Biochemical Engineering Journal 38 (2008) 302–308

Biochemical Engineering Journal

www.elsevier.com/locate/bej

Stability of sludge flocs under shear conditions

Guo-Ping Sheng [a], Han-Qing Yu [a,*], Xiao-Yan Li [b]

[a] School of Chemistry, University of Science & Technology of China, Hefei 230026, China

[b] Department of Civil Engineering, University of Hong Kong, Pokfulam Road, Hong Kong, China

Received 19 December 2006; received in revised form 13 July 2007; accepted 29 July 2007

Abstract

The shear stability and surface characteristics of aerobic and anaerobic flocs that are formed in biological wastewater treatment processes were investigated. The aerobic flocs of activated sludge were found to be more stable during the shear test, with a low shear sensitivity of 0.032, than the anaerobic flocs of sludge digestion, which had a higher shear sensitivity of 0.088. In addition, the surface characteristics of the sludge flocs, such as hydrophobicity, surface charge and fractal dimension, changed rather differently for the aerobic and anaerobic flocs during the shear tests. The significant changes took place in the first 30 min when the flocs were exposed to an elevated shear and little change was observed in the later stages of the shear tests. For quantitative description on the concentration of small primary particles in sludge solution, a modified adhesion–erosion model was used to describe the stability of the sludge flocs under shear conditions. The modification takes into account the effect of Brownian motion on particle dynamics in a sludge suspension, which effectively extends the application of the model to systems with a low shear intensity.

Keywords: Aerobic sludge; Anaerobic sludge; Shear sensitivity; Sludge flocs; Stability; Surface characteristics

1. Introduction

Both activated sludge and anaerobic digestion processes are widely used in biological wastewater treatment. The activated sludge process is mainly employed for the treatment of domestic and municipal wastewater, whereas anaerobic digestion is commonly used for sludge volume reduction and biogas production [1]. Aerobic and anaerobic sludge in biological wastewater treatment systems mainly takes the form of flocs with a loose structure. A sludge floc is a heterogeneous mixture of particles, microorganisms, colloids, extracellular polymeric substances (EPS) and cations [2]. The properties of individual sludge flocs regulate the flocculation and dewatering characteristics of the biomass and the performance of solid/liquid separation in a clarifier [3]. A large amount of work has been carried out on the biological and physicochemical properties of flocs. The structure of flocs in wastewater treatment systems also has been analyzed from microtome sliced images and confocal laser scanning microscope images [4,5]. These studies on sludge flocs, however, concentrate on aerobic flocs and little information is available for anaerobic flocs.

The stability of flocs has recently drawn more attention in the field of biological wastewater treatment. It has been found that reduced floc stability leads to an increase in effluent turbidity and poor dewatering properties [6,7]. Primary particles would erode from sludge surface because of hydrodynamic shear force, and this has a significantly negative effect on the solid/liquid separation process [7]. However, the complexity of floc constituents and their chaotic structure make it difficult to determine the strength and stability of sludge flocs. Many efforts have been made to describe the concentration of primary particles in sludge suspension using mathematic methods based on sludge adhesion process. An adhesion–erosion (AE) model was recently developed on the basis of the Langmuir adsorption isotherm theory for the characterization of the stability of particle flocs [8]. From a macroscopic viewpoint, the AE model correlates the floc stability with the concentration of dispersed particles that are eroded from flocs under shear conditions. In this model, two equations were used to describe the effects of solid content and shear intensity on the equilibrium concentration of primary particles. This model was successful in describing the sludge desorption phenomenon at a high shear intensity domain [7,8]. However, the AE model does not take into account the effect of Brownian

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

1369-703X/$ – see front matter
doi:10.1016/j.bej.2007.07.026

motion on particle dynamics, which introduces a certain margin of error in the computation of the concentration of dispersed particles, particularly in conditions of low shear intensity. In order to apply the AE model at a low shear intensity domain, this model should be modified with a consideration of the Brownian motion effect. Furthermore, although the stability of the sludge flocs is closely associated with the surface characteristics of flocs, the correlation between the floc stability and surface characteristics has not been fully addressed.

