Bioresource Technology 219 (2016) 521–526

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

A new approach to construct three-dimensional surface morphology of sludge flocs in a membrane bioreactor

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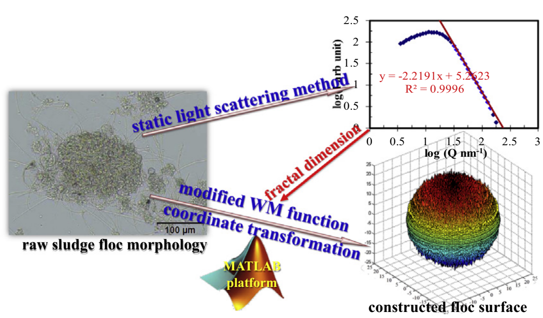
HIGHLIGHTS

- Sludge flocs showed apparent fractal characteristics.
- Fractal geometry and coordinate transformation were used to construct floc surface.
- The constructed floc surface was close to the natural floc surface morphology.
- Fractal dimension was a key factor affecting the constructed surface.
- The new approach was feasible and superior over the conventional methods.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 2 August 2016
Accepted 3 August 2016
Available online 5 August 2016

Keywords:
Fractal geometry
Surface construction
Sludge floc
Membrane fouling
Membrane bioreactor

ABSTRACT

In this paper, a novel approach to construct three-dimensional (3D) surface morphology of sludge flocs in a membrane bioreactor (MBR) was proposed. The new approach combined the static light scattering method for fractal dimension (D_f) determination with the modified two-variable Weierstrass-Mandelbrot (WM) function based on fractal geometry and coordinate transformation for spherical surface construction. It was found that the sludge flocs in the MBR showed apparent fractal characteristics. Results showed that the constructed 3D morphology of sludge flocs was very sensitive to D_f, and higher D_f induced a more compact and smoother surface morphology. With a set of proper parameter data, the constructed 3D surface morphology of sludge flocs could be quite similar to the real floc surface morphology, showing the feasibility of the proposed approach. The proposed solution to floc surface construction could be potentially used in interfacial interaction assessment, giving important implications for membrane fouling research.

1. Introduction

Membrane separation process, particularly, membrane bioreactor (MBR), has been increasingly used in treatment of a wide variety of wastewaters, and has been conceived as one of the most promising technologies in the 21st century (Huang et al., 2010; Wang et al., 2014). However, membrane fouling problem is a concomitant of membrane technology, which can reduce productivity, increase energy consumption, deteriorate permeate quality, shorten membrane life. It is generally accepted that membrane fouling is the major obstacle limiting development of membrane and MBR technology (Lin et al., 2014; Wang et al., 2014).

Adsorptive fouling caused by adhesion of foulants on membrane surface is the major form of membrane fouling (Lin et al., 2009; Su et al., 2014). Susceptibility of a membrane to foulant

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http://dx.doi.org/10.1016/j.biortech.2016.08.005
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adhesion can be generally predicted by the interfacial interactions between membrane and foulants (Hong et al., 2013; Wang et al., 2013). These interfacial interactions were theoretically depicted by the extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) theory (Hong et al., 2013; van Oss, 1995) or its extensions like Derjaguin approximation (Bhattacharjee and Elimelech, 1997; Hoek and Agarwal, 2006). Although theoretical descriptions of these interactions deal exclusively with idealized smooth surfaces, real foulant particles are often characterized by irregular surface. Obviously, foulant surface morphology exerts profound effects on the interfacial interactions. Therefore, in order to exactly understand the interactions between membrane and foulants, it is essential to properly construct the morphology of the foulant particles.

Many efforts have been devoted to construct irregular rough surface. Basically, two conventional methods have been developed. One is to randomly place regular geometries as protrusions or depressions on a smooth flat surface (Bhattacharjee et al., 1998). Various regular geometries, including hemispheres (Chen et al., 2012; Hoek et al., 2003), cylinders (Martines et al., 2008) and cones (Suresh and Walz, 1996), have been adopted in the literature. However, applying this method for spherical surface construction encounters the difficulty of complicated coordinate transformations. The other method is describing surface morphology by periodic functions. For example, Lenhof (1994) directly used a rippled equation to describe the rough spherical surface. While these efforts gave significant insights into construction of rough particle surface, it could be directly gauged that the constructed particle surfaces by the conventional methods were far from the real rough particle surface. The reason for this phenomenon possibly lies in the assumption in those studies that surface morphology of solid particles was a stationary process (Morag and Etsion, 2007). Actually, experiments have shown that the surface morphology of a natural subject is a nonstationary process (Sayles and Thomas, 1978). A general feature related with nonstationary process is that, when a section of the rough surface is magnified, smaller scales of roughness appear. This means typical self-similarity/multiscale and fractal features of the natural subjects including sludge flocs. Apparently, conventional methods cannot reflect these features, and therefore, fail to construct three-dimensional (3D) surface morphology of particles highly close to the real surface.

