Effect of hydrodynamic conditions on biofilm oxygen consumption rate in a fixed-bed nitrifying reactor

M. Carrión*,, J. Alba* and F. Thalasso***

*Department of Biotechnology, CINVESTAV, México City, Mexico
(E-mail: *thalasso@mail.cinvestav.mx; jalba@mail.cinvestav.mx*)

**Department of Environmental Engineering, University of Quintana Roo, Quintana Roo State, Mexico
(E-mail: *jmcarrion@correo.uqroo.mx*)

Abstract The effect of the hydrodynamic conditions on oxygen consumption rate was studied in a fixed-bed nitrifying reactor. For that purpose, the k_La, the overall oxygen consumption rate and the maximum biofilm respiration rate were measured under several mixing powers. It was observed that the maximum biofilm respiration rate was dependent on the hydrodynamic conditions. From the results obtained, a simplistic model was developed to predict the overall oxygen consumption rate from the mixing power applied.
Keywords Nitrifying biofilm; oxygen consumption rate; submerged filter

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Nomenclature

C^*	saturation oxygen concentration (kg/m^3)
C_l	overall oxygen concentration (kg/m^3)
k_La	oxygen mass transfer coefficient (h^{-1})
K_{SO_2}	oxygen affinity constant or half saturation constant (kg/m^3)
OTR	oxygen transfer rate (kg/m^3.h)
P/V	mixing power (W/m^3)
QO_2X_{max}	maximum biofilm respiration rate (kg/m^3.h)
r_{O_2}	overall oxygen consumption rate (kg/m^3.h)

Introduction

Fixed film reactors have been successfully used in wastewater nitrification. These reactors are characterized by complex aerobic biological mechanisms involving ammonia and nitrites oxidizing lithoautotrophic bacteria. In these reactors, mass transfer in the vicinity and into the biofilm are of major importance and can control the overall process (Siegrist and Gujer, 1985). Mass transfer is highly dependent on the hydrodynamic conditions of the reactor since turbulence reduces the stationary liquid film thickness and promotes eddy diffusion (Kugaprasatham *et al.*, 1992; Nagaoka and Ohgaki, 1988). In a previous paper, Carrión *et al.* (2003) proposed a method, called the "double gassing-out" technique, to measure biofilm respiration rate in fixed-bed reactors. Contrary to the traditional gassing-out technique (Gearney *et al.*, 2001), when applied to fixed-bed reactors, this method allows the determination of the oxygen consumption rate while the hydrodynamic conditions of the reactor are maintained constant. The objective of this paper was to study the effect of the mixing power on the overall oxygen consumption in a nitrifying fixed biofilm reactor, using the "double gassing-out" technique.

Model development

The "double gassing-out" technique (Carrión *et al.*, 2003) allows the determination of the overall oxygen consumption rate which is, in fixed-bed reactors, approximately equal to the biofilm respiration rate (r_{O_2}). When measured under non-limiting oxygen concentrations ($C_l \gg K_{SO_2}$), the biofilm respiration rate is equal to a maximum biofilm respiration rate (QO_2X_{max}, Equation 1) that depends mainly on the kinetic constant, the biomass concentration and the hydrodynamic conditions of the reactor. Assuming a Monod kinetic, Equation 1 expresses the overall biofilm respiration rate taking into account the biological and physico-chemical conditions of the reactor.

$$r_{O_2} = QO_2X_{max}\frac{C_l}{C_l + K_{SO_2}} \tag{1}$$

$$k_La\,(C^* - C_l) = QO_2X_{max}\frac{C_l}{C_l + K_{SO_2}} \tag{2}$$

Under stationary state, the oxygen mass balance can be described by Equation 2. In this equation both oxygen mass transfer coefficient (k_La) and QO_2X_{max} depend on the hydrodynamic conditions. If the hydrodynamic conditions are described by the mixing power (P/V), Equation 2 can be replaced by Equation 3, where both k_La and QO_2X_{max} are substituted by a Θ and Ω function of the mixing power. If the oxygen affinity constant (K_{SO_2}) is known, Equation 3 can be solved through non-linear adjustment and the overall oxygen consumption rate can be determined for any mixing power.

