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Numerical investigation of COD reduction in compact bioreactor with bubble plumes

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HIGHLIGHTS

- Full 3D bubble plume system is used to simulate wastewater purification bioreactor.
- This model includes a total of 14 categories of bacteria's and 56 different species.
- Uniform injection is better than central injection of microbubbles in a short tank.

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ABSTRACT

Water purification using microbubbles has become an important topic, owing to its enhanced mass transfer effect. Therefore, a full 3D numerical model is developed for wastewater purification using microbubbles with bacterial biochemical reactions. Microbubbles are injected into the bioreactor, and the oxygen obtained from microbubble dissolution is used by the bacteria for substrate consumption. This consumption performance may depend on several factors, including physical parameters such as bubble size, column height, and injection type. Optimization of the bioreactor performance based on these parameters would lead to significantly faster purification. In this study, the dependences of these parameters are investigated numerically. The bioreactor model is provided by the mixed Eulerian-Lagrangian formulation for fluid flow and bubble motion tracking in the system. Mass transfer, gas dissolution, and mixing using the Sherwood number approach are employed in this model. Biochemical reactions based on various literatures, including activated sludge models, are used for the current simulation of wastewater purification. Simulations are carried out for an aerobic bacterial system with carbohydrates as the chemical oxygen demand source. The bioreactor height is varied from 1:1 to 4:1 to the base ($\sim$0.1 m), the bubble size is varied from 200 μm to 1 mm, and the central and uniform injection systems are compared. The analysis demonstrates that, for microbubbles with a uniform injection system, a drastic reduction in bioreactor height can be achieved without a performance reduction. An important conclusion is that, for a shorter bioreactor height with 200 μm-microbubble injections, the uniform injection system offers significantly superior performance, while for a longer height with larger (500 μm or 1 mm) bubbles, the central and uniform injections provide nearly the same performance.

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1. Introduction

According to reports from the WHO (2016) and UNICEF (2013), the majority of water-related deaths in developing countries are closely related to water contamination. Biological treatment is often applied in order to remove waste and contaminants in polluted water. Biological treatment can be broadly classified as aerobic, anoxic, and anaerobic processes, based on the conditions under which the treatment is performed. The standard wastewater treatment process is illustrated in Fig. 1. Wastewater is passed through the aeration tank, where bacterial reactions occur. Thereafter, the sludge is allowed to settle and the clean water is removed from the top of the clarifier-settler. The aeration tank (represented in orange in Fig. 1) is the focus of our research, which we are modeling.

Levin and Gealt (1993) concluded that the efficiency of the pollution removal reaction is dependent on the bubble flow

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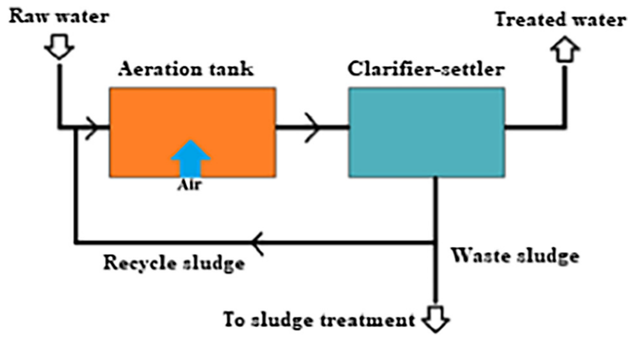

Fig. 1. Activated sludge system.

hydrodynamics inside the tank, in addition to the bacterial reactions. Thus, all aspects of the bioreactor must be modeled, including biochemical reactions, bubble flow, and oxygen dissolution.

For conversion of biodegradable substrate using an aerobic process, aerobic reactions are carried out in the aeration tank, where oxygen or air bubbles are supplied to the aerobic bacterial species (aerobes). Aerobic reactions are generally carried out using activated sludge systems, in which the aerobes consume the substrates and completely break them down into carbon dioxide and water, generating high amounts of energy. As the bacterial reactions proceed, the available substrates will undergo oxidation into carbon dioxide and water, along with the formation of new bacteria. Grady et al. (2011) demonstrated that a reduction in chemical oxygen demand (COD) is a critical parameter for efficient wastewater treatment.

Although research related to chemical reactions for the numerical modeling of activated sludge systems began back in the 1960s, Henze et al. (1987) initiated and developed the first recognized mathematical model, known as the activated sludge model 1 (ASM1). The model has been found to provide an effective description of the activated sludge process, which illustrates COD and nitrogen in the suspended growth processes. The ASM1 model includes eight sub-processes of activated sludge, as described by Nelson and Sidhu (2009), namely: aerobic and anoxic growth of heterotrophic biomass, death of heterotrophic biomass, aerobic growth of autotrophic biomass, decay of autotrophic biomass, ammonification of soluble organic nitrogen, and hydrolysis of both entrapped particulate organic matter and entrapped organic nitrogen. Based on certain requirements, this model was later extended to several other models, including ASM2 by Gujer et al. (1995) to include phosphorus accumulating organisms (PAOs) and biological nutrient removal behavior, ASM2D by Henze et al. (1999), in which the denitrifying activity of PAOs was introduced, and ASM3 by Gujer et al. (1999), incorporating the storage of organic substrates as a new process. Hoover and Porges (1952) estimated an empirical formula for microorganisms; more specifically, for activated sludge. They provided a formula of $C_5H_7O_2N$, including carbon, oxygen, nitrogen, and hydrogen. Similarly to ASMs, work on anaerobic digestion modeling began in 1997 in Sendai, Japan, by IWA, and the anaerobic digestion model (ADM) was familiarized by Batstone et al. (2002) for modeling generalized anaerobic digestion.

However, the abovementioned models do not consider flow characteristics in the different aeration tanks, and only model biochemical reactions (0-dimensional models). As stated previously, bubble flow modeling is necessary for the simulation of wastewater purification bioreactors.

In relation to the flow characteristics in the aeration tank, bubble plumes with mass transfer can be observed in different biological applications, including wastewater purification (Fan, 1989).

Numerous experimental studies have been carried out on bubble plumes, including those of Murai and Matsumoto (1998), Deen et al. (2000), Degaleesan et al. (2001), Warsito and Fan (2005), Zimmerman and Tesar (2012), and Rehman et al. (2015). Numerical simulations of bubble plumes have been carried out by means of either a Eulerian-Eulerian or Eulerian-Lagrangian approach. The Eulerian-Eulerian approach simulates both the continuous and dispersed phase in the Eulerian framework. However, the Eulerian-Lagrangian approach has been used extensively in the study of the dispersed phase motion in a continuous phase with a low void fraction, which is beneficial for bubble plume simulation. Three types of Eulerian-Lagrangian approaches are available: one-way, two-way, and four-way coupling. One-way coupling involves only the dispersed phase being affected by the continuous phase (Berlemont et al., 1990; Desjonqueres et al., 1987; Gouesbet and Berlemont, 1999). Two-way coupling involves the effects of one-way coupling and the dispersed phase on the continuous phase (Squires and Eaton, 1991; Mazzitelli et al., 2003; Murai and Matsumoto, 1998). Four-way coupling involves coupling of both the continuous and dispersed phases, and the interactions within the dispersed phase (Laviéville et al., 1995; Sommerfeld, 2003; Lain and Sommerfeld 2008). Two types of two-way coupling exist. In one of these, fluid with a large volume fraction in the flow field is treated as the continuous phase, and interactions between the two phases are explicitly provided as source terms in the continuous phase momentum equation (Delnoij et al., 1997; Climent and Magnaudet, 1999). The second method treats the entire mixture of liquid and bubbles with the Eulerian approach, and solves the mixture motion using one set of momentum equations and coupling of the continuity equation (Sokolichin et al., 2004; Gong et al., 2007).

Bubble column reactors for water treatment have been investigated numerically using both the Euler-Euler approach (Le Moullec et al., 2008; Jakobsen et al., 2005; Pfleger and Becker, 2001) and the Euler-Lagrange approach (Gong et al., 2009; Lain et al., 2002; Lapin and Lübbert, 1994). Furthermore, on the experimental front, several attempts have been made to improve aeration tanks for water treatment, such as the works of Rosso et al. (2008), Zimmerman et al. (2011), and Rubio et al. (2002).

Oxygen mass transfer of oxygen is a fundamental process in water purification systems, and the bubble size reduction to microbubbles provides improved oxygen dissolution and mass transfer. For this purpose, microbubble generation and the improvement thereof for water purification reactors have being studied in recent years. Important studies include: microbubble generation using a converging-diverging nozzle for water purification systems by Fujiwara et al. (2003), a technique for the generation of microbubbles smaller than 200 μm in diameter using a Venturi tube at a high void fraction by Kaneko et al. (2012), a study on CO_2 mass transfer mechanisms by Al-Mashhadani et al. (2011), a study on enhanced mixing in bioreactors by Mahmood et al. (2015), and the design of an aerator for microbubbles by Hanotu et al. (2017). Other notable research includes Makuta et al. (2006), Ying et al. (2014), and Hanotu et al. (2016).

Owing to the high computational costs of direct numerical simulation (DNS) of mass transfer phenomena, which involves computing the mass transfer boundary layer and requires very fine grids, the averaged Sherwood number, based on the motion of bubbles relative to the surrounding liquid (Clift et al., 1978), is often used to study mass transfer in bubble plumes by means of point-like assumption of the bubbles (Kim and Kang, 1997; Darmana et al., 2005). Gong et al. (2007) simulated the mass transfer in bubble plumes by tracking each bubble individually using the Eulerian-Lagrangian approach, in which the information of each bubble, such as velocity, diameter, and location, was used to calculate the mass transfer rate directly, in order to provide improved resolution.

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