ELSEVIER

Chemical Engineering Journal 140 (2008) 241–246

Chemical Engineering Journal

www.elsevier.com/locate/cej

Model-evaluation of the erosion behavior of activated sludge under shear conditions using a chemical-equilibrium-based model

Guo-Ping Sheng, Han-Qing Yu *, Hua Cui

Laboratory of Environmental Engineering, School of Chemistry, University of Science & Technology of China, Hefei 230026, China

Received 2 April 2007; received in revised form 5 August 2007; accepted 3 October 2007

Abstract

The primary particles would erode from the sludge surface under shear conditions. As the primary particles have significant effects on the solid–liquid separation process, the erosion behaviors of activated sludge in biological wastewater treatment processes under shear conditions were investigated using a chemical-equilibrium-based model. The equilibrium dispersed mass concentration of the primary particles in the sludge solution was found to nonlinearly increase with the solid content and shear intensity, and could be well described by the model. Compared with other sludge reported in literatures, the activated sludge used in this study was found to be more stable during the shear test, with a high equilibrium constant K^0 of 30.2 and a low Gibbs' free energy of adhesion (ΔG^0) of -3.41 at a shear intensity of $800\,s^{-1}$. The two parameters could be used to evaluate the strength of the sludge. The negative value of ΔH indicates the energy demand for the erosion process. The low value of ΔH for the activated sludge used in this study indicates that the erosion process was more energy demanding and the erosion process was less shear dependent for the activated sludge used in this study.

Keywords: Activated sludge; Chemical-equilibrium-based model; Erosion behavior; Shear

1. Introduction

Activated sludge process is widely used in biological wastewater treatment, and mainly employed for the treatment of domestic and municipal wastewater. The properties of sludge regulate the flocculation and settlement of the biomass and the performance of solid–liquid separation in a clarifier [1]. The loose structure of sludge greatly affects the solid–liquid separation efficiency in biological wastewater treatment systems [2,3]. Sludge flocs are a heterogeneous mixture of primary particles, microorganisms, colloids, extracellular polymeric substances and cations [4]. The primary particles have a significant effect on solid–liquid separation process, as a low primary particle concentration would bring a significant decrease in the solid–liquid separation efficiency. Under shear conditions, the primary particles would erode from sludge surface because of hydrodynamic shear force [5]. However, the behaviors of sludge under shear conditions have not been given sufficient attention yet. Although the complexity of sludge constituents and its chaotic structure make it difficult to study its behavior under shear conditions, it is of an engineering significance in biological wastewater treatment.

Some efforts have been made to characterize sludge behaviors by measuring the changes of sludge size distribution or sludge volume index under given shear conditions [6,7]. A dissociation constant was also employed to characterize the sludge strength [8,9]. A physically relevant index for describing the total network strength of sludge with rheological tests was proposed [10]. However, these methods may not be adequate for describing such a solid–liquid separation process, in which the primary particle concentration is essential.

A flocculation–deflocculation model was developed by Parker and co-workers [11] based on a mechanistic approach considering the balance of flocculation–deflocculation process. This effort has used to describe the concentration of primary particles in sludge suspension using mathematic methods based on sludge self-flocculation process, and is appropriate for describing the flocculation of activated sludge at low shear intensities [11]. Based on Langmuir adsorption isotherm theory, an adhesion–erosion model was established from a macroscopic viewpoint for quantifying the concentration of dispersed pri-

* Corresponding author. Fax: +86 551 3601592.
E-mail address: hqyu@ustc.edu.cn (H.-Q. Yu).

1385-8947/$ – see front matter
doi:10.1016/j.cej.2007.10.001

mary particles due to erosion under shear conditions [5,12]. However, these two models for describing the primary particle concentration of sludge suspension under shear conditions had limitations, e.g., the flocculation–deflocculation model was not applicable for describing the process at a high solid content or at a high shear intensity [5], the adhesion–erosion model had some limitation in the conditions of low shear intensity or high sludge content [13]. To solve these problems, a new model based on chemical equilibrium theory, was established to evaluate the behaviors of an anaerobic hydrogen-producing sludge [13]. This model assumed that there was a dynamic equilibrium between the primary particles and flocs under shear conditions, just like a reversible chemical reaction. The model is applicable to more actual conditions, even at high solid contents or low shear intensities.

The main objective of this work was to evaluate the behaviors of activated sludge under shear conditions using the chemical-equilibrium-based model. The relationships between the concentrations of dispersed primary particles and shear intensity or sludge content were investigated. The results of this study are useful for understanding the response of sludge to shear stress and for controlling hydrodynamic conditions in bioreactors.

