Journal of Membrane Science 368 (2011) 54–63

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Modelling the effect of biomass induced oxygen transfer limitations on the nitrogen removal performance of membrane bioreactor

Güçlü Insel[a,*], S. Murat Hocaoğlu[b], E. Ubay Cokgor[a], Derin Orhon[a,c]

[a] Environmental Engineering Department, Istanbul Technical University, ITU Insaat Fakultesi, 34469 Maslak, Istanbul, Turkey
[b] TUBITAK Marmara Research Center, Environment Institute, 41470 Gebze, Kocaeli, Turkey
[c] Turkish Academy of Sciences, Piyade Sokak No. 27, 06550 Çankaya, Ankara, Turkey

ARTICLE INFO

Article history:
Received 10 May 2010
Received in revised form 20 October 2010
Accepted 2 November 2010
Available online 9 November 2010

Keywords:
Nitrogen removal
Mass transfer limitation
Viscosity
Half saturation constant
Simultaneous nitrification and denitrification

ABSTRACT

The study investigated the stability of the simultaneous nitrification and denitrification process in membrane bioreactors with specific emphasis on mass transfer limitations for oxygen diffusion. It mainly focused on the effect of biomass (MLSS) concentration on the relative magnitude of mass transfer coefficients. For this purpose, a functional relationship was derived between MLSS concentrations in membrane bioreactor and the oxygen half saturation parameters based on available experimental results. Model simulation using the generated data indicated that full nitrogen removal could be achieved in MBR systems operated at different MLSS levels with the provision of selecting optimal DO set-points corresponding to each operating conditions. The required optimal DO set-points increased with higher biomass concentrations due to higher mass transfer limitation and they remained operative in a wider DO range. Elevated MLSS levels required higher aeration energy and a relatively less robust DO set-point control approach was sufficient. The simulation results also indicated that MBR operation with a level of around 12,000–14,000 mg MLSS L^{-1} provided an optimal compromise between reducing the reactor footprint and minimizing mass transfer limitation for effective nitrogen removal.

1. Introduction

Gravity settling has always been a major drawback for conventional activated sludge systems; it imposed a threshold level for the biomass concentration that can be maintained in the reactor or restricted innovative design because of the risk of poor settling characteristics involved. In this respect, the membrane bioreactor (MBR) technology provided a new dimension by replacing gravity settling by membrane separation; without facing the limitations of poor settling activated sludge, the MBR offered the flexibility in selecting substantially higher biomass concentration levels for the biological reactor design and operation [1,2]. This innovative feature provided the possibility for a reduced bioreactor volume (or footprint) or operation at much higher sludge ages, as significant design advantages especially for nutrient removal configurations. Furthermore, substantially higher oxygen demand per unit volume of reactor operated at high biomass level, while involving a higher operating cost for organic carbon removal and nitrification, also became a major advantage for the MBR, where effective nitrogen removal could be achieved by means of the simultaneous nitrification denitrification (SNdN) process with appropriate adjustment of the aeration regime [3–5].

Nitrogen removal is well studied and conventionally requires a separate anoxic volume for denitrification [6,7]. This requirement may be partially or totally compensated by SNdN sustained in a single reactor with the provision that the outer parts of the microbial flocs provide nitrification while the inner parts denitrify under anoxic conditions [8]. It is obvious that SNdN can only be achieved with effective manipulation of aeration where dissolved oxygen concentration (DO) set-point control is utilized in the optimization of effluent nitrogen through SNdN: In fact, the adjustment of the dissolved oxygen concentration especially at low levels was found to be a relevant approach for maintaining synchronous nitrification and denitrification with enhanced nitrogen removal efficiencies [9–11].

