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Long-term formation of microbial products in a sequencing batch reactor

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ABSTRACT

Activated sludge in a sequencing batch reactor (SBR) is subjected to alternating feast-and-famine conditions, which may result in the enhanced production of microbial products: extracellular polymeric substances (EPS), soluble microbial products (SMP), and internal storage products (X_{STO}). In this work, the long-term formation of these three microbial products by activated sludge in an SBR is investigated using an expanded unified model with a parallel experimental study. We also use the model to compare the impacts in an SBR to those in a continuous-flow activated sludge system. The model captures all experimental trends for all components with solids retention time (SRT) for global steady state and within a cycle. At an SRT of 20 days, the active microorganisms constitute about 28% of the mixed liquor volatile suspended solids (MLVSS); the remaining biomass is comprised of residual inert biomass (X_I) of 40%, EPS of 31%, and X_{STO} of ~1%. The active biomass becomes a smaller fraction with the increasing SRT, while the inert biomass becomes increasingly dominant. For soluble components, effluent chemical oxygen demand (COD) is dominated by SMP, which varies to some degree in a cycle, peaking as external substrate becomes depleted. Within the SBR cycle, external substrate (S) declines strongly in the first part of the cycle, and SMP shows a small peak at the time of S depletion. X_{STO} is the only biomass component that varies significantly during the cycle. It peaks at the time that the input substrate (S) is depleted. Simulation for a continuous-flow activated sludge system and comparison with an SBR reveals that the constant "famine" conditions of the continuous system lead to lower EPS and X_{STO}, but higher MLVSS and X_I.

1. Introduction

The sequencing batch reactor (SBR) has been widely used to treat municipal wastewater (Irvine and Ketchum, 1989; Furumai et al., 1999; de Kreuk et al., 2005; Otawa et al., 2006), landfill leachates (Timur and Ozturk, 1999), and various industrial wastewaters (Irvine and Ketchum, 1989; Segar et al., 1995; Kortekaas et al., 1998) since it was invented by Irvine and his co-workers (Irvine and Busch, 1979). The SBR is a fill-and-draw system, where each tank is subjected to the following operations: fill (static or mixed), react (static or mixed), settle, idle, and decant (or draw) for predetermined time periods. These periods can be used for various microbial reactions requiring different environmental conditions (Irvine and Busch, 1979).

Activated sludge subjected to alternative feast-and-famine conditions in an SBR can take up the carbon substrate rapidly while producing different microbial products that are important sinks for the electrons and carbon derived from the

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original substrate: extracellular polymeric substances (EPS), soluble microbial products (SMP), and internal storage products (X_{STO}) (Ni et al., 2009). These different types of microbial products are significant carbon and electron sinks whose impacts should be accentuated in systems exposed to feast-and-famine conditions that promote their accumulation and subsequent utilization (van Loosdrecht et al., 1997; Krishna and van Loosdrecht, 1999; de Silva and Rittmann, 2000a,b; Pratt et al., 2004; Sin et al., 2005; Ni et al., 2009).

The microbial response to dynamic conditions can be different from a simple increase in cell number (“growth”) and includes other substrate-removing mechanisms and microbial products formation. It is important to distinguish these different mechanisms in order to understand properly the process dynamics and to build up a practically useful model for activated sludge design and operation. For example, EPS are involved in adhesion phenomena, formation of the matrix structure, controlling the microbial physiology, and the long-term stability of the sludge (Sheng et al., 2006). Likewise, the storage and subsequent utilization of X_{STO} are a main mechanism for the organic material in activated sludge operated under dynamic conditions (Ni et al., 2009), while SMP comprise the majority of soluble organic materials in the effluents from biological treatment systems (Laspidou and Rittmann, 2002a,b). In addition, EPS and SMP play an importance role in membrane biofouling of membrane bioreactors (MBRs) (Meng et al., 2009).