$$\Theta\left(\frac{P}{V}\right)(C^* - C_l) = \Omega\left(\frac{P}{V}\right)\frac{C_l}{C_l + K_{SO_2}} \tag{3}$$

$$\mathrm{OTR} = k_La\,C^* \tag{4}$$

Material and methods

Two glass fixed-bed reactors were used (0.12 m internal diameter, 0.62 m height, 7 L total volume). These columns were filled with 3/8″ ceramic Rashig rings (Pynco, México), leaving a working volume of 3.9 L. The columns were fed with mineral medium using a peristaltic pump (Masterflex, Cole-Parmer, USA) at a liquid flow rate of 0.36 ± 0.01 L/h. The liquid medium composition was (mg/l): $(NH_4)_2SO_4$, 1,000; $NaHCO_3$, 1,050; KH_2PO_4, 96; $MgSO_4.7H_2O$, 57; $CaCl_2$, 38; $FeCl_3.6H_2O$, 6. Air was injected from the bottom of the reactors through a 5 cm diameter glass porous plate (Provilab, Mexico) at an air flow rate of 0.82 L/L.min (0.82 VVM, P/V 85 W/m^3) and controlled by a mass flow controller (Aalborg Instruments, USA). Dissolved oxygen was measured with polarographic electrodes (Ingold, USA) located in the middle part of the columns and connected in parallel to oxygen controllers and data acquisition systems (Volt 101, Cole-Parmer, USA). pH was maintained at 8 ± 0.1 by addition of a 1M NaOH solution using a pH controller (JSL, Mexico). The whole system was operated at constant temperature (22 ± 2°C). The first reactor, called the "biotic reactor", was inoculated using nitrifying sludge obtained from a continuous stirred tank reactor (Autonomous Metropolitan University, Mexico). This reactor was started up and maintained for approximately 5 months under steady-state. The second reactor was equal to the first one and fed with the same medium but it was not inoculated and was started just before the respirometric experiments. Since the respirometric experiments in the abiotic reactor were made during a short period of time (about 1 hour, each time as required), the growth of any significant amount of biomass was dis-

carded. The respirometric experiments consisted in substituting the air flow rate in both reactors by an equal nitrogen flow rate. The difference between the oxygen depletion rates observed in both reactors was considered equal to the biofilm respiration rate (see Carrión *et al.* (2003) for details). The biofilm respiration rate was always determined at dissolved oxygen concentration superior to 2×10^{-3} g/l, previously observed as the non-limiting concentration (results not shown). The biofilm respiration rate (r_{O_2}) was therefore considered equal to the maximum biofilm respiration rate (QO_2X_{max}). During the experiments, k_La was determined in the abiotic reactor by the gassing-out technique (Moo-Young and Blanch, 1980). Respirometric experiments at gas flow rate ranging from 0 to 0.82 L/L.min (P/V: 0 to 85 W/m^3) were made, in triplicate for each gas flow rate tested. The mixing power was calculated according to the de Bello *et al.* (1985) method. The overall oxygen consumption rate was estimated from the non-linear fit of Equation 3. Prior to the respirometric experiments, the oxygen affinity constant of the nitrifying reactor was determined by ammonia pulse injection, according to Chandran and Smets (2000).

Results and discussion

The biotic reactor was operated under steady-state during 5 months at a P/V ratio of 85 W/m^3 prior to the respirometric experiments. The steady-state was characterized by an ammonia loading rate of 1.1 kg NH_4^+-N/m^3.d, an ammonia removal efficiency of $98.5 \pm 0.5\%$ and a nitrate production efficiency (nitrate produced over ammonia removed) of $96.7 \pm 0.7\%$. An oxygen affinity constant of $0.59 \times 10^{-3} \pm 0.19 \times 10^{-3}$ g/l was measured. After this reactor characterization, respirometric experiments were made at P/V ratios from 0 to 85 W/m^3. Figure 1 presents an example of the dissolved oxygen profile observed during the respirometric experiments. The profile (A) shows the oxygen depletion obtained at $P/V = 0.0$ W/m^3 while the profile (B) shows the oxygen depletion obtained at $P/V = 39.1$ W/m^3. The profile (C) presents the estimated oxygen depletion due to biofilm respiration at $P/V = 39.1$ W/m^3 (profile B minus oxygen displacement rate due to nitrogen). The difference between profiles A and C shows that the hydrodynamic conditions significantly influenced the maximum biofilm respiration rate.

Figure 2 presents the k_La as well as the maximum biofilm respiration rates observed at several P/V ratios. Both the k_La and the maximum biofilm respiration rate increased when the mixing power increased. The best fit of the experimental results was obtained with an asymptotic equation for QO_2X_{max} ($r^2 = 0.991$) and a second degree polynomial

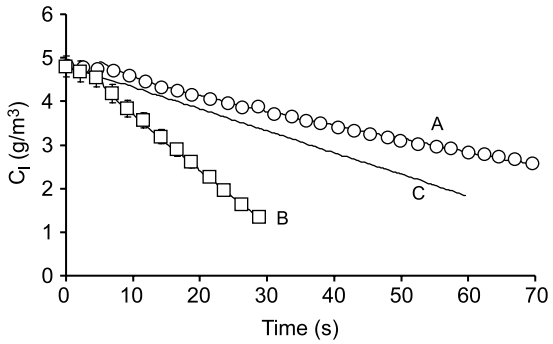

Figure 1 Example of dissolved oxygen profile during respirometric experiments at $P/V = 0$ (A) and 39 W/m^3 (B). Profile C represents the estimated oxygen profile due to biofilm respiration

