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Application of the gas tracer method for measuring oxygen transfer rates in subsurface flow constructed wetlands

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ABSTRACT

The oxygen transfer rate (OTR) has a significant impact on the design, optimal operation and modelling of constructed wetlands treating wastewater. Oxygen consumption is very fast in wetlands and the OTR cannot be determined using an oxygen mass balance. This problem is circumvented in this study by applying the gas tracer method. Experiments were conducted in an unplanted gravel bed (dimensions L × W × d 125 × 50 × 35 cm filled with a 30-cm layer of 10–11-mm gravel) and a planted horizontal subsurface flow constructed wetland (HSSFCW) (L × W × d 110 × 70 × 38 cm filled with a 30-cm layer of 3.5-mm gravel with *Phragmites australis*). Tap water saturated with propane as gas tracer (pure or commercial cooking gas, depending on the test) was used. The mass transfer ratio between oxygen and commercial propane gas was quite constant and averaged $R = 1.03$, which is slightly lower than the value of $R = 1.39$ that is usually reported for pure propane. The OTR ranged from 0.31 to 5.04 g O_2 m^{-2} d^{-1} in the unplanted gravel bed and from 0.3 to 3.2 g O_2 m^{-2} d^{-1} in the HSSFCW, depending on the hydraulic retention time (HRT). The results of this study suggest that the OTR in HSSFCW is very low for the oxygen demand of standard wastewater and the OTR calculations based on mass balances and theoretical stoichiometric considerations overestimate OTR values by a factor that ranges from 10 to 100. The gas tracer method is a promising tool for determining OTR in constructed wetlands, with commercial gas proving to be a viable low-cost alternative for determining OTR.

1. Introduction

Constructed wetlands are an alternative for wastewater treatment and in comparison to conventional technologies have the advantage of being low-cost and easy to operate and maintain. Small constructed wetland systems are very common in Europe in single households, farms and small communities with design population loads in the range of 15–2000 PE (Puigagut et al., 2007). The most widely used are subsurface flow constructed wetlands, which consist of a planted gravel bed through which water flows either vertically or horizontally. This study focused on the horizontal subsurface flow type (HSSFCW).

Kadlec and Wallace (2009) described three pathways for oxygen transfer to wetlands: (1) direct transfer from the air at the contact surface of water and atmosphere, (2) plant-mediated transfer from leaves and stems to below ground biomass, and (3) oxygen dissolved in influent water. Oxygen is usually undetected or present in very low concentrations in wastewaters, so the oxygen input by the influent is generally negligible and lower than direct transfer from air and plant-mediated transfer.

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According to Kadlec and Wallace (2009), the direct oxygen transfer from air to water in HSSFCW is related to oxygen deficit as it is usually considered in running waters. The magnitude of the oxygen deficit depends on the oxygen mass transfer coefficient, which is directly proportional to the water velocity and inversely proportional to the water depth. Empirical functions for calculating mass transfer coefficients are available for rivers, but they cannot be applied to HSSFCW because they have very different turbulence regimes.

Plant-mediated oxygen transfer has long been a subject of debate. Research to quantify rates of oxygen release by plants have led to the general consensus that plants do not release enough oxygen into their immediate root environment to remove all of the organic matter in standard urban wastewater in horizontal or vertical subsurface flow constructed wetlands (Brix, 1997; Tanner, 2001; Bezbaruah and Zhang, 2005).

Oxygen is consumed in the wetlands by several processes including aerobic respiration, nitrification and sulphide oxidation. The overall oxygen transfer rate (OTR) to the bulk water of an HSSFCW cannot be estimated using direct measurements of oxygen concentration in water because oxygen is consumed immediately (Ojeda et al., 2008). Therefore, the OTR (including direct transfer from air to water and plant-mediated transfer) has been estimated previously using mass balances and theoretical stoichiometric calculations (Brix et al., 2002; Cooper, 2005). There is no experimental study that confirms OTR values obtained from mass balances and this type of calculation appears to overestimate the OTR given the importance of anaerobic reactions, especially in horizontal SSFCW (García et al., 2007). It is therefore necessary to develop methods that provide experimental evidence of OTR values.

