Journal of Environmental Management 219 (2018) 125–137

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Sidestream superoxygenation for wastewater treatment: Oxygen transfer in clean water and mixed liquor

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ARTICLE INFO

Article history:
Received 20 October 2017
Received in revised form
30 March 2018
Accepted 6 April 2018

Keywords:
Speece cone
Oxygen transfer
Activated sludge
Aeration efficiency
Membrane bioreactor
Wastewater treatment

ABSTRACT

The performance of a pilot-scale superoxygenation system was evaluated in clean water and mixed liquor. A mass balance was applied over the pilot-scale system to determine the overall oxygen mass transfer rate coefficient (K_La, h^{-1}), the standard oxygen transfer rate (SOTR, kg O_2 d^{-1}), and the standard oxygen transfer efficiency (SOTE, %). Additionally, the alpha factor (α) was determined at a mixed liquor suspend solids (MLSS) concentration of approximately 5 g L^{-1}. SOTEs of nearly 100% were obtained in clean water and mixed liquor. The results showed that at higher oxygen flowrates, higher transfer rates could be achieved; this however, at expenses of the transfer efficiency. As expected, lower transfer efficiencies were observed in mixed liquor compared to clean water. Alpha factors varied between 0.6 and 1.0. However, values of approximately 1.0 can be obtained in all cases by fine tuning the oxygen flowrate delivered to the system.

1. Introduction

Aeration is a key process in aerobic biological wastewater treatment. Making enough oxygen available for bacterial growth allows the mineralization and removal of most of the pollutants from wastewater. Diffused aeration has been widely used for decades as the preferred alternative for introducing dissolved oxygen (DO) into water, despite its low oxygen transfer efficiency. The SOTE for fine bubble diffusers in clean water ranges from 2 to 7% per meter depth of reactor (Mueller et al., 2002), and even lower SOTEs have been reported in activated sludge process water; that is, most of the air that is compressed and pumped into the aerobic reactor in a wastewater treatment plant (WWTP) is released back to the atmosphere. In order to overcome the low SOTE in bubble aeration, sufficient retention time for the bubbles to interact with the mixed liquor needs to be provided by applying relatively low air flow rates, and by having deeper bioreactors. That is, to sustain the highest possible SOTE in bubble aeration, the maximum air flowrate allowed through each individual diffuser is compromised. This makes the surface area available in the aerobic reactor a key design parameter, since it determines the amount of diffusers that can be accommodated in the reactor; consequently, the amount of air that can be supplied. Assuming that the volume of the aerobic basin is a fixed outcome in the design process, the deeper the aerobic basin, the smaller the actual surface area available for placing diffusers. The reactor depth and available surface area, together with the biological oxygen demand and atmospheric site conditions, ultimately determine the motor size and power consumption of the air blower-compressor. Moreover, lower SOTEs are expected in process water compared to clean water due to: i) the effect of the suspended solids in the mass transfer process which translates into alpha factors of approximately 0.6 and 0.5 for conventional activated sludge (CAS) systems and for membrane bioreactors (MBR), respectively (Krause et al., 2003; Germain et al., 2007; Trussell et al., 2007; Henkel et al., 2011); and ii) the biofouling of the diffusers which progressively reduces the OTEs and demands additional maintenance (Garrido-Baserba et al., 2016). The aforementioned disadvantages worsen at high biomass concentrations due to: i) the increased resistance the suspended solids

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https://doi.org/10.1016/j.jenvman.2018.04.035

oppose to the mass transfer process (lower alpha values); ii) the diminished gas-liquid contact area due to enlarged bubble size when biofouling of the diffusers causes unwanted coalescence; and iii) uneven air distribution accompanied by progressively reduced air flowrates due to diffuser pore-blocking.

The low SOTEs provided by conventional fine bubble diffusers introduces limitations on the design of wastewater treatment systems. For instance, when designing portable wastewater treatment systems (low depth), high air flowrates are required to compensate for the low SOTEs introduced by the low available water depth provided at these type of wastewater treatment systems. That is, the high air flowrates requirements introduce high energy demands limiting the treatment capacity of these portable wastewater treatment systems. Another example of an application constraint includes the limitations imposed by bubble diffusers on expanding the design possibilities for MBR systems. The maximum designed MLSS concentration in MBRs (therefore, the MBRs treatment capacity and footprint) is limited to approximately 15–18 g L^{-1} due to the low SOTE exhibited by fine bubble diffusers at higher MLSS concentrations. Alpha factors as low as 0.2 have been reported at MLSS concentrations in the 20 g L^{-1} range; and negligible alpha factors have been reported at approximately 40 g L^{-1} (Muller et al., 1995; Germain et al., 2007; Judd, 2008; Racault et al., 2010; Henkel et al., 2011; Durán et al., 2016). Therefore, innovative aeration technologies, and their integration in wastewater treatment processes, are needed to overcome the current limitations imposed by conventional bubble diffusers aeration systems for designing more efficient and compact wastewater treatment systems. Sidestream superoxygenation systems may offer an alternative to cope with the extremely low SOTEs imposed by bubble diffusers; particularly, when working at high MLSS concentrations. Pure oxygen based systems have been recently studied with promising results (Livingston, 2010; Barber et al., 2015; Barreto et al., 2017).

