Short communication

Significance and estimation of oxygen mass transfer coefficient in simulated waste stabilization pond

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ABSTRACT

In this paper an effort has been made to theoretically estimation of overall oxygen mass transfer coefficient (K_L) in field conditions by applying wind correction to the oxygen mass transfer coefficient (K_{Lphy}) estimated in a simulated pond in laboratory conditions using physical absorption method. The value of K_{Lphy} (8.44×10^{-6} m/s) was estimated experimentally by three well-mixed reactors of three different interfacial areas. Further, the value of K_{Lphy} was used to estimate the overall oxygen mass transfer coefficient (K_L) in field conditions. The K_L values in the field condition was estimated for waste stabilization ponds at sewage treatment plants of Kalyani and Bandipur in the state of West Bengal and were estimated to be 1.08×10^{-5} and 1.19×10^{-5}, respectively. Study gives a handy approach of application of estimated overall oxygen mass transfer coefficient (K_L) for rational design of waste stabilization ponds.

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1. Introduction

Waste stabilization ponds (WSP) are considered to be among the easiest, most economical and efficient methods for biological wastewater treatment (Abeliovich, 1984; Bryant, 1987) and have been used extensively to provide wastewater treatment throughout the world (Arceivala and Asolekar, 2006; Kaya et al., 2007; CPCB, 2009; Kehl et al., 2009; Olukanni and Joel, 2011). WSPs are predominantly subjected to stochastically varying environmental factors of various kinds, for example, temperature, rainfall and evaporation regimes, wind speed and direction and solar energy intensity (Mara, 1997; Mara and Pearson, 1998; Abbasa et al., 2006). Oxygen transfer in WSPs happens to be an important operational parameter that shows a great deal of daily and hourly variation (Kayombo et al., 1999). Oxygen mass transfer across the air–water interface has been proved to be an important system design parameter (Minhee, 2002). There are two possible routes for transfer of oxygen into the natural systems which includes (1) interfacial oxygen mass transfer across the air–water interface, and (2) transfer of oxygen produced during the photosynthesis process by aquatic micro and macrophytes including algae (Peavy et al., 1985). The rate of oxygen production is a function of the concentration of algae and other influencing functions (Kayombo et al., 1999) which contributes little as compared to the overall demand of oxygen for degrading the organic wastes. Also, if the influent has higher organic content, irrespective of the depth of the pond, interfacial oxygen transfer across the air–water interface becomes the sole mechanism to satisfy the oxygen needs of the system because algae cannot grow in organic-rich environment (Pittman et al., 2010). Nevertheless, bacteria and plants have better abilities to use the organic matter as an electron donor especially when oxygen transfer across the interface is prominent.

Notably, oxygen transfer across the air–water interface is one of the major factors affecting the efficiencies in biological wastewater treatment. Therefore, absorption, an important phenomenon, was taken into account while carrying out the study pertaining to estimation of oxygen mass transfer at the gas–liquid interface. In this paper, an attempt has been made to estimate the oxygen mass transfer coefficient (MTC) (K_{Lphy}) at the air–water interface in a laboratory-simulated pond followed by theoretical prediction of the overall oxygen MTC (K_L) in field conditions by applying appropriate wind corrections.

The interfacial oxygen transfer depends upon various factors, such as wind velocity, salinity, temperature etc. (Meire et al., 2013). There could be four interfaces in the WSPs where oxygen mass transfer occurs, which include: (1) air–water interface, (2) air–plant interface, (3) water–soil interface and (4) rhizosphere–water interface. At the air–plant interface, most of the oxygen

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produced during photosynthesis process of plants goes into the atmosphere. Therefore, this interfacial oxygen transfer will not help in the performance of the wastewater treatment. But part of the above oxygen is translocated to the stems and roots of plants and finally to the water body. Thus, the rhizosphere–water interface comes into picture. This interface also makes site for microbial biodegradation. At the water-soil interface, gaseous exchange takes place produced during the anaerobic biodegradation process. At the air–water interface, gaseous exchange and water evaporation takes place. The interfacial oxygen transfer rate is directly proportional to oxygen concentration gradient across the interface and the proportionality constant is nothing but the mass transfer coefficient (K_L) (Treybal, 1981). The relation is given as:

$$\text{Oxygen transfer rate} \, \alpha (C_A^* - C)$$

Thus, Specific volumetric transfer rate $= K_L a(C_a^* - C)$ (1) where $K_L a =$ oxygen mass transfer coefficient; $d^{-1} = K_L a = K_L$ (A/V); $a =$ specific interfacial area, m^{-1}; $A =$ true interfacial area, m^2; $V =$ true system volume, m^3; $C_A^* =$ interfacial saturation concentration of A in water governed by the Henry's law, i.e., solubility of oxygen in wastewater, $kg\,m^{-3}$; $C_A =$ instantaneous oxygen concentration in bulk wastewater, $kg\,m^{-3}$.

