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Research review paper

Mathematical modeling of aerobic granular sludge: A review

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ABSTRACT

Aerobic granulation may play an important role in the field of wastewater treatment due to the advantages of aerobic granules compared to the conventional sludge flocs, such as denser structure, better settleability and ensured solid-effluent separation, higher biomass concentration, and greater ability to withstand shock loadings, which is promising for a full-scale implementation. As an aid for this implementation, mathematical modeling would be an invaluable tool. In this paper, the existing mathematical models available in literature concerning aerobic granule systems are reviewed, including the modeling of the dynamic facets of the aerobic granulation process, the mass transfer and detachment in aerobic granules, the granule-based sequencing batch reactor, the fate of microbial products in granules, and the multi-scale modeling of aerobic granular sludge. An overview of the parameters used in the aerobic granular modeling approaches is also presented. Our growing knowledge on mathematical modeling of aerobic granule might facilitate the engineering and optimization of aerobic granular sludge technology as one of the most promising techniques in the biological wastewater treatment.

Contents

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1. Introduction

In the last decade, intensive research has demonstrated that aerobic granular sludge technology is a novel and promising development in the field of biological wastewater treatment (Morgenroth et al., 1997; Beun et al., 1999, 2002; Jiang et al., 2002, 2006; Jang et al., 2003; de Bruin et al., 2004; de Kreuk et al., 2005a,b; Adav et al., 2007, 2008a; Yilmaz et al., 2008; Liu et al., 2009). Aerobic granulation process is usually completed in sequencing batch reactors (SBRs), with a cycle configuration chosen such that a strict selection for fast settling sludge and a frequent repetition of distinct feast and famine conditions occur. In an SBR, wastewater is mixed with the aerated activated sludge in a pulse-feed mode. Then, the sludge and input substrate "react" in a form of batch treatment. This highly dynamic feed regime leads to the growth of stable and dense granules (Liu and Tay, 2002, 2004; Su and Yu, 2005; Zheng et al., 2005, 2006; Liu et al., 2009). Compared to the conventional activated sludge flocs, aerobic granules have several advantages. An outstanding feature is their excellent settling ability, which is a prerequisite for good solid–liquid separation. Moreover, aerobic granular sludge provides a high and stable rate of metabolism, resilience to shocks and toxins due to the protection by a matrix of extracellular polymeric substances (EPS), long biomass residence times, biomass immobilization inside granules, and therefore, the possibility for bioaugmentation (Su and Yu, 2005; Lemaire et al., 2008a,b; Yilmaz et al., 2008).

To facilitate and promote its practical application for wastewater treatment, researchers worldwide have extensively investigated the fundamentals of aerobic granulation. Several review papers have been published in the past five years and most of aspects regarding microbial granulation have been covered by them. Liu and Tay (2004) and Maximova and Dahl (2006) gave the most encompassing reviews on the bioaggregation processes. Hulshoff Pol et al. (2004), de Kreuk et al. (2007a), Adav et al. (2008b), and Liu et al. (2009) have provided reviews on the state of the art for the anaerobic and aerobic granules respectively.

From extensive laboratory-scale investigations into this system and its scaling up (Schwarzenbeck et al., 2005; de Kreuk and van Loosdrecht, 2006; Zheng et al., 2006; Ni et al., 2009), it has been concluded that the system holds a considerable promise for full-scale implementation. To aid the design, operation and optimization of, and further research into this system, mathematical simulation model would be invaluable as an evaluation tool. Moreover, mathematical modeling has proven to be very useful to study complex processes, such as the aerobic granular sludge systems (Beun et al., 2001; Su and Yu, 2006a,b; de Kreuk et al., 2007b; Xavier et al., 2007). Biological reaction processes in aerobic granules are determined by concentration gradients of oxygen and diverse substrates. The substrate and dissolved oxygen (DO) concentration profiles are the result of many factors, e.g., diffusion coefficient, conversions rate, granule size, biomass spatial distribution, and density. All of these factors tightly influence each other; thus the effect of separate factors cannot be studied experimentally. Model simulation and prediction, combined with model analysis, together with techniques like uncertainty and sensitivity analysis within the wastewater community (Sin et al., 2009), can provide a solid foundation for design and operation of biological treatment systems including the aerobic granular sludge system.

Despite of the obvious importance of modeling of aerobic granular sludge systems, and the increasing number of publications, there has never been any attempt to summarize all the modeling information in a comprehensive review. Therefore, in this paper, the modeling of the dynamic facets of the aerobic granulation process, the physicochemical processes in aerobic granules, the granule-based reactor, the microbial storage and the fate of microbial products in aerobic granules, and the multi-scale modeling of aerobic granules are delineated. An overview of the parameters used in the aerobic granular modeling approaches is also presented. This review aims at providing knowledge on mathematical modeling of aerobic granular sludge and related reactors to facilitate the engineering and optimization of this novel technology.

2. Modeling the aerobic granulation process

In this section, we give a concise overview about the modeling approaches for the aerobic granulation processes. The section presents efforts where empirical models were applied for aerobic granulation processes or where modifications to biofilm formation model were performed to describe the granulation. This section also describes the simple models that are closest to being applicable in practice and is, thus, very useful for end-users. It includes an introduction and four important aspects: granule size variation, selection pressure, settling velocity, and biomass dynamics. The most significant progress in this field is the development of new mathematical models incorporating microbial growth, oxygen transfer, substrate diffusion, increased granule size, and biomass detachment to describe the aerobic granulation process of activated sludge.

2.1. Empirical models for aerobic granulation

To simulate the aerobic granulation process, some empirical models have been developed initially on the basis of logistic curves (Su and Yu, 2005) or a linear phenomenological equation (Yang et al., 2004). A modified logistic model has been adopted by Su and Yu (2005) to describe the granulation process in terms of granule size:

$$R(t) = \frac{R_{\max}}{1 + e^{-k(t-t_0)}} \quad (1)$$

where t is the operating time (days), $R(t)$ is the mean radius of aerobic granules on day t (mm), $R_{\max}$ is the asymptote of the curve, i.e., the maximum mean radius of aerobic granules (mm), k is the specific growth rate by diameter (1/day), and t_0 is the lag time (day). A regression was performed with the experimental data by Su and Yu (2005) and it was found that the granulation process could be well simulated by this model.

With the linear phenomenological equation (LPE), Yang et al. (2004) have developed a kinetic model to describe the growth of aerobic granules under different conditions by applying the LPE to the aerobic granulation process.

$$R - R_0 = \left(R_{eq} - R_0\right)\left[1 - e^{-\mu(t-t_0)}\right] \quad (2)$$

where R is the size of microbial aggregate at time t (mm), R_{eq} is the size of microbial aggregate at equilibrium, μ is the specific growth rate of aggregate by size (day^{-1}), t_0 is the time at end of lag phase, and R_0 is the size of microbial aggregates at time t_0.

This simple kinetic model shows that the growth of aerobic granules in terms of equilibrium size and size-dependent growth rate were inversely related to shear force imposed to microbial community. A high organic loading favored the growth of granules, leading to a large size granule. However, these experiment-oriented models might not be applicable for describing the complex aerobic granulation process and optimizing the operating conditions for granulation in a generalized way.

2.2. Selection pressure for aerobic granulation

Successful and stable granulation of activated sludge in an SBR is dependent heavily on the applied selection pressures in the forms of settling time, volume exchange ratio or discharge depth, and discharge time (Arrojo et al., 2004; Hu et al., 2005; Kim et al., 2004; McSwain et al., 2004; Qin et al., 2004a,b; Wang et al., 2004). For a