The SNdN was first tested in conventional activated sludge systems: lowering the DO concentration down to 0.10–0.75 mg L^{-1} promoted the nitrogen removal via SNdN [3,12,13]. Despite efficient nitrogen removal, the conventional SNdN activated sludge systems often suffered from settling problems (high sludge volume index levels) with severe deterioration of the effluent quality. In this context, the MBR become the most viable activated sludge configuration for operation as a SNdN process and attracted substantial research effort [2,4,5,14]. Choo and Stensel [15] reported a laboratory study where a MBR was operated successfully at

* Corresponding author. Tel.: +90 212 285 73 02; fax: +90 212 285 33 67.
E-mail addresses: inselhay@itu.edu.tr (G. Insel), selda.murat@mam.gov.tr (S.M. Hocaoğlu), ubay@itu.edu.tr (E.U. Cokgor), orhon@itu.edu.tr (D. Orhon).

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doi:10.1016/j.memsci.2010.11.003

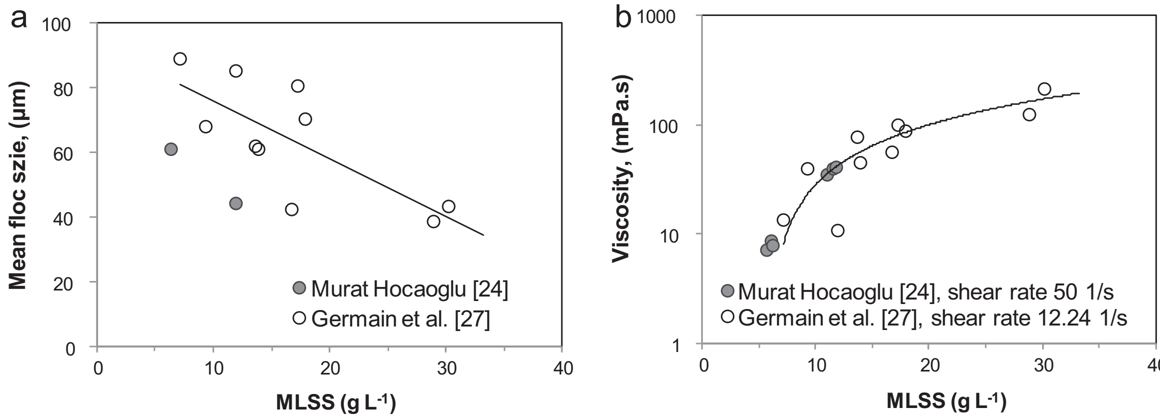

Fig. 1. Effect of MLSS on (a) floc size and (b) viscosity.

low DO concentrations (<1.0 mgO$_2$ L^{-1}) to accomplish simultaneous nitrification–denitrification at a biomass concentration of 10,000 mgSS L^{-1}. Sarioglu et al. [2,5] evaluated the impact of diffusion on the mass transfer limitation of oxygen in relation with the SNdN for systems operated at a MLSS concentration of 13,000–16,000 mg L^{-1}. On the other hand, Manser et al. [16] and Jiang et al. [17] estimated much lower low half saturation coefficients and reported relatively improved diffusion in MBRs. The reported results were quite specific and underlined the need for a systematic modelling for appropriate evaluation.

Modelling nitrogen removal with its specific processes and model components is well documented in the literature [18,19]. While MBR is an activated sludge configuration, it exhibits specific diffusion limitation characteristics concerning the role of DO in SNdN. Therefore, existing activated sludge models need to be properly modified to account for mass transfer limitations associated with simultaneous nitrification and denitrification processes. The rate expressions for these processes commonly include Monod-type switching functions in activated sludge models [18,19]. Recent studies indicated that the half saturation coefficients in these functions reflected the magnitude of the DO and nitrogen concentrations required to create the driving force for mass diffusion under different operating conditions and biomass concentrations. Consequently, the impact of diffusion limitation of oxygen from the bulk liquid into the floc was explained by increased half saturation constants assigned for the heterotrophs and autotrophs [2,20].