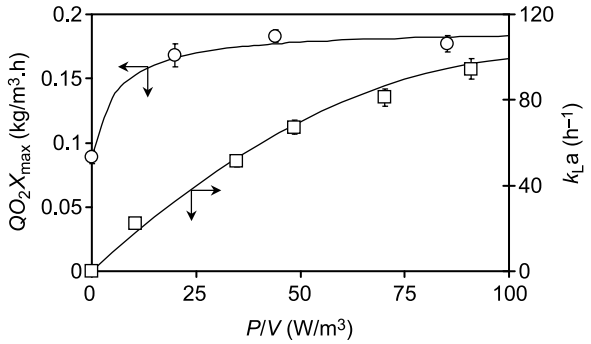

Figure 2 Effect of the mixing power on the maximum biofilm respiration rate (QO_2X_{max}) and the k_La

for the k_La ($r^2 = 0.996$). Figure 2 confirms that the mixing power promoted the QO_2X_{max} probably due to reduction of the stationary liquid film thickness and an improved eddy diffusion in the vicinity and into the biofilm as described by Kugaprasatham *et al.* (1992) and by Nagaoka and Ohgaki (1988).

From these results and according to Equation 3, the oxygen transfer rate (OTR, Equation 4), the QO_2X_{max} and the overall oxygen consumption rate (r_{O_2}) were estimated for a mixing power from 0 to 50 W/m^3, taking into account the oxygen affinity constant of the process ($0.59 \times 10^{-3} \pm 0.19 \times 10^{-3}$ g/l). Figure 3 presents the results obtained. At mixing power inferior to 12 W/m^3 (dotted line), the QO_2X_{max} is superior to the OTR and the system is therefore mass transfer limited. At mixing power superior to 12 W/m^3, the mass transfer is not limiting (superior to the QO_2X_{max}) and the overall oxygen consumption rate asymptotically reaches the QO_2X_{max}.

From the same model simulation, Figure 4 shows the influence of the mixing power on the treatment cost (adimensional cost, arbitrary scale, 1 being the lowest treatment cost). As can be observed, at low mixing power, oxygen transfer is limiting and the treatment cost increases due to the investment costs. At high mixing power, the system is biologically limited and the treatment cost increases due to energy cost. This estimation shows the existence of an optimum mixing power that depends on the energy over investment cost (0.1, 1 and 10 for Figures 4A, 4B and 4C respectively).

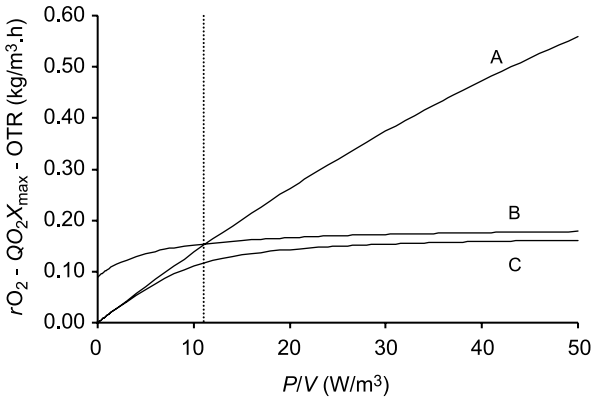

Figure 3 OTR (A), QO_2X_{max} (B) and r_{O2} (C) versus the mixing power applied

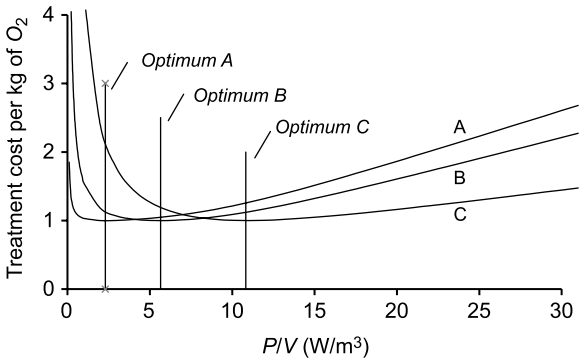

Figure 4 Effect of the mixing power on the treatment cost (arbitrary monetary units per kg of oxygen consumed), according to several energy over investment costs (A: 0.1, B: 1, C:10)

Conclusions

According to the "double gassing-out" technique, the effect of the hydrodynamic conditions on oxygen consumption rates was studied. The results show that the mixing power influences both the QO_2X_{max} and the r_{O_2}. According to these results, a model was developed that predicts the fixed film reactor performance from the mixing power applied and allows the determination of the economical optimum.

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