Pursuing the literature shows that the non-stationary and fractal feature of a natural surface can be represented by fractal geometry (Majumdar and Bhushan, 1991; Peng and Guo, 2007). Jaggard and Sun (1990) introduced the fractal geometry into rough surface construction, and found that fractal geometry could combine short-range disorder with long-range order, well reflecting the physical properties of natural rough surfaces. Hitherto, fractal geometry has been used to describe many natural rough surfaces, including ocean floors, wind-blown sea surfaces, and deposited film surfaces (Jaggard and Sun, 1990). To our knowledge, no one used this conception to construct biomass surfaces, let alone spherical sludge flocs. As morphology of sludge flocs are inextricably related with membrane fouling and other properties of sludge, it is quite desirable to develop a new method for constructing 3D surface morphology of sludge flocs.

Therefore, this study aims to develop a new solution to construct spherical sludge flocs in a membrane bioreactor. Accordingly, fractal dimension of sludge flocs, the most important parameter for fractal geometry, was firstly determined by static light scattering method. Meanwhile, Weierstrass-Mandelbrot (WM) function involving the fractal geometry, combined with coordinate transformation, were proposed to model spherical surface of sludge flocs. The measured fractal dimension, together with other parameters with proper values were then used to simulate the model and construct the floc surface. Thereafter, effect of fractal dimension on the surface morphology was investigated. Finally, the constructed floc surface was compared with the surfaces constructed by the conventional methods. This study provided a novel and complete solution to construction of sludge floc surface morphology.

2. Materials and methods

2.1. Fractal geometry

Fractal geometry, which initially denoted irregular and broken objects, was firstly conceived by Mandelbrot (1967). This conception has been discussed in various depths and successfully used to describe various natural phenomena, such as turbulence, precipitation, and surface topography (Yan and Komvopoulos, 1998). These natural phenomena are not regular geometric shapes of the standard Euclidean geometry. Fractal geometry provides proper ways of describing, measuring and predicting these natural phenomena. Self-similarity and fractal dimension represent two of the most important properties of fractal geometry. Self-similarity means that an object is composed of sub-units and sub-sub-units on multiple levels that (statistically) resemble the structure of the whole object. An example for rough surface is the appearance of smaller scales of roughness when the section of the rough surface is magnified. A fractal dimension is an index for characterizing fractal patterns or sets by quantifying their complexity as a ratio of the change in detail to the change in scale (Mandelbrot, 1982).

2.2. Sludge liquor samples

The sludge liquor samples were taken from a long term running (more than 200 days) submerged MBR system which had an effective volume of 65 L. The reactor was operated to treat simulated municipal wastewater. A polyvinylidene fluoride (PVDF) flat sheet membrane module with effective area of 1.0 m^2 was used as separation unit for the reactor. The hydraulic retention time (HRT) and sludge retention time (SRT) for the MBR were controlled to be 5.5 h and 45 d, respectively. The details of the wastewater composition and reactor configuration can refer to the previous study (Lei et al., 2016).

2.3. Particle size distribution

A Malvern Mastersizer 2000 instrument with a helium-neon laser was used to measure the particle size distribution (PSD) of the sludge liquor samples. The PSD of the sludge liquor samples was measured based on the light scattering method where the scattered light is detected by means of a detector. The instrument consists of 31 photosensitive detectors which convert the signal to a size distribution based on volume. The detection range of the instrument was 0.02–2000 μm. The sludge liquor sample was continuously recycled through the sample cell of the Malvern with a peristaltic pump to be exposed to a laser (632.8 nm wavelength). Each sample was measured in triplicate.

2.4. Fractal dimension determination

The fractal dimension (D_f) was calculated from the raw data of light scattering from the Malvern Mastersizer 2000 instrument according to the static light scattering method (Guan et al., 1998). D_f can be determined from the negative slope of a log-log plot of the light intensity scattered by the floc, I(Q), as a function of the wavenumber used, Q (the magnitude of the difference between the incident and scattered wave vectors).

$$I(Q) \propto Q^{-D_f} \quad (1)$$