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Measurement of bubble size distribution in activated sludge bubble column bioreactor

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ABSTRACT

Bubble size, bubble rise velocity and the corresponding distributions were directly measured by a dual-tip electro resistivity probe and to present empirical correlations to estimate the average bubble size and bubble rise velocity in activated sludge. Experiments were conducted in a 9 cm diameter bubble column while superficial gas velocity was in range of 0.5–7 cm/s. Four samples of activated sludge with mixed liquor suspended solid (MLSS) concentrations from 1.082 to 10.82 g/L were used in the experiments. It was found that increasing the MLSS concentration resulted in increase in the bubble chord length and bubble rise velocity and decrease in the gas hold up. It was shown that in the homogeneous regime, the probability distributions of bubble chord length and bubble rise velocity are sharp and unimodal. To estimate bubble size and bubble rise velocity in activated sludge, correlations were developed which includes effect of MLSS concentration besides physical properties and operating conditions. The experimental results of this study were compared with the proposed correlations in literature obtained in two and three phase bubble column. It was shown that neither of the previous correlations can predict the bubble size and bubble rise velocity in the activated sludge system properly while the proposed correlation in this work shows a good precision for estimating these parameters.

1. Introduction

Wastewater management is becoming a considerable environmental problem for industries [1]. There are different technologies, including chemical, physical and biological methods of treatment and the biological pre-treatment has proved to be as the most economical method with least environmental impacts [2]. Many biological waste water treatment methods involve activated sludge aeration or air flotation process [3]. The three phase environment of these processes can be mostly found in aerated bio-reactors, such as bubble column and air lift reactors, because of their good mixing, ease of operation and economic benefits [4]. Efficiency of these reactors is highly affected by the hydrodynamics of the gas phase: bubble rise velocity and their relative bubble size distribution. Therefore, gathering experimental data on each of these parameters is a need to understand hydrodynamics and is necessary to scale up and control of the reactor.

Numerous experimental studies have been conducted in transparent systems to correlate bubble size to physical properties of the liquid and operating conditions [5–13]. However, due to experimental limitations inherent to optical methods, experimental data in opaque systems are rare. Modeling studies also cannot accurately address the bubble dynamics in activated sludge because of the complex rheological behavior of the sludge [14]. Hydrodynamics of slurry bubble columns and activated sludge bioreactors has been investigated experimentally using non-intrusive methods such as X-ray tomography, electrical resistance tomography (ERT), electrical impedance tomography (EIT) and electrical capacitance tomography (ECT) [14–23]. Although these methods are non-intrusive and applicable in opaque systems, they cannot evaluate the exact values of bubble dynamics, including bubble size, bubble rise velocity and their distributions. Therefore, there are no direct measured data on the bubble dynamics and their distributions in such systems, except for the gas hold up [4,24–26]. Moreover, these methods have several sources of error which is discussed elsewhere [27]. Gas holdup can be measured using these methods directly and the average bubble properties have been estimated based on bubble volume which was estimated from the measured gas holdup. Also, the value of average bubble size was shown to be highly overestimated [13]. Recently, Babaie et al. [15] and Jin et al. [22] estimated distribution of different bubble classes using dynamic gas disengagement (DGD) method and proposed estimated distributions of bubble dynamic parameters, yet not directly obtained.

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Nomenclature

AF	Acceleration factor, –
C	MLSS concentration, gr/L
C_D	Drag coefficient, –
C_v	Solids volume fraction, –
C_s	Particle fraction in the slurry phase, –
d_b	Bubble diameter, m
$d_{b'}$	Bubble chord length, m
d_c	Internal diameter of bubble column bioreactor, m
f	Bubble frequency, Hz
G'	Storage modulus, Pa
G''	Loss modulus, Pa
h	Height of the probe position, m
H	Column height, m
K	Consistency index, Pa s^n
Mw_{Air}	Air molecular weight, gr/mole
n	Flow index, –
SF	Scale correction factor, –
t_i	Peak width, s
T	Test time, s
u_{gs}	Superficial gas velocity, m/s
u^*	Superficial gas velocity at regime transition point, m/s
V_0	Rise velocity of a single bubble, m/s
V_B	Bubble rise velocity, m/s
X_w	Concentration of purest component in the liquid mixture, wt/wt

