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The use of electrical resistance tomography for the characterization of gas holdup inside a bubble column bioreactor containing activated sludge

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HIGHLIGHTS

- Employing ERT for holdup measurements in an activated sludge bubble column.
- Fitting the rheology for MLSS in the range 0.712–15.86 g/L to the power law model.
- Finding an increasing–decreasing trend for overall gas holdup versus MLSS.
- Analyzing radial and axial variations of gas holdup versus gas velocity and MLSS.

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ABSTRACT

Gas holdup is a determinant factor regarding the efficiency of the activated sludge processes. Despite the numerous studies on the characterization of gas holdup in two or three phase systems, lack of experimental data in systems including actual cells as the solid phase has been emphasized in the literature. This study is a response to the need for an appropriate knowledge on the gas holdup behavior in the real activated sludge systems. The capabilities of electrical resistance tomography in performing local and global measurements in a non-intrusive manner made it possible to examine the influence of MLSS concentration and aeration intensity on the overall as well as spatial distribution of gas holdup within the activated sludge bioreactor. In order to cover all activated sludge processes, a wide range of MLSS concentration (0.712–15.86 g/L) was employed, and the effect of MLSS on rheological characteristics of the corresponding mixed liquor was measured and modeled. The results of the present study revealed an initially increasing followed by decreasing variation of overall gas holdup with increasing MLSS concentration which is reported in this paper for the first time. Radial distribution of gas holdup was also modeled and the variations of central, wall, and cross sectional average gas holdups with axial location, MLSS, and air velocity were specified.

1. Introduction

Biological methods are widely used for treating both municipal and industrial wastewaters. Among different methods utilized for biological wastewater treatment, activated sludge process – which is a suspended growth treatment method – has had a large number of applications. Presence of different kinds of bacteria, fungi, and protozoa in the sludge flocs gives the capability of complete mineralization of pollutants to this process [1]. In addition to conventional activated sludge process, sequencing batch reactor and membrane bioreactor (MBR) are other well-known modified activated sludge processes [2,3].

In the activated sludge bioreactors, which are included in the category of three phase reactors, aeration is utilized for both the supply of oxygen to the biomass and the maintenance of mixed conditions within the bioreactor [4]. Considering the indispensable role of aeration, the quantity of gas holdup and its distribution throughout the bioreactor are among the most critical hydrodynamic characteristics in the activated sludge processes. For this purpose, knowledge regarding the effect of pertinent design, operational and environmental parameters on gas holdup and its spatial distribution in the activated sludge bioreactors is a prerequisite for their optimum design and operation.

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Numerous modeling and experimental studies have been performed to understand the hydrodynamics of the activated sludge bioreactors. Computational fluid dynamics (CFD) technique has been applied repeatedly for multiphase flow field modeling and oxygen transfer prediction in aeration tanks [5–8] and MBRs [9]. An extensive literature is also available on the experimental investigations of the hydrodynamics within reactors like aeration ditch [10], MBR [11], activated sludge bubble column [12], and activated sludge airlift reactors [13]. Despite the large amount of information obtained by these studies, the lack of representative and non-invasively collected experimental data has been remained a serious problem.

Because of the necessity of fluid transparency for the application of many measuring techniques and difficulties of working with real activated sludge systems, previous researchers have instead used surrogates such as water, xanthan gum solutions, yeast suspensions, and carboxylmethyl cellulose (CMC) solutions in their experiments [6,14–17]. But the representativeness of these surrogates is questionable. The composition of a typical activated sludge is water, dissolved and particulate wastewater constituents, sludge flocs, and biological products like extracellular polymeric substances (EPS) and soluble microbial products (SMP) [18]. Thus the quality of incoming wastewater and the operational parameters influence the activated sludge characteristics in a very intricate and unpredictable way. It is also obvious that the liquid phase of this fluid is different from water, and activated sludge cannot be defined as a mixture of water and sludge flocs. Moreover, in activated sludge processes, the rheological properties of the fluid should be studied properly, because they are considered to be very important and determinant regarding the hydrodynamics, mixing characteristics, and oxygen transfer rate [18].