Commonly used models do not simulate the dynamics of all these components, i.e., EPS, X_{STO}, and SMP (Henze et al., 1987, 2000; Gujer et al., 1999). Therefore, Ni et al. (2009) developed an expanded unified model that integrates production and consumption of X_{STO} into a unified model for EPS, SMP, and active and inert biomass in activated sludge. The model captured experimental observations accurately for the soluble and solid components in activated sludge exposed to dynamic feast-and-famine conditions (Ni et al., 2009). In addition, the model illustrated that X_{STO}, EPS, and the biomass components had distinctly different behaviors during feast-and-famine periods.

The main objective of this work is to evaluate the long-term behaviors of the different microbial products in an SBR by using the expanded unified model and a parallel experimental study. The relationships among the concentrations of EPS, SMP, X_{STO}, cycle characteristics of the SBR, and solids retention time (SRT) are the focus. The results show that the solid components in the SBR are strongly governed by the SRT, but the soluble components are controlled by the cycle characteristics of the SBR. We also use the expanded unified model to compare the impacts in an SBR to those in a continuous-flow activated sludge process.

2. Model description

Ni et al. (2009) developed the expanded unified model to describe the important solid-phase and soluble components in an activated sludge system carrying out aerobic heterotrophic reactions. The model employs the following symbols for concentrations of components: external substrate (S), active heterotrophic biomass (X_H), internal storage products (X_{STO}), residual inert biomass (X_I), utilization-associated products (S_{UAP}), biomass-associated products (S_{BAP}), soluble microbial products ($S_{SMP} = S_{UAP} + S_{BAP}$), extracellular polymeric substances (X_{EPS}), and dissolved oxygen (S_O).

The fundamental mechanisms and kinetics for the formation and hydrolysis of EPS, the formation and biodegradation of UAP and BAP, X_{STO} formation and utilization, substrate consumption and active biomass and X_I accumulations, and oxygen transfer and consumption were described in detail in Ni et al. (2009). Tables 1 and 2 summarize the stoichiometry and kinetic expressions of the expanded unified model in Petersen-matrix format.

Table 3 defines all the parameters used in the expanded unified model, their symbols, units, and values for simulation in this work. Most of the parameter values are taken from Ni et al. (2009), since they apply directly to aerobic, heterotrophic systems. In particular, model simulations with these parameters matched experimental results for all components in four independent experiments (Ni et al., 2009), showing that the structure of the model was accurate. However, because Ni et al. (2009) utilized a soybean-processing wastewater, while we used an acetate synthetic wastewater in the present study, we calibrated four stoichiometric and kinetic parameters associated to the substrate; they are identified in Table 3.

The four parameter values ($Y_{H,STO}$, k_{STO}, $\mu_{H,STO}$, and K_S) were estimated by minimizing the sum of squares of the

Table 1 – Stoichiometric matrix for the microbial products model.

Component Process	S_O O_2	S COD	S_{UAP} COD	S_{BAP} COD	X_I COD	X_{EPS} COD	X_H COD	X_{STO} COD
Growth on S	$-\frac{[1-k_{EPS}-k_{UAP}-k_{STO}-Y_{H,S}(1-k_{EPS}-k_{UAP}-k_{STO})]}{Y_{H,S}}$	$-\frac{1}{Y_{H,S}}$	$\frac{k_{UAP}}{Y_{H,S}}$			$\frac{k_{EPS}}{Y_{H,S}}$	$1-k_{UAP}-k_{EPS}-k_{STO}$	$\frac{k_{STO}}{Y_{H,S}}$
Growth on X_{STO}	$-\frac{1-Y_{H,STO}}{Y_{H,STO}}$						1	$-\frac{1}{Y_{H,STO}}$
Growth on S_{UAP}	$-\frac{1-Y_{UAP}}{Y_{UAP}}$		$-\frac{1}{Y_{UAP}}$				1	
Growth on S_{BAP}	$-\frac{1-Y_{BAP}}{Y_{BAP}}$			$-\frac{1}{Y_{BAP}}$			1	
Release of X_{EPS}				1		−1		
Endogenous respiration	$-(1-f_I)$				f_I		−1	