Superoxygenation systems, such as the Speece cone, have been used mainly for the ecological restoration of aquatic ecosystems. The Speece cone reported high oxygen transfer efficiencies and operational flexibility under a wide range of applications without most of the limitations observed in conventional aeration methods (Speece, 1975; Ashley, 1985; Ashley et al., 2008, 2014). The oxygen transfer process occurs in a pressurized vessel built in a side-stream configuration. An oxygen supersaturated stream can be delivered to a receiving basin without depending on the current limitations imposed by bubble diffusers such as the maximum number of submerged bubble diffusers that can be placed on a given surface area. The use of this aeration method may allow both the design of shallow wastewater treatment reactors for portable sanitation applications, as well as the operation of high oxygen demand wastewater treatment systems such as MBRs operated at high MLSS concentrations.

Previous studies reporting on the factors influencing the oxygen transfer on Speece cone systems in clean water have been conducted for hypolimnetic aeration of aquatic ecosystems applications (Ashley, 1985; McGinnis and Little, 1998; Ashley et al., 2008, 2014). However, the integration of the Speece cone system in the wastewater treatment field has not been explored. For instance, the effects of the MLSS concentration on the oxygen transfer capacities of the Speece cone technology have not been researched. Despite the enormous potential advantages of the superoxygenation technologies over conventional aeration methods, the performance of these systems have not been evaluated in the context of wastewater treatment applications. Once proven successful in wastewater treatment applications, more compact, portable, and energy efficient wastewater treatment systems can become a standard practice in the wastewater treatment field. For instance, MBR systems operated at high MLSS concentrations in combination with other strategies such as energy optimization (Gabarrón et al., 2014) can maximize the impact and application of decentralized wastewater treatment systems for water reclamation (Atanasova et al., 2017). Potential advantages of a high MLSS MBR system include: reduced generation of waste activated sludge (WAS), reduced footprint requirements, better portability, and enhanced operational flexibility, among others as reported in a previous study on a high MLSS MBR conducted by Barreto et al. (2017).

The objective of this study was to evaluate the oxygen transfer performance of a Speece cone system in the context of wastewater treatment applications. Particularly, the effects of the operational conditions on the oxygen transfer performance were assessed both in clean and process water at relevant CAS MLSS concentrations. The evaluated operational conditions included: i) the pressure inside the cone, ii) the inlet velocity to the cone, iii) the recirculation flowrate through the cone, and iv) the pure oxygen flowrate into the cone.

2. Material and methods

2.1. Experimental setup description

The evaluations were performed feeding high purity oxygen (HPO) to the cone at gas flowrates ranging between 5 and 40% of the cone's theoretical maximum oxygen disolution capacity. The overall oxygen mass transfer rate coefficient (K_La; h^{-1}), the standard oxygen transfer rate (SOTR; kg O_2 d^{-1}), and the standard oxygen transfer efficiency (SOTE; %), were determined by performing a mass balance over the system. These parameters were determined under pressures inside the cone of 10 and 40 psig, recirculation flowrates of 3 and 6 m^3 h^{-1}, and liquid inlet velocities of 1.2 and 3.4 m s^{-1}. In addition, when working with mixed liquor, the alpha factor (α) was determined at an MLSS concentration of approximately 5 g L^{-1}.

The experiments were performed at the Delft Blue Innovations research facility (www.delftblueinnovations.nl) at the Harnaschpolder wastewater treatment plant in Delft, The Netherlands. The oxygen transfer performance of the Speece cone was evaluated using the same pilot scale membrane bioreactor (MBR) as described in Barreto et al. (2017). This work is part of a research project investigating the oxygen transfer characteristics of a Speece cone in activated sludge for its application in the wastewater treatment field.

2.1.1. Speece cone-MBR system

A pilot scale Speece cone (Speece, 1975) with a theoretical oxygen delivery capacity of approximately 5 kg O_2 d^{-1} was coupled to a pilot scale MBR. The equipment arrangement is presented below (Fig. 1). The pilot Speece cone (ECO Oxygen Technologies LLC, USA) had the following dimensions: 115 cm height with base and top diameters of 30 and 10 cm, respectively; the intake and discharge connections were coupled to ANSI flanges 4 inches in diameter. A progressive cavity pump (Netzsch, NM045BY02512B, Germany) was provided with a variable frequency drive to feed the cone at different flowrates. The desired inlet velocity was set by placing PVC (polyvinyl chloride) inserts with different diameters at the cone's inlet. The internal pressure could be monitored and adjusted by means of a manometer and a discharge valve at the cone's outlet. The cone discharged an oxygen supersaturated stream in two opposite corners of the MBR's aerobic chamber; the location of the discharge streams was selected to enhance the mixing conditions in the aerobic reactor. The aerobic chamber in the MBR had a maximum volume capacity of one cubic meter (1 m × 1 m × 1 m). Additionally, and in order to provide complete mixing conditions,