Table 1 presents some literature data on the activated sludge rheology that were collected in nearly the same range of MLSS concentration and shear rate that were used in the present study. According to this table, the results obtained in different studies are not consistent at all. One reason is that the rheological behavior of activated sludge is affected by numerous factors including MLSS concentration, conductivity, pH, EPS, floc structure, and temperature [18,19]. The other reason is the various measurement procedures employed by different researchers [18]. Therefore, many different rheological models and model parameters have been proposed for activated sludge in literature, but due to above mentioned limitations, choosing an appropriate model for a particular application is a very difficult and unreliable task [9,18].

Measurement techniques that have been used so far for characterization of gaseous phase in the activated sludge bioreactors have some restrictions such as disturbing the flow field within the bioreactor, inapplicability to opaque fluids, and performing global measurements rather than local ones. For example, a double optical probe was utilized for characterizing the gas phase behavior in a pilot scale aeration ditch in which clean water represented the activated sludge [10]. The volume expansion method has been also used for measuring the overall gas hold up in bubble column and airlift reactors with the real activated sludge as the fluid phase [12,13].

The above mentioned survey of literature points to a need for gas holdup data in activated sludge bioreactors in which real activated sludge is employed, using methods which do not interfere with the flow field inside the bioreactor and which, as well as global values, provide gas holdup measurement for any location inside the bioreactor. Electrical resistance tomography (ERT) is an advanced and non-invasive flow visualization technique which is applicable to opaque fluids and has the capability of performing on-line measurements in different axial and radial locations within the reactor. ERT has been used successfully for gas holdup characterization in several two phase and three phase reactors including bubble column reactors [23–25], internal and external loop airlift reactors [26,27], gas-inducing mechanically stirred vessel [28], gas–liquid pipe flows [29,30], and circulating fluidized beds [31,32].

In this study, for the first time electrical resistance tomography (ERT) was utilized for characterization of gas holdup in a bubble column reactor containing activated sludge. The effects of aeration intensity and mixed liquor suspended solids (MLSS) concentration on the overall gas holdup as well as the axial and radial distribution of gas holdup were investigated. The range of MLSS employed was chosen to cover the wide range of MLSS that is employed in various activated sludge bioreactor designs, including MBR. The rheological characterization of the mixed liquor employed as a function of MLSS was also performed in order to enable the presentation of gas holdup correlations in terms of rheological parameters instead of MLSS.

2. Experiment

Experiments were conducted in a bubble column bioreactor of 0.248 m inside diameter and 1 m height (Fig. 1). Polyvinyl chloride (PVC) material was used for the construction of this bioreactor. A cross shaped gas sparger was located at the bottom of the column, and a rotameter was utilized for measuring the air flow rate. The cross shaped sparger had six arms of 0.078 m long and each arm had four holes of 1 mm diameter.

An electrical resistance tomography (ERT) system (P2000, Industrial Tomography Systems Ltd, Manchester, UK) was utilized to obtain the conductivity distribution across different sensor planes. The ERT system comprised of three components: electrodes, data acquisition system (DAS), and image reconstruction system. Six sensor planes were located along the bioreactor height, and for each plane, sixteen equally spaced stainless steel rectangular electrodes were non-invasively fitted to the internal wall of the bioreactor. The dimensions of the electrodes are a function of the different factors such as reactor diameter, range of the fluid conductivity, fluid velocity, and the required image speed. The

Table 1
Rheological properties of activated sludge in different studies.

Sludge source	Shear rate (s^{-1})	MLSS (g/L)	Rheological model	Range of model parameters τ (mPa)	References
Wastewater treatment plant	20–200	2–10	$\tau = a\ln(\dot{\gamma}) - b$	a: 4615.4–14,425 b: 11,095–32,411	[13]
Wastewater treatment plant	1.8–73.4	2–18	Power law	MLSS = 3.68 g/L ($K = 4$, $n = 0.77$) MLSS = 10.76 g/L ($K = 20.9$, $n = 0.595$)	[19]
Membrane bioreactor & Aeration tank	10–600	10	Power law	MBR: $K = 13$, $n = 0.72$ Aeration tank: $K = 52$, $n = 0.62$	[20]
Membrane bioreactor	0.1–100	15	Power law	$K = 1660$ $n = 0.11$	[21]
Membrane sequencing batch reactors	NM	0.39	Casson Herschel Bulkley Power law	$\tau_0 = 9.6$, $K = 27.7$ $\tau_0 = 10.2$, $K = 4.1$, $n = 0.7471$ $K = 8.9$, $n = 0.5894$	[22]