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Determination of the external mass transfer coefficient and influence of mixing intensity in moving bed biofilm reactors for wastewater treatment

Bruno L. Nogueira [a,b], Julio Pérez [b], Mark C.M. van Loosdrecht [b], Argimiro R. Secchi [a,*], Márcia Dezotti [a], Evaristo C. Biscaia Jr. [a]

[a] Programa de Engenharia Química, COPPE — Universidade Federal do Rio de Janeiro — Centro de Tecnologia, Bl. G-115, Ilha do Fundão, CEP: 21941-972 Rio de Janeiro, RJ, Brazil

[b] Department of Biotechnology, Delft University of Technology, Julianalaan 67, 2628 BC Delft, The Netherlands

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ABSTRACT

In moving bed biofilm reactors (MBBR), the removal of pollutants from wastewater is due to the substrate consumption by bacteria attached on suspended carriers. As a biofilm process, the substrates are transported from the bulk phase to the biofilm passing through a mass transfer resistance layer. This study proposes a methodology to determine the external mass transfer coefficient and identify the influence of the mixing intensity on the conversion process in-situ in MBBR systems. The method allows the determination of the external mass transfer coefficient in the reactor, which is a major advantage when compared to the previous methods that require mimicking hydrodynamics of the reactor in a flow chamber or in a separate vessel. The proposed methodology was evaluated in an aerobic lab-scale system operating with COD removal and nitrification. The impact of the mixing intensity on the conversion rates for ammonium and COD was tested individually. When comparing the effect of mixing intensity on the removal rates of COD and ammonium, a higher apparent external mass transfer resistance was found for ammonium. For the used aeration intensities, the external mass transfer coefficient for ammonium oxidation was ranging from 0.68 to 13.50 m d^{-1} and for COD removal 2.9 to 22.4 m d^{-1}. The lower coefficient range for ammonium oxidation is likely related to the location of nitrifiers deeper in the biofilm. The measurement of external mass transfer rates in MBBR will help in better design and evaluation of MBBR system-based technologies.

1. Introduction

Moving bed biofilm reactors (MBBR) have been used for the biological treatment of industrial and municipal effluents. They are applied also for the upgrade and retrofit of existing treatment plants (Ferrai et al., 2010). In these systems, the growth of microorganisms occurs on carriers which freely move inside the reactor. This movement can be achieved by aeration or mechanical stirring in aerobic or anaerobic/anoxic

* Corresponding author. Tel.: +55 21 3938 8307; fax: +55 21 3938 8300.
E-mail address: arge@peq.coppe.ufrj.br (A.R. Secchi).
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Nomenclature

Abbreviations

COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EMT	External Mass Transfer
MBBR	Moving Bed Biofilm Reactor
vvm	Volume of Gas per Volume of Liquid per Minute

Symbols

A	Total superficial area (L^2)
D	Coefficient of diffusion ($L^2\ T^{-1}$)
J	Flux ($M\ L^{-2}\ T^{-1}$)
k	External mass transfer coefficient ($L\ T^{-1}$)
L	Thickness of the biofilm (L)
q	Substrate specific conversion rate ($M\ M^{-1}\ T^{-1}$)
r	Volumetric removal rate ($M\ L^{-3}\ T^{-1}$)
R	Volumetric removal rate without external mass transfer resistance ($M\ L^{-3}\ T^{-1}$)
S	Mass concentration ($M\ L^{-3}$)
V	Volume of the liquid phase (L^3)
X	Biomass density ($M\ L^{-3}$)
z	Spatial variable in the biofilm (L)
γ	Stoichiometric factor
δ	Boundary layer thickness (L)
σ^2	Variance of the volumetric removal rate ($M^2\ L^{-6}\ T^{-2}$)

Superscripts

biof	Biofilm phase
BL	Boundary layer
bulk	Bulk
exp	Experimental
interf	Interface
water	Water

Subscripts

Het	Heterotrophic bacteria
Max	Maximum
Nit	Nitrifier Bacteria

processes, respectively (Rusten et al., 2006). The carriers are retained inside the reactor by a sieve arrangement at the reactor outlet and, therefore, the microorganisms are kept inside the reactor favouring the retention of slow growing bacteria as nitrifiers (Wang et al., 2005; Rusten et al., 2006; Bassin et al., 2011).

In biofilm processes, the substrates are transported from the bulk phase to the biofilm, where they diffuse through and are consumed by bacteria. The compounds diffusion in and out of the biofilm plays an important role (Rusten et al., 2006), being the performance of the reactor controlled by both consumption rate and substrate transport (Rasmussen and Lewandowski, 1998). Before reaching the biofilm, the pollutants pass through a mass transfer resistance layer. Within the biofilm, the substrates are transported by diffusion due the concentration gradient generated by the consumption of the pollutants.

The external mass transfer resistance is usually described as a stagnant film between the bulk phase and the biofilm surface where all external mass transfer processes are included (Beyenal and Tanyolaç, 1998). One important factor which affects the external mass transfer to the biofilm is the mixing intensity within the reactor (Kugaprasatham et al., 1992; Chen et al., 2006). High mixing intensities increase the external mass transfer coefficient causing an increase in the mass transfer rate and an improvement on the pollutant removal performance (Wanner et al., 2006).

Several works (Zhang and Bishop, 1994; Stoodley et al., 1997; Rasmussen and Lewandowski, 1998; Wäsche et al., 2002; Boessmann et al., 2004) utilized microelectrode measurements for the determination of the external mass transfer coefficient in different biofilm processes. The use of this methodology provides the oxygen profile along and nearby the biofilm, which makes it possible to determine the mass transfer coefficients (Rasmussen and Lewandowski, 1998). Microelectrode measurements on MBBR carriers require fixing the mobile carriers in a flow cell, which influences the external mass transfer boundary and make the measurements non representative.

Despite the crescent use of MBBR, there are few studies concerning external mass transfer, and all of them in a nitrifying system. Hem et al. (1994) found a near first order nitrification kinetic for oxygen when it was the limiting substrate. Since the oxygen concentrations studied were above values for substrate half saturation constant, this could be explained by a strong influence of the external mass transfer in these systems. Gapes and Keller (2009) studied the influence of two different carrier types (Kaldnes K1, Natrix C10/10) under two different growth conditions using a titrimetric and off-gas analysis (TOGA) sensor. Differences in external mass transfer coefficient values were observed for biofilms grown under different ammonium loading rates. At higher loading rates the more heterogeneous biofilm surface resulted in higher mass transfer coefficients. Mašic et al. (2010) using BiofilmChip P carrier measured the oxygen profile by microelectrodes. These measurements showed the strong drop in oxygen concentration in the boundary layer.

In this study, a method to determine the external mass transfer coefficient in-situ in MBBR systems is presented. The method employs the same reactor configuration in which the biofilms are formed at normal operation, i.e., the measurements are performed under the same mixing conditions. Moreover, this methodology is also capable to evaluate the effect of mixing intensity on the external mass transfer resistance and consequently on the conversion of the substrates by MBBR systems. The studied system was operated performing simultaneous nitrification and COD removal in order to allow comparing the effect of external mass transfer resistance on both processes.

2. Material and methods

2.1. Reactor

The experiments were performed at a lab-scale moving bed biofilm reactor operated in continuous mode to remove COD