Greek symbols

ε	Gas holdup
γ	Shear rate, s^{-1}
μ_{app}	Apparent viscosity, Pa s
μ_L	Apparent viscosity of liquid, Pa s
ρ	Density, kg/m^3
ρ_{Air}	Density of air, kg/m^3
ρ_{DS}	Density of dry biomass, kg/m^3
ρ_L	Density of liquid phase, kg/m^3
ρ_p	Density of particle, kg/m^3
σ	Surface tension, N/m
σ_L	Surface tension, N/m

It can be concluded from the above discussion that there is a substantial need for a more exact measurement of bubble rise and bubble size distribution in activated sludge system by an appropriate experimental method. Therefore, this study was contributed to provide experimental data on direct measurements of bubble dynamics parameters. A dual tip electro-resistivity probe was used for this purpose since it can directly measure the bubble dynamics by the proper method of signal processing, regardless of the opacity of the sludge environment. Bubble rise velocity and bubble chord length distributions were presented and their mean were correlated to the operating conditions and physical properties of the system using dimensionless numbers. The presented correlation was compared with those reported in literatures for transparent viscous liquids.

2. Experiments

2.1. Set-up and materials

The experimental set-up configuration is schematically shown in Fig. 1. A cylindrical bubble column with four different loads of activated sludge, as the liquid phase, was used in experiments. The column used in the experiments was a Plexiglas cylinder with 9 cm inner diameter, 10 cm outer diameter and 1.75 m height. None aerated column had a static liquid level of 130 cm in all experiments. The air flow rate was measured and controlled by an ALICAT MC Series mass flow controller. Air was injected to the column through a perforated plate distributor with 196 holes of 0.5 mm diameter (0.3% opening area). The gas flow rate was changed in every individual liquid mixture and the superficial gas velocity was varied from 0.5 to 7 cm/s. All experiments were carried out at ambient temperature (20 °C) and atmospheric pressure. Each test was started two days after feeding nutrients to the bacteria, thus, the oxygen demand of bacteria in the activated sludge was very low.

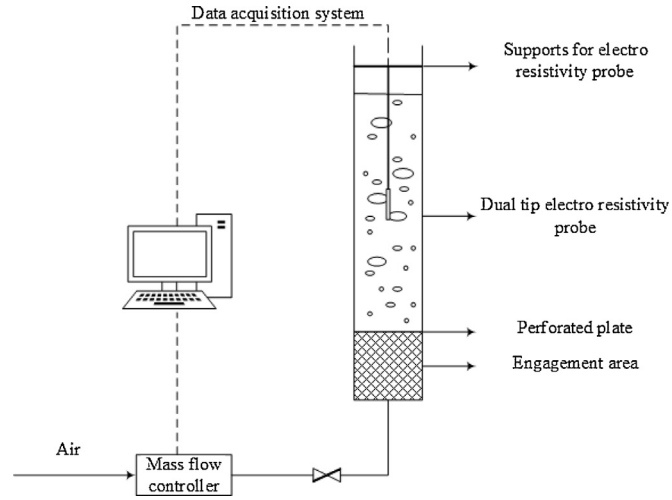

Fig. 1. Schematic of the experimental setup.

Table 1
Physical properties of activated sludge samples.

MLSS concentration, g/L	σ[a], N/m	ρ, kg/m^3	μ_{app}, mPa s (@ $\gamma = 100\ s^{-1}$)
10.82	0.0682	1002.16	10.1434
5.41	0.0723	1001.08	3.5862
3.426	0.072	1000.68	1.8072
1.082	0.072	1000.21	0.3207
0 (water)	0.073	1000	1

[a] The values of surface tension were extracted from Duran et al. [16].

The bio-solids of the activated sludge samples were collected from a municipal wastewater treatment plant in Tehran, Iran. For each activated sludge concentration, the MLSS concentration was measured by sampling the mixed liquor when it was well stirred. Activated sludge samples of four different concentrations of MLSS (10.82, 5.41, 3.426 and 1.082 g/L), in addition to tap water, were used in experiments. The initial MLSS was selected as the most thickened sludge and other samples were obtained by diluting it using the same sludge liquor to achieve the other three samples, as shown in Table 1. Liquid viscosity and density were estimated for each sample using following equations. The density of the mixed liquors was evaluated from [28]:

$$\rho = MLSS + 1000\left(1 - \frac{MLSS}{\rho_{DS}}\right) \quad (1)$$

where ρ_{DS} is the density of dry biomass, equal to 1250 kg/m^3. Densities of samples are given in Table 1.

The rheological behavior of the mixed liquors is shear thinning [14,29,30]. It has been shown experimentally that apparent viscosity of activated sludge liquor is a function of shear rate, operating condition and MLSS concentration [30]. Apparent viscosity of the