In this context, the objective of the study was to evaluate the relationship between DO, biomass concentration and the extent of resulting SNdN using process modelling applicable to MBR systems. Firstly, the effect of different biomass (MLSS) concentrations on mass transfer parameters (i.e. K_{OH}, K_{OA}, K_{NO} and K_{NH}) was investigated through evaluation of the modelling results of current practice. Secondly, the study involved model simulation in order to calculate the effect of mass transfer conditions (i.e. biomass concentration) on SNdN performance of the MBR and the achieved level of nitrogen removal. A relation between mass transfer parameters of the adopted activated sludge model and MLSS concentrations was developed and relevant selection of the biomass concentration level with the corresponding DO set-point level was evaluated to optimize process performance for nitrogen removal.

2. Conceptual framework

Two factors affect the availability of dissolved oxygen as an electron acceptor through the biomass floc: (a) the rheology of biomass/mixed liquor and (b) the DO level in the bulk liquid.

The dissolved oxygen concentration plays an important role to maintain nitrification and denitrification processes in bioreactors. Thus, dissolved oxygen (DO) set-point is the primary control parameter to maintain the corresponding aerobic and/or anoxic conditions. In activated sludge modelling, the transfer of oxygen (and nutrients) into biomass are governed by Monod type switching functions which incorporates the half saturation parameters K_{OA}, K_{NH} and K_{OH}, K_{NO} for the autotrophic and heterotrophic bacteria [19]. Accordingly, expressions related to nitrification and denitrification processes also include these switching functions, where the half saturation coefficients K_{OA} and K_{OH} act as control model parameters: (a) K_{OA} adjusts the rate of nitrification process under aerobic conditions and (b) K_{OH} defines the extent of denitrification process under anoxic environment (Eqs. (1) and (2)). Under aerobic conditions, the ammonia is oxidized to nitrate by autotrophic biomass, X_A (Eq. (1)). In the absence of dissolved oxygen, the oxidized nitrogen is converted to N$_2$ gas by heterotrophs, X_H (Eq. (2)). This behavior is defined in terms of activated sludge model parameters regulating the impact of DO (S_{O_2}) on growth of autotrophs and heterotrophs in the corresponding process rate expressions as follows:

aerobic conditions :

$$-\frac{dS_{NH}}{dt} = \frac{dS_{NO}}{dt} = \frac{1}{Y_A}\hat{\mu}_A \frac{S_{NH}}{K_{NH}+S_{NH}} \frac{S_{O_2}}{K_{OA}+S_{O_2}} X_A \tag{1}$$

anoxic conditions :

$$-\frac{dS_{NO}}{dt} = -\frac{1-Y_H}{2.86\cdot Y_H}\cdot\hat{\mu}_H \frac{S_S}{K_S+S_S} \frac{S_{NO}}{K_{NO}+S_{NO}} \frac{K_{OH}}{K_{OH}+S_{O_2}} X_H \tag{2}$$

The half saturation coefficients are known as lumped parameters, conveniently yielding the impact of the overall mass diffusion mechanism on microbial growth. Recently, many researchers have evaluated the impact of diffusion on nitrification and denitrification processes [16,21,22]. Mass transfer limitation in mixed liquor at high MLSS concentrations has also been reported [2,20]. On the contrary, Manser et al. [16], Jiang et al. [17] and Murat Hocaoglu et al. [21] reported much lower half saturation coefficients and relatively improved diffusion for the MBR operation. Shortly, high half saturation parameters indicate that the transfer of related compound (DO and/or nitrogen) into activated sludge floc is rather difficult, and much higher bulk concentrations are required to create mass diffusion. The process rate increases if the related saturation coefficient is lowered [4,10].

It is often argued that floc size affects dissolved oxygen diffusion and smaller floc sizes induces faster diffusion of DO – nitrogen – into the floc matrix: Depending on the floc size, a part of the inner portion of the biomass sustains its metabolic functions using oxidized