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Analysis of gas phase characteristics and mixing performance in an activated sludge bioreactor using electrical resistance tomography

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HIGHLIGHTS

- ERT was used to study the gas phase behavior in an activated sludge bubble column.
- Sauter mean bubble diameter was correlated to the aeration rate and rheology.
- Impact of rheology on the mixing characteristics of bubble column was analyzed.
- A decreasing–increasing trend was found for bubble rise velocity and size vs. MLSS.
- An increasing–decreasing trend was found for mass transfer specific area vs. MLSS.

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ABSTRACT

Gas phase characteristics have a significant impact on hydrodynamic conditions and oxygen mass transfer rate in activated sludge bioreactors. In the present study, the dynamic gas disengagement (DGD) technique was utilized to determine major gas phase properties (namely the number of bubble size classes, the contribution of each class to the overall gas holdup, bubble rise velocity, bubble size, and specific interfacial area for oxygen mass transfer) in an activated sludge bubble column bioreactor containing a wide range of MLSS concentration (0.712–15.86 g/L) for superficial gas velocities in the range 0.081–1.303 cm/s. Mixing performance of the activated sludge bubble column was also studied. All measurements were conducted by electrical resistance tomography (ERT) method because of its unique advantages in hydrodynamic analysis. Variations of bubble rise velocity, bubble size, specific interfacial area for oxygen mass transfer, and mixing time with MLSS concentration revealed the complex role of rheology in hydrodynamics and indicated that it is impossible to make a general conclusion about the impact of rheology without considering a wide range for its variations. A correlation was also presented for relating bubble size to the aeration rate and sludge rheology.

1. Introduction

Different kinds of activated sludge processes are used for wastewater treatment because of the unique operational, economical, and environmental advantages associated with them [1–3]. In these three phase processes, the microbial community – in the form of a solid phase – is responsible for biodegradation of pollutants, and availability of enough oxygen for biological reactions is considered a critical factor which emphasizes the importance of an appropriate air supply to the bioreactor. Activated sludge bioreactors are usually agitated pneumatically, and their efficiency is greatly affected by the hydrodynamic conditions within them [4–7]. For a specific configuration and under otherwise constant operating conditions, two key factors influencing the hydrodynamics inside these bioreactors are: (1) the mode and rate of aeration, and (2) the rheological properties of activated sludge. Having a comprehensive knowledge on how these parameters contribute to the hydrodynamics is a fundamental need.

Many experimental and modeling studies have been conducted in this regard [8–12]. However, a wide range of activated sludge concentrations has not been employed in these research works. The main reason for this drawback is the opacity of activated sludge which causes serious obstacles for using many measuring techniques including particle image velocimetry (PIV), laser Doppler anemometry (LDA), and high-speed photography [11].

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As a solution to this problem, surrogates have frequently replaced activated sludge in hydrodynamic investigations. But, the complex non-Newtonian rheological behavior of activated sludge – which cannot be faithfully simulated by any kind of surrogates – makes it difficult to rely on the results obtained by these studies [11]. Therefore, hydrodynamic characterization of activated sludge bioreactors should be conducted using real sludge samples instead of any kind of representatives, and a wide range of MLSS concentration should be taken into consideration to cover different types of municipal and industrial activated sludge wastewater treatment plants. The MLSS concentration encountered in conventional activated sludge processes can be up to 5 g/L whereas novel systems like membrane bioreactors usually have MLSS concentrations in the range 10–15 g/L.

Furthermore, to yield a realistic hydrodynamic data set, methods should be used which are not intrusive to the flow field, and at the same time are capable of doing point measurements rather than only overall ones. In this regard employing electrical resistance tomography (ERT) – which is an advanced flow visualization technique – can be considered as a wise choice because of its interesting features including: (1) lack of disturbance of the flow field inside the bioreactor, (2) the ability to provide both global and local measurements, (3) applicability to both transparent and opaque fluids, and (4) high speed data gathering capabilities [13]. ERT has had a large number of applications in the study of hydrodynamics in different kinds of chemical engineering processes [14–21]. Thus, applying this technique for the study of hydrodynamics in an activated sludge bioreactor with a wide range of MLSS concentrations can be very advantageous and instructive.

