

Control of nitrification/denitrification in an onsite two-chamber intermittently aerated membrane bioreactor with alkalinity and carbon addition: Model and experiment

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ABSTRACT

Denitrifying membrane bioreactors (MBRs) are being found useful in water reuse treatment systems, including net-zero water (nearly closed-loop), non-reverse osmosis-based, direct potable reuse (DPR) systems. In such systems nitrogen may need to be controlled in the MBR to meet the nitrate drinking water standard in the finished water. To achieve efficient nitrification and denitrification, the addition of alkalinity and external carbon may be required, and control of the carbon feed rate is then important. In this work, an onsite, two-chamber aerobic nitrifying/denitrifying MBR, representing one unit process of a net-zero water, non-reverse osmosis-based DPR system, was modeled as a basis for control of the MBR internal recycling rate, aeration rate, and external carbon feed rate. Specifically, a modification of the activated sludge model ASM2dSMP was modified further to represent the rate of recycling between separate aerobic and anoxic chambers, rates of carbon and alkalinity feed, and variable aeration schedule, and was demonstrated versus field data. The optimal aeration pattern for the modeled reactor configuration and influent matrix was found to be 30 min of aeration in a 2 h cycle (104 m³ air/d per 1 m³/d average influent), to ultimately meet the nitrate drinking water standard. Optimal recycling ratios (inter-chamber flow to average daily flow) were found to be 1.5 and 3 during rest and mixing periods, respectively. The model can be used to optimize aeration pattern and recycling ratio in such MBRs, with slight modifications to reflect reactor configuration, influent matrix, and target nitrogen species concentrations, though some recalibration may be required.

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1. Introduction

Submerged membrane bioreactors (SMBRs), or membrane bioreactors (MBRs) with membrane installed in the aeration tank, have attracted significant attention for municipal wastewater treatment due to their efficient removal of organics and small footprint (Judd, 2010). This efficiency has been attributed to high mixed liquor suspended solids (MLSS) concentrations due to longer sludge retention times (SRTs) (Hai et al., 2014; Henze et al., 2008; Zarragoitia-González et al., 2008), and the resulting high effluent

quality makes the system particularly attractive for direct potable water reuse (Abegglen et al., 2008). For example, an SMBR has been used as the secondary treatment step in a nearly closed-loop, non-reverse osmosis-based direct potable water reuse (DPR) treatment system, preceding filtration and advanced oxidation chemical treatment, to substantially mineralize organic mass (Gassie et al., 2016; Wu and Englehardt, 2016). This approach, termed net-zero water (NZW) management, can provide energy-positive treatment, i.e. save more energy than is used to operate the plant, while addressing water shortage (Wu and Englehardt, 2015).

In advanced oxidation-based DPR systems which do not employ high-energy reverse osmosis or other salt-separation method, control of nitrate/nitrite is important to meet drinking water standards in the treated water (Gassie et al., 2016; Wu and Englehardt, 2016, 2015). In such systems, the addition of external

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alkalinity and/or carbon to the MBR aerobic and anoxic zones, respectively, may be needed to maintain nitrifier/denitrifier growth (Abegglen et al., 2008), depending on their concentrations in the influent wastewater (Agathos and Reineke, 2003; Henze et al., 2008; Ivanov, 2011; Peng et al., 2007; Tchobanoglous et al., 2003). However, the addition of these external substrates may need to be controlled carefully (Dalmau et al., 2013; Olsson and Newell, 1999).

Mathematical modeling may be a particularly useful tool for the control of effluent nitrogen in DPR systems. Such models originally focused on either the biological process or the physical filtration process. However, integrated models (Mannina et al., 2010) have been developed more recently to address interactions between the two processes, by connecting the biological and physical sub-models via principal influential variables, and these models have been shown to predict experimental results more accurately (Di Bella et al., 2008; Mannina et al., 2011b; Zarragoitia-González et al., 2008). Also, because the biological processes employed in MBRs are essentially similar to those of activated sludge processes, activated sludge models (ASMs) have been directly applied in modeling biological sub-models in MBRs (Fenu et al., 2010; Henze et al., 2000). However, membrane fouling is a significant factor in MBR performance, and soluble microbial products (SMPs), constituents have been found to be the principal cause of fouling in MBRs (Benyahia et al., 2013; Di Bella et al., 2008; Hai et al., 2014; Jiang et al., 2008; Zuthi et al., 2013). Hence, modified ASMs include SMPs explicitly, and recent predictions with such models have compared fairly well with experimental pilot plant results (Di Bella et al., 2008; Jiang et al., 2008; Mannina et al., 2011b).