Oxygen consumption is also very rapid in wastewater treatment technologies other than wetlands, but gas tracer methods have enabled reliable estimations of OTR (Boumansour and Vasel, 1998). A gas tracer is a chemically and biologically inert gas that is neither produced nor consumed in the system and whose mass transfer rate is proportional to the OTR. The same relationship exists between propane and oxygen (Rathbun et al., 1978).

The main objective of this study was to evaluate the suitability of the gas tracer method as a tool for estimating the OTR in HSSFCW. We also studied the effect of gas purity, which is related to the cost of the method, and hydraulic retention time (HRT) on OTR. To our knowledge, this is the first time that a gas tracer method has been applied to study OTR in subsurface flow constructed wetlands. Transfer rates have a significant impact on the design, optimal operation and modelling of constructed wetlands. Experiments were conducted in a planted system (HSSFCW) and unplanted gravel bed systems to evaluate the suitability of the method under various conditions.

2. Theoretical background

The interaction of air and water at their interface leads to the transfer of oxygen to bulk water through the thin boundary layer saturated with water vapour. This mass oxygen transfer is commonly expressed as (Lewis and Whitman (1924) cited in Boumansour and Vasel (1998)):

$$d[O_2]/dt = K_L a,\ \ O_2 \times (C_{sat} - C_t) \quad (1)$$

where: $d[O_2]/dt$ is the volumetric OTR, mg O_2 L^{-1} h^{-1}; $K_L a$,O_2 is the oxygen mass transfer coefficient, h^{-1} C_{sat} is the DO concentration at saturation (temperature dependent), mg L^{-1}; C_t is the DO concentration at time t, mg L^{-1}

$K_L a$,O_2 can be determined by performing a simple oxygen transfer experiment. In the absence of oxygen consumption processes (e.g. sterile tap water in contact with air), one could simply measure the change in oxygen concentration over time, starting at a concentration lower than that of saturation. $K_L a$,O_2 can then be calculated with a linearized version of Equation (1):

$$K_L a,\ \ O_2 \times t = \ln[(C_{sat} - C_0)/(C_{sat} - C_t)] \quad (2)$$

where: C_0 is the DO concentration at initial time, mg L^{-1}; t is time in hours

The central assumption for the gas tracer method is that there is a constant ratio (R) between the oxygen that enters the water and the tracer gas (propane in this study) that leaves the water. This ratio is given as (Rathbun et al., 1978):

$$R = K_L a,\ \ O_2/K_L a,\ \ P \quad (3)$$

where: R is the ratio between the mass transfer coefficient of the two gases (dimensionless); $K_L a$,P is the mass transfer coefficient of propane, h^{-1}

Not every gas tracer has a constant ratio in respect to oxygen with varying temperatures, water quality and turbulence. However, in the case of pure propane, ratio R is independent of changes in temperature, suspended solids and mixing conditions (Rathbun et al., 1978; Madsen et al., 2006, 2007).

The oxygen transfer in a constructed wetland is commonly expressed as the OTR (g O_2 m^{-2} h^{-1}), which relates the specific mass transfer factor $K_L a$,O_2 to the dimensions of the wetland. It can be calculated using the following equation modified from Kadlec and Wallace (2009) to take into account volume and surface of the wetland:

$$OTR = [K_L a,\ \ O_2 \times (C_{sat} - C_t) \times V]/A \quad (4)$$

where: V is the volume of pore water in the wetland, m^3; A is the surface area of the wetland, m^2

3. Materials and methods

Two clearly different experiments were carried out to study the suitability of the gas tracer method. The first was an indoor experiment with a continuously fed experimental unplanted gravel bed using pure propane as a tracer gas. The second was an outdoor experiment with an experimental planted HSSFCW that was also operated with continuous feeding. During the second experiment, impure propane (commercially available cooking gas) was used as a tracer gas in order to reduce the cost of the method.

3.1. *Indoor experiment with unplanted gravel bed*

This experiment was conducted in the laboratory of the UNESCO-IHE Institute for Water Education in Delft, the