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Fluidic oscillator-mediated microbubble generation to provide cost effective mass transfer and mixing efficiency to the wastewater treatment plants

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ABSTRACT

Aeration is one of the most energy intensive processes in the waste water treatment plants and any improvement in it is likely to enhance the overall efficiency of the overall process. In the current study, a fluidic oscillator has been used to produce microbubbles in the order of 100 μm in diameter by oscillating the inlet gas stream to a pair of membrane diffusers. Volumetric mass transfer coefficient was measured for steady state flow and oscillatory flow in the range of 40–100 l/min. The highest improvement of 55% was observed at the flow rates of 60, 90 and 100 l/min respectively. Standard oxygen transfer rate and efficiency were also calculated. Both standard oxygen transfer rate and efficiency were found to be considerably higher under oscillatory air flow conditions compared to steady state airflow. The bubble size distributions and bubble densities were measured using an acoustic bubble spectrometer and confirmed production of monodisperse bubbles with approximately 100 μm diameters with fluidic oscillation. The higher number density of microbubbles under oscillatory flow indicated the effect of the fluidic oscillation in microbubble production. Visual observations and dissolved oxygen measurements suggested that the bubble cloud generated by the fluidic oscillator was sufficient enough to provide good mixing and to maintain uniform aerobic conditions. Overall, improved mass transfer coefficients, mixing efficiency and energy efficiency of the novel microbubble generation method could offer significant savings to the water treatment plants as well as reduction in the carbon footprint.

1. Introduction

Aeration is one of the most energy intensive processes in the waste water treatment, consuming 45–75% of the total plant energy cost (Rosso et al., 2008) and in the developed world that corresponds to 1% of the total electricity usage (Zimmerman et al., 2011a). Aeration is mainly achieved by mechanical means such as entrainment by rotors or by injecting air as bubbles through liquid. Mechanical aerators, however, have lower transfer efficiency, are relatively more energy intensive and usually have high operational costs (Georges et al., 2009). The processes responsible for making aeration so energy intensive are dissolved oxygen demand, respiration of biomass, sufficient mixing to maintain aerobic conditions in the aerator and maintenance of minimum oxygen concentration for chemical and biological demand (COD/BOD) (Tchobanoglous et al., 2003). Aeration efficiency can be improved by enhancing the mass transfer from gas to liquid (Eckenfelder, 1989).

Although fine pore diffusers are ubiquitous in the waste water industry, they are not sufficient to produce bubbles in the range of 200–800 μm. Conventional aeration systems use steady flow to produce bubbles on order of 1–3 mm. These bubbles on average are an order of magnitude larger than the pore size. This disparity can be explained by the dynamics of bubble formation. The forces responsible for bubble formation and release are the surface tension force that holds the bubbles to the pores, buoyancy force of the bubbles responsible for its rise, and the inertial force of the gas phase acting on the top part of the bubble. The bubble breaks off from the diffuser surface when the buoyancy force and the inertial force overcomes the surface tension force (Zimmerman et al., 2008). Usually this break off point comes at an order of magnitude higher than the pore size. This could be explained using the Young–Laplace equation which governs the relation between the

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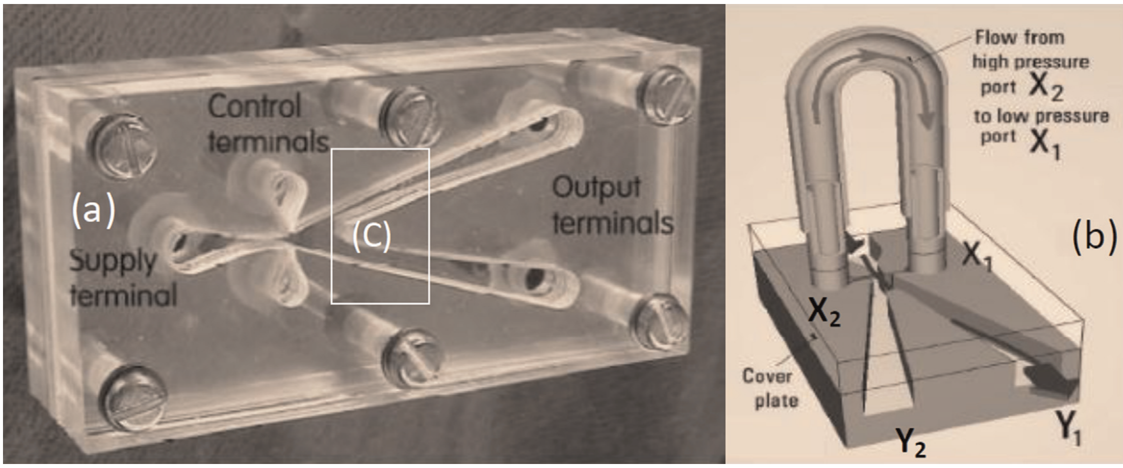