The oxygen transfer process across air–water interface is simply described as:

$$O_2(g) \leftrightarrow O_2(aq) \tag{2}$$
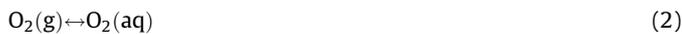
Typically, for the gases having low solubility such as oxygen, the gas side mass transfer resistance is neglected. Therefore, the overall liquid side oxygen MTC (K_L) decides the rate of above reaction. There are several formulations used to calculate the K_L value, but the most common ones are 'Two Film Model' (Liss, 1973; Liss and Slater, 1974) and 'Surface Renewal Model' (Danckwerts, 1951). The oxygen MTC across the air–water interface of large water bodies, such as, ponds is contributed by the water flow velocity and the wind speed. The theoretical model for oxygen MTC (K_L) at such a surface is as follows:

$$K_L = K_{flow} + K_{wind} \tag{3}$$

K_{flow} is the oxygen MTC due to the water flow in the pond and is a function of the kinematic viscosity of liquid, molecular diffusion coefficients of gas, surface tension, characteristics length and velocity of flow. On the other hand, K_{wind} is the oxygen MTC due to wind flow over the water surface, which is a function of the wind velocity, temperature of air, etc. In shallow ponds, surface turbulence is due to the water flow velocity and the pond bottom structure, wherein the water flow velocity may fall either in a laminar or a turbulent flow regime. In a turbulent flow regime, large eddies are the principle cause of surface renewal and the characteristic length is the flow depth of the pond. This flow depth goes on diminishing due to solid depositions. However, in deeper ponds, surface turbulence is due to the wind velocity. It is important to note that the oxygen transfer depends upon the wind velocity too. Thus, oxygen transfer across the air–water interface is one of the major factors affecting natural treatment of wastewaters.

2. Materials and methods

In the present work, laboratory experiments have been conducted to estimate the oxygen MTC at air–water interface in an open system. The experiments were carried out by employing three well-mixed reactors R_1, R_2, and R_3 with different interfacial areas (82–320 cm^2). The experimental set-up consisted of cylindrical shallow tanks (1–2.5 L volumes) with gentle stirring using a magnetic stirrer to maintain well-mixed condition in the bulk liquid. Monitoring of DO and temperature were carried out using the DO probe (LDO101: standard luminescent/optical dissolved oxygen) at regular time interval. The DO measurement was also confirmed by iodometric titration at the start of the experiment (APHA, 2005). The physical absorption experiments were carried out to estimate the oxygen MTC at the air–water interface. The overall MTC was estimated using Fick's law of diffusion at the air–water interface. The rate of oxygen absorption was mathematically modeled by incorporating interfacial oxygen MTC into a lumped parameter model (overall MTC).

3. Results and discussion

Aiming at evaluation of mass transfer across air–water interface in natural systems, laboratory experiments were carried out in a simulated pond. Sodium dithionite was used as the chemical reagent, which reacts with the DO in the system (Kawagoe and Robinson, 1981; Jhaveri and Sharma, 1968). In these experiments, pH of water sample was in the range of 5–7. The sodium dithionite (added in stoichiometric amount) reacts with the dissolved oxygen in the water and $NaHSO_3$ and $NaHSO_4$ were formed as follows:

$$Na_2S_2O_4 + O_2(aq.) + H_2O \leftrightarrow NaHSO_3 + NaHSO_4 \tag{4}$$

This reaction is instantaneous and the DO of the system becomes zero. At time $t = 0$, the value of DO is zero so that the driving force for oxygen will be increased and absorption continued for a longer time until the equilibrium is attained. If the reaction is carried out in an alkaline medium, then $NaHSO_3$ and $NaHSO_4$ would exist as Na_2SO_3 and Na_2SO_4, respectively. Sulfite would get oxidized to sulfate as follows:

$$SO_3^{2-} + \frac{1}{2}O_2(aq.) \rightarrow SO_4^{2-} \tag{5}$$

Within an infinitesimal time, the DO becomes zero. Then absorption of atmospheric oxygen takes place. Absorption reaction will be:

$$\underset{A(g)}{O_2(gas)} \leftrightarrow \underset{A(aq.)}{O_2(aq.)}$$
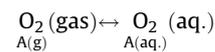
This is the equilibrium reaction, and equilibrium concentration of oxygen in both phases is a function of various parameters like temperature, water characteristics (suspended solids, salinity etc.). Initial DO in water sample reacts instantaneously with sodium dithionite as in Eq. (4). DO become zero and the interfacial oxygen mass transfer starts. Reaction (5) is an equilibrium reaction between gaseous and aqueous phase. Based on Fick's second law of diffusion at the interface, for absorption of oxygen into the system, following correlation could be used:

$$\frac{dC_A}{dt} = K_L a(C_A^* - C_A) \tag{7}$$

where $C_A =$ oxygen concentration in bulk liquid at time t, i.e., $C_A(t)$, mg/L, $t =$ time, h; $C_A^* =$ interfacial saturation concentration of oxygen in water (solubility of oxygen in water) mg/L; $K_L =$ liquid film oxygen mass transfer coefficient at air–water interface, m/h; $a =$ specific interfacial area at air–water interface, m^2/m^3.

Perry and Green (1984), and Sawyer et al. (2000) gave the values for oxygen solubility in water (C_A^*) at different temperatures. Plot of $\ln(C_A^* - C_A)$ vs time is shown in Fig. 1. The slope of this curve gives (K_{Lphy}) values for three different reactors. These (K_{Lphy}) values were plotted against the specific interfacial areas of reactors (depicted in Fig. 2). The slope of graph is nothing but the oxygen MTC, $K_{Lphy} = 0.0304$ m/h (i.e., 8.44×10^{-6} m/s). The oxygen MTC