2. Experimental

2.1. Sludge

The activated sludge was collected from an aeration tank at the Wangxiaoying Municipal Wastewater Treatment Plant in Hefei, China. Before use, the sludge was passed through 0.45-mm sieves and washed twice with tap water to remove the residual components and dispersed small particles. The sludge was then thickened to approximately 15–18 g SS L^{-1} (SS: suspended solids). Afterwards, the samples were diluted to 1.5–10 g SS L^{-1} for the shear tests. The SS of the sludge samples were determined according to the Standard Methods [14].

2.2. Shear tests

In all of the shear tests a baffled paddle-mixing chamber was used at 20–25 °C. The initial testing volume was 1000 mL. Sludge was sheared at a pre-determined shear intensity by mechanical stirring with a flat paddle mixer (JJ-4, JCGS Instrument Co., Jiangsu, China). The shear intensity was quantified by the root-mean-square velocity gradient (G): $G = \sqrt{P/\eta V}$, where P is the power input, η is the fluid viscosity and V is the suspension volume [5]. The actual G during a test was achieved by adjusting the paddle rotation rate in rpm based on a laboratory calibration of G versus rpm. Since the sludge solutions are non-Newtonian fluids, the sludge content has an influence on the sludge viscosity and the calculation of G, especially at a high SS sludge content (above 20 g L^{-1}) [15]. In the present work, the sludge content ranged between 1.2 and 8.0 g L^{-1} only, and previous results demonstrated that a low sludge content would have little influence on the viscosity of sludge solutions. Thus, the viscosity of water was used for the calculation of the shear intensity G in this work. The release of cells and small particles as a result of shear was determined by the change in the supernatant turbidity. Samples of 3 mL were withdrawn from the testing chamber at pre-determined time intervals for the turbidity measurement. The turbidity was measured from the absorbance at 650 nm (UV751GD, Analytical Instrument Co., Shanghai, China) for the supernatant following 2 min of centrifugation at 2200 rpm. The dispersed mass concentration was then estimated using the turbidity/SS-concentration conversion factor given by Wahlberg et al. [11].

2.3. Chemical-equilibrium-based model

In sludge suspension, the particle size distribution is bimodal, mainly containing two particle classes, i.e., primary particles (0.5–5 μm) and flocs (25–100 μm) [5]. Assuming that there is a dynamic equilibrium between the primary particles and flocs under shear conditions, just like a reversible chemical reaction. The thermodynamic equilibrium constant K^0 at a constant shear intensity could be expressed as follows in terms of mass concentration [13]:

$$K^0 = \frac{m_{\mathrm{T}} - m_{\mathrm{d},\infty}}{m_{\mathrm{d},\infty}^{\alpha}} \tag{1}$$

in which α is the characteristic parameter of sludge, m_{T} is the sludge content, $m_{\mathrm{d},\infty}$ represents the equilibrium mass concentration of dispersed primary particles, and could be estimated using a diffusion equation [5]:

$$m_{\mathrm{d},t} = m_{\mathrm{d},\infty} + (m_{\mathrm{d},0} - m_{\mathrm{d},\infty})\frac{6}{\pi^2}\sum_{N=1}^{9}\frac{1}{N^2}\,\mathrm{e}^{-N^2 Dt} \tag{2}$$

where $m_{\mathrm{d},0}$ and $m_{\mathrm{d},t}$ are the dispersed mass concentrations of primary particles at initial time and time t, respectively, N is an integer and D is an effective diffusion constant.

The Gibb's energy of adhesion at a constant shear intensity could be estimated from the following physicochemical equation:

$$\Delta G^0 = -RT \ln K^0 \tag{3}$$

Based on the physicochemical principles, the change in the Gibb's energy can show the direction of equilibrium shift between primary particles and flocs.

Eq. (1) could be rearranged into:

$$m_{\mathrm{T}} = m_{\mathrm{d},\infty} + K^0 m_{\mathrm{d},\infty}^{\alpha} \tag{4}$$

From the non-linear regression between m_{T} and $m_{\mathrm{d},\infty}$, the values of K^0 and α could be calculated at a constant shear intensity.

In the experiments for strength testing, the effect of shear intensity could be treated by analogy with that of temperature at a conventional chemical equilibrium [5]. The van't Hoff equation can be integrated into:

$$\ln K^0 = -\frac{\Delta H}{R}\frac{1}{G} + q \tag{5}$$