Fig. 1. The fluidic oscillator (a) Photograph of a fluidic oscillator made by laser cutting in acrylic plates. (b) Operation of the device (Zimmerman et al., 2008).

radius of the bubble and the pressure difference (ΔP) across the gas–liquid interface (Tesař, 2012). Also, if the pore arrangement is too closely packed, these bubbles could coalesce with neighbouring bubbles to produce even larger bubbles. The coalescence could also occur due to the polydispersity of bubbles and different rise velocities. Another reason for not forming smaller bubbles from fine porous materials is the channelling in diffuser material (Fig. 1 (a), (Zimmerman et al., 2008).

Bubbles that are over 1 mm in diameter are subjected to a relatively high buoyancy force; hence rise rapidly reducing the residence time for mass transfer. In addition, the surface area to volume ratios of these bubbles are also low relative to microbubbles which reduces the mass transfer across the gas liquid interface. Microbubble however, have high surface to volume ratios and high residence times; hence increased mass transfer across the gas–liquid boundary (Al-Mashhadani et al., 2011).

Surface wetting properties are also found to be of great importance in bubble production. Hydrophobic surfaces cause gas to spread over a larger area beyond the pore size and increase the anchoring force that holds the bubble to the diffuser surface (Zimmerman et al., 2011b). Therefore an increased buoyant force is required to dislodge the bubble from the pore surface and hence the bubble volume to overcome it. Conversely, hydrophilic surfaces have a thin liquid film between the bubble and the diffuser surface, so a hydrophobic gas such as air does not spread on the solid surface. Here, the bubbles are ejected from the pores due to the inertial force of the oscillating gas stream contrary to the slow formation of bubbles from the diffuser pores at steady flow (Zimmerman et al., 2011b).

Conventionally, microbubble generation relies on instabilities described by Zimmerman et al. (2008). However, with fluidic oscillation, bubbles could be released from the pore surface when they form a hemispherical shape which is the smallest possible volume in which a bubble could be formed in the strong adverse effect of the surface tension at higher curvatures (Zimmerman et al., 2008).

Generally, microbubbles can be produced by three different methods. The most common method involves compressing a gas to a higher pressure (~6 bar) and then releasing through a specially designed nozzle. Microbubbles could also be produced by using ultrasound. However, high power densities are required for generation of small bubbles by these techniques (Zimmerman et al., 2008). The third method involves oscillating the fluids either by mechanical vibrations or using a fluidic oscillator (Zimmerman and Tesar, 2013). Fluidic oscillators potentially offer the cheapest means to produce microbubbles and require low maintenance due to no moving parts within the oscillator itself. A fluidic oscillator consists of two components – the amplifier and the feedback loop. An amplifier is shown in the right of Fig. 3. It is made of CNC machined Acrylic glass plates to form a specially designed cavity. The second component, the feedback loop, connects the two control terminals of the amplifier. As a fluid enters the main cavity through the nozzle, it emerges as a jet causing the fluid to entrain from either side of the jet. The low pressure regions developed in the vicinity of the walls cause the jet to attach to one side of the cavity due to the Coanda Effect. This flow attachment results in a pressure difference across the control terminals that generates a pressure wave in the feedback loop (from X_2 to X_1) diverting the jet to the other outlet (Y_2) and vice versa. The oscillation frequency depends on the length of the feedback loop and the inlet flow rate for a given fluidic oscillator (Zimmerman et al., 2008).

It is believed that the outcome will be relevant to any gas–liquid mass transfer process as this novel aeration technology can be retrofitted to existing plants, potentially with little disruption. This experimental study is focused on measuring the performance of microbubbles generated by fluidic oscillation in mass transfer compared to that of steady state aeration using the same pair of diffusers used for wastewater treatment.

2. Materials and methods

2.1. Experimental setup

Two sets of experiments were carried out to determine the mass transfer coefficient (K_la) and bubble size distributions for oscillatory and steady flow conditions.

2.1.1. Estimation of K_la

In the first set of experiments, K_la of oxygen from gas to liquid was estimated by dissolved oxygen measurements. Fig. 2 shows a schematic representation of the experimental rig used for this purpose. A glass tank with dimensions of 1.2 m × 0.59 m × 0.5 m was filled with 350 l of tap water and a pair of disc diffusers (Suprafil™, diameter 30 cm, OXYFLEX®-MT 300) commonly used in wastewater treatment plants was mounted at the bottom of the tank.

A handheld YSI 556 dissolved oxygen (DO) probe was used to determine the dissolved oxygen concentration in the water over time. The DO probe was placed away from the rising bubbles in order to avoid direct contact/attachment of bubbles with the sensor to avoid errors in K_la estimation. Water was first