MBR configurations include both alternating aerobic and anoxic zones within a single compartment, as well as separate aerobic and anoxic compartments with internal recycling (Kim et al., 2010), and current integrated MBR models can predict nitrification and denitrification based on the recycle ratio, i.e. the ratio of inter-chamber flow to average daily flow (Kim et al., 2010). Results of previous integrated models (Di Bella et al., 2008; Mannina et al., 2011b) suggest an effluent NO_3^- concentration of ~35 mg/L, above US potable water standards (EPA, 2015), without the addition of external alkalinity, e.g. as calcium carbonate, and carbon substrate, e.g. as an alcohol or sugar, with municipal raw sewage as influent. However, these studies were not focused on nitrogen removal, and

recent work has demonstrated better nitrogen removal, e.g. ~17 mg/L (Cosenza et al., 2013) and ~8.8 mg/L (Dalmau et al., 2013) effluent TN, with addition of carbon substrate.

NZW systems can be implemented onsite, due to lack of need for routine residuals disposal, and such applications require simplicity of operation. In that context, aeration rate may be adjustable only through scheduling. In fact, intermittent aeration can enhance denitrification efficiency (Capodici et al., 2015; Lim et al., 2007), and dramatically reduce the recycling ratio in MBRs (Kim et al., 2007). However, aeration schedule interacts with recycling ratio in its influence on nitrification/denitrification. Hence, models are needed to optimize the addition of carbonaceous substrate, together with aeration schedule and recycle ratio, to understand and optimize nitrogen removal efficiency for process design and control.

The purpose of this paper is to present a model of an onsite aerobic nitrifying/denitrifying MBR with variable mixing between separate aerobic and anoxic chambers, variable aeration schedule, and external alkalinity and carbon addition, useful in operating net-zero water DPR and other MBR-based treatment systems to minimize effluent NO_3^- concentration. Model components were adapted from previous work (Di Bella et al., 2008; Mannina et al., 2011b), and modified to account for external alkalinity and carbon addition, variable aeration schedule, and mixing between dual compartments of an SMBR. Kinetic parameters were calibrated, and the model was demonstrated versus data collected in current research (Wu and Englehardt, 2015) on a net-zero water DPR system. Observations and recommendations for future work are presented. Physical filtration process modeling was outside of the scope of this work due to the essentially constant filtration rate over the experimental period.

2. Materials and methods

A 500 gal/d (design flow) BioBarrier-N® (BioMicrobics, Inc., Shawnee, KS), 4.15 m³ dual compartment MBR was installed as one component of a net-zero water, i.e. nearly closed-loop (85% wastewater recycling), DPR system (with an average flow of 260 gal/d) at a four-bedroom, four-bath residence hall apartment with dishwasher and washing machine described previously (Englehardt et al., 2013). Wastewater from the apartment was

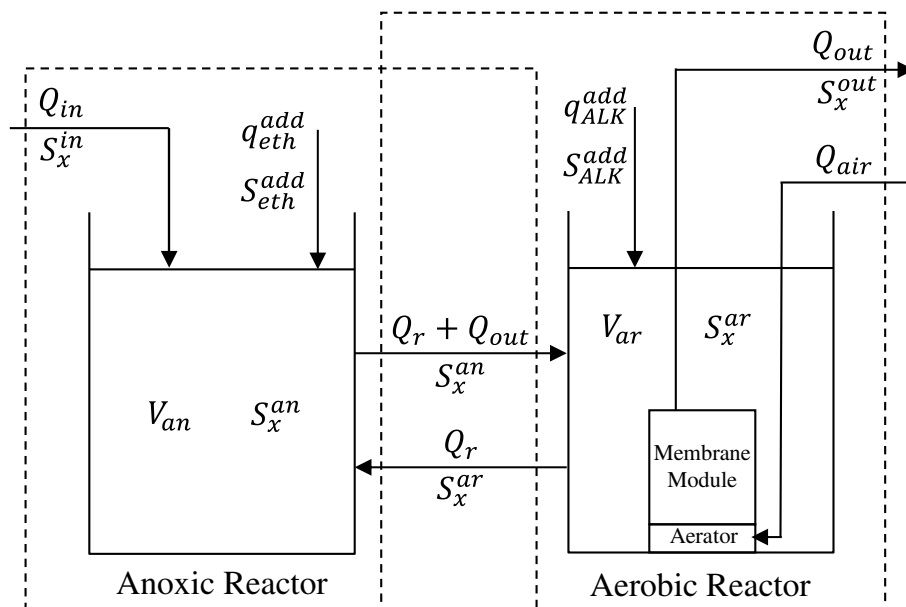


Fig. 1. Schematic diagram of the reactor.

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