The main objective of this work was to investigate the relationship between the sludge surface characteristics (e.g., hydrophobicity, surface free energy, and surface charge) and the stability of both types of sludge flocs. In addition, the AE model was modified to describe the stability of aerobic and anaerobic flocs under shear conditions. The results of this study are essential for understanding the response of sludge flocs to shear stress and for controlling hydrodynamic conditions in bioreactors.

2. Materials and methods

2.1. Sludge flocs

The aerobic flocs were collected from an aeration tank at the Wangxiaoying Municipal Wastewater Treatment Plant in Hefei, China. The anaerobic methanogenic flocs were sampled from a pilot-scale upflow anaerobic sludge blanket reactor treating soybean-processing wastewater. Before use, the flocs were passed through 0.45 mm sieves and were washed with tap water twice to remove the residual components and dispersed small particles. The flocs were then thickened to approximately 15–18 g SS/l (SS: suspended solids) for the aerobic flocs and 20–30 g SS/l for the anaerobic flocs. Afterwards, the samples were diluted to 1.5–10 g SS/l for the shear tests. The SS of the sludge samples were determined according to the Standard Methods [9].

2.2. Shear tests

In all of the shear tests a baffled paddle-mixing reactor was used at ambient temperatures of 20–25 °C. The reactor consists of a 105 mm × 140 mm (inner diameter × height) cylinder and four vertical baffles with 10 mm × 12 mm (width × height) placed in the inner surface of the cylinder. The initial testing volume was 1 l. Flocs were sheared at a pre-determined shear intensity G 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 the fluid viscosity and V is the suspension volume [7]. 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. As mentioned by Mikkelsen and Keiding [7], G is valid only when considering particles smaller than the Kolmogorov microscale (η_K) of turbulence given by $\eta_K = \sqrt{\nu/G}$, where ν is the dynamic viscosity. Thus, in the range of shear intensities applied (100–1400 1/s), the corresponding Kolmogoroff microscales range from 95 to 25 μm at 25 °C. In the case of sludge flocs, the primary particles mainly are single cells with the average size 0.5–5 μm [8]. In this manuscript, the sizes of primary particles in aerobic and anaerobic flocs were also measured using NanoSizer ZS (Malvern Co., UK), and were determined as 0.7–1.0 μm and 0.9–1.9 μm, respectively. The primary particles are much smaller than the Kolmogoroff microscales. Thus, G is assumed to be appropriate for turbulence characterization, as supported by the good fits of the model with experimental results [7,8].

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 of 1.2 mg SS/l/FTU reported previously [7,10]. To evaluate the additional deflocculation of anaerobic flocs as a result of the aerobic condition during the shear tests, control experiments in which no mechanical shear was applied were also conducted in parallel. The aerobic and anaerobic flocs were aerated by a slow air flow at a rate of 615 ml/min to impose an additional aerobic stress, without mechanical stirring, on the floc structure.

The dispersed mass concentration of small particles at equilibrium ($m_{d,\infty}$) was estimated by fitting the erosion kinetics of small particles to the diffusion expression [8]:

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

where $m_{d,t}$ and $m_{d,0}$ are the dispersed mass concentrations at time t and at initial, respectively, N is an integer and D is an effective diffusion constant. The effects of the solid content and shear intensity on $m_{d,\infty}$ can be written as following equations [8]:

$$m_{d,\infty} = m_T - \frac{m_{a,\max} K_m m_{d,\infty}}{1 + K_m m_{d,\infty}} \tag{2}$$

$$m_{d,\infty} = e^{(\Delta H_G/R)/G} e^{q_m} \tag{3}$$

where m_T is the total solid concentration, $m_{a,\max}$ the upper limit of the absorbed small particles, K_m the adhesion–erosion equilibrium constant, R the gas constant, ΔH_G the adhesion "enthalpy" based on the shear experiments, which takes a negative value when particle adhesion is more dominant than erosion and q_m is a constant for a given solid concentration.

Taking the effect of Brownian motion into account, Eq. (3) can be modified into:

$$m_{d,\infty} = e^{(\Delta H_G/R)/G}\, e^{q_m} + m_0 \tag{4}$$

where m_0 is the equilibrium mass concentration under a quiescent condition that depends on the solid content and temperature.

If m_T and $m_{d,\infty}$ are quantified in units of volumetric activity, the effective adhesion free energy at the given shear intensity should be estimated from the physical chemistry equation: