bed heights. The operation of the double-stage fluidized bed flocculator (DG-FBF) was as follows: separate spherical resin beads with a mean diameter of 800 μm and a wet density of 1366 kg/m^3 were also packed into the SG-FBF, and then the two types of solid particles were naturally separated into two grades after fluidization, i.e., silica gel beads were fluidized in the bottom section of the bed and the resin beads were fluidized above those silica gel beads.

In the experiments, a Kaolin clay solution with a concentration of 150 mg/L was pumped into the bottom of the unit as the liquid slurry phase. pH and temperature of the slurry were 7.0 and 20 °C, respectively. Kaolin clay (Tianjin Guangfu, China) was employed to simulate the suspended solids of a typical wastewater in this work. The average area equivalent diameter of the clay was 5.7 μm as analyzed by a Laser Particle Size Analyzer (Better 2000, China). The polymer aluminum chloride (PAC) flocculant dosage was 60 mg/L.

2.2. Dynamic parameters

The relevant dynamic parameters for a conical fluidized bed flocculator in this work were calculated by the following methods. The detailed derivation of the equations used can be found in our previous work [2].

The flocculation time, T, is related to the expanded bed height, H, voidage fraction of the bed, ε and the superficial velocity at the bottom, U,

$$T = \frac{\varepsilon H}{U} \tag{1}$$

The value of velocity gradient, G, can be calculated using,

$$G = \left[\frac{g(\rho_s - \rho_l)(1-\varepsilon)U}{\varepsilon\mu}\right]^{1/2} \tag{2}$$

where ρ_s and ρ_l is the density of solid phase and the fluid slurry, respectively, g is the gravitational acceleration constant, and μ is the dynamic viscosity.

Multiplying Eq. (1) by Eq. (2), the Camp Number GT, is derived as [7]:

$$GT = \left[\frac{g\varepsilon H^2\,(\rho_s - \rho_l)(1-\varepsilon)}{\mu U}\right]^{1/2} \tag{3}$$

By assuming that the conical bed was composed of numerous cylindrical sections with increasing diameter along the axial direction, the GT value can be obtained by integrating $d(GT)$ over the bed height. The average velocity gradient of the conical fluidized bed flocculator can be obtained from the integration of Eq. (2) over the total bed height. It can be seen that the Camp Number is a function of the inlet flow rate and the initial bed height.

2.3. Analytical methods

The concentration of the suspended Kaolin clay was determined by spectrophotometry based on the calibration curve of the light absorbance values versus the concentration of the suspensions. Inlet and outlet suspension concentrations were those of the synthetic wastewater, and the supernatant of the slurry obtained by collecting outlet samples and then settling in a wide neck container for 20 min, respectively. The abatement efficiency was then evaluated based on the inlet and outlet concentrations.

The mean area equivalent diameter of the flocs was obtained from at least 50 floc samples, and the areas of the flocs were measured by microscope with the Pro-Micro Scan system equipped the software of Scopephoto, and then the diameter was calculated based on the measured areas.

2.4. Fractal dimension

Assuming that the structure of the flocs follows a self-similarity, this structure can be described by a fractal dimension [8,9]. The two-dimensional fractal dimension model was employed in this work,

$$A = \alpha P^{D_2} \tag{4}$$

where A is the surface area of the floc, P is the circumference of the floc, α is a constant and D_2 is the two-dimensional fractal dimension.

By logarithmic transformation of Eq. (4), D_2 can be obtained from the slope of the following equation,

$$\ln A = \ln\alpha + D_2 \ln P \tag{5}$$

The surface area and the circumference of the flocs were determined by an optical microscope equipped with a pre-calibrated graticule.

3. Results and discussion

3.1. Single-stage velocity gradient fluidized bed flocculator

3.1.1. Abatement characteristics

Camp Number (GT) is the product of velocity gradient (G) and flocculation-coagulation time (T), which reflects the combined contributions of the turbulence intensity and the aggregation time. As Camp Number has been widely employed as a design parameter for flocculators, the effects of the GT value in the SG-FBF on the abatement efficiencies of 150 mg/L Kaolin clay suspensions are shown in Fig. 2. In general, the abatement efficiency is higher than 70% and gradually increased with an increase in the Camp Number in the range of 515.8–1065.7 investigated here, which is consistent with our previous work [2]. Such a trend was more obvious as the turbulence intensity was appropriately controlled in the range of 74.96–94.77 s^{-1} (the calculation of G; see Eq. (2)) and the flocculation time

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