For activated sludge processes – in which aeration is utilized for both agitation and providing oxygen to the reactions – maintaining oxygen mass transfer rate and efficiency in an acceptable level is considered as a vital task [22,23]. Oxygen mass transfer rate, R_{O_2}, can be calculated from Eq. (1) [23]:

$$R_{O_2} = k_l a(C^* - C) \quad (1)$$

In this equation, k_l is the oxygen mass transfer coefficient, a is the specific interfacial area per total volume, C^* and C are saturated dissolved oxygen concentration and dissolved oxygen concentration, respectively.

Gas phase characteristics (e.g. gas holdup, bubble rise velocity, and bubble size) have a crucial effect on the oxygen mass transfer rate [24,25]; thus they should be determined closely. The influence of different factors on these characteristics should also be investigated properly. In our previous research work, variations of global and local gas holdups with aeration intensity and MLSS concentration were studied in an activated sludge bubble column bioreactor, and the results showed an interesting trend of gas holdup versus MLSS which was never reported before in the literature [26]. Such an observation led us to investigate the influence of MLSS concentration and aeration rate on other gas phase characteristics such as bubble rise velocity and bubble size. Dynamic gas disengagement (DGD) technique – which is an established gas phase analysis method – can be employed for this purpose [17,27–29].

The application of the high-speed data capturing capabilities of the ERT technique combined with the DGD technique principles would be very promising for inspecting various gas phase features in activated sludge bioreactors. Having such information about gas phase characteristics can help in the determination of parameter a which is a critical factor regarding oxygen mass transfer rate and efficiency [24,30]. It should be noted that although there are numerous studies on the effect of various pertinent parameters on $k_l a$ in activated sludge bioreactors [4,22,23,30,31], for a better realization of oxygen mass transfer phenomena, an independent study of parameter a is indispensable [30].

Mixing performance of aerated systems is another key factor which is greatly affected by gas phase specifications [19,30,32]. Generally, mixing time is one of the most important hydrodynamic characteristics in different types of chemical engineering reactors, and it is also considered as a determinant parameter for design and scale up purposes [6,19,33]. Some techniques such as dye addition [34], conductivity probe [35], radioactive liquid tracer [36], and thermocouple-based methods [37] have been used by many researchers for mixing time measurements. However, the ERT technique eliminates the limitations of these conventional methods. This technique has been successfully used for measuring the mixing time in various processes including a multi-lamp photoreactor, internal and external loop airlift reactors, and mixing tanks [18–20,32,38,39].

The aim of the present study was the determination of major gas phase behavior related parameters (i.e. the number of bubble size classes, contribution of each class to the overall gas holdup, bubble rise velocity, bubble size, and parameter a) using the ERT and DGD techniques in an activated sludge bubble column bioreactor over a wide range of MLSS concentration. The MLSS concentration range employed (0.712–15.86 g/L) was selected to simulate the corresponding values obtained in both conventional as well as novel activated sludge processes. Additionally, a correlation relating bubble size to the superficial gas velocity and sludge rheology was developed and mixing characteristics were studied using the ERT technique.

2. Experiment

2.1. Experimental setup

A bubble column of 0.248 m inside diameter and 1 m height – constructed of polyvinyl chloride (PVC) – was employed for hydrodynamic experiments (Fig. 1). Air was supplied to the bioreactor using a cross shaped gas sparger which had six arms of 0.078 m long with four holes of 1 mm diameter at each arm. Gas sparger was located at the bottom of the column and the air sparging rate was measured by a rotameter.

2.2. Electrical resistance tomography (ERT)

An electrical resistance tomography (ERT) system (P2000, Industrial Tomography Systems Ltd., Manchester, UK) was employed to measure the electrical conductivity at different locations inside the bubble column. Details of the ERT system has been described elsewhere [26]. Fig. 1 also illustrates the major parts of this measuring system including: electrodes, data acquisition system (DAS), and image reconstruction system. For these set of experiments, an excitation frequency of 19,200 Hz and an injection current of 15 mA were employed.

2.3. Experimental procedure

Activated sludge was obtained from the aeration unit of the Ashbridges Bay wastewater treatment plant in Toronto, Ontario, Canada. Seven different MLSS concentrations were employed for the hydrodynamic studies and MLSS analysis was performed based on standard methods [40]. According to the significant role of rheology in hydrodynamics, the rheological experiments were previously carried out on the sludge samples at 22 ± 0.5 °C, and the power law model was reported as the most suitable description for MLSS concentrations in the range 0.712–15.86 g/L [26]. As MLSS concentration increased, the consistency index (K) and flow behavior index (n) varied in the ranges 0.005–0.054 Pa s^n and 0.689–0.414, respectively.