

The Analysis of a Modified Membrane-Aerated Biofilm Reactor for Space Flight Applications

Nicholas Landes, W. Andrew Jackson and Audra Morse
Texas Tech University

Copyright © 2008 SAE International

ABSTRACT

A modified membrane-aerated biofilm reactor (mMABR) was constructed by incorporating two distinct biofilm immobilization media: gas-permeable hollow fiber membranes and high surface area inert bio-media. In order to evaluate the mMABR for space flight applications, a synthetic ersatz early planetary base (EPB) waste stream was supplied as influent to the reactor, and a liquid loading study was conducted at three influent flow rates. On average, percent carbon removal ranged from 90.7% to 93.1% with volumetric conversion rates ranging from $25 \pm 3.3 \text{ g / m}^3 \text{ d}$ and $95 \pm 13.4 \text{ g / m}^3 \text{ d}$. Simultaneous nitrification/denitrification (SND) was achieved in a single reactor. As the liquid loading rate increased from 0.15 mL/min to 0.45 mL/min, the volumetric denitrification rates elevated from $27 \pm 3.3 \text{ g / m}^3 \text{ d}$ to $65 \pm 5.2 \text{ g / m}^3 \text{ d}$. Additionally, it was found that nitrification and denitrification were linearly related with respect to both percent efficiency and volumetric reaction rates. The mMABR provides an equivalent systems mass (ESM) cost comparative alternative to previously studied two-stage biological systems.

INTRODUCTION

The implementation of improved wastewater reclamation systems suitable for water reuse is an imminent reality. Domestic water reuse of treated municipal wastewater is a feasible solution to water shortages; nonetheless, sociopolitical factors have rendered this option unacceptable at the current time. Contrary to terrestrial applications, space missions do not have the benefit of readily available water resources; therefore, advanced solutions to closed-loop, wastewater treatment and reuse scenarios are pivotal to the realization of extended space missions. One solution, integrated water recovery systems (IWRS), concomitantly employs physiochemical and biological unit processes in order to efficiently and effectively treat a source-separated wastestream without imparting a burdensome equivalent system mass (ESM). Inclusion of biological reactors as pretreatment options can be beneficial since post-processing systems will handle a significantly reduced wastestream, thereby

decreasing consumables, footprint, energy demand, and maintenance issues. With respect to reverse osmosis, Crawley et al. (2007) determined that biological pretreatment beneficially impacted system performance. Furthermore, an ESM analysis conducted by Garland et al. (2005) demonstrated that increasing ammonium conversion from 70% to 90% in the bioreactor stage would reduce post-processing ESM costs by 40% and 80% for early planetary base (EPB) and transit space missions, respectively. This study was conservative and would underestimate the positive impact of biological pretreatment since ammonium was the only species considered as a penalty in the analysis; however, carbon and nitrate concentrations impact post-processing performance to a comparable degree as ammonium and reduced concentrations of these constituents would further increase ESM savings.

One option for biological pretreatment is membrane-aerated biofilm reactors (MABRs) in which a gas permeable membrane serves to supply oxygen and immobilize biofilm. Inherent to membrane-aerated biofilms, a unique stratification of biological species can be generated due to the counter diffusion of growth limiting substrates, specifically oxygen and carbon, thereby promoting the coexistence of interrelating bacterial populations such as nitrifiers and denitrifiers on the same biofilm. In other words, MABRs simplify and support nitrogen removal via simultaneous nitrification/denitrification (SND) by encouraging nitrifying activity in a protected region adjacent to the oxygenated permeable membrane while promoting growth of denitrifiers in the more anoxic biofilm layers that contact carbon-rich bulk liquid. Figure 1 compares substrate diffusion in a membrane-aerated biofilm with that of a traditional biofilm characterized by co-current diffusion.

Within the area of NASA funded bioreactor projects, MABRs have been used in coupled nitrification/denitrification systems (Finger et al. 1999, McLamore et al. 2004), stand-alone nitrification (Morse et al. 2003), enhanced nitrification through rotation induced turbulence (Rector et al. 2006), and autotrophic denitrification by supplying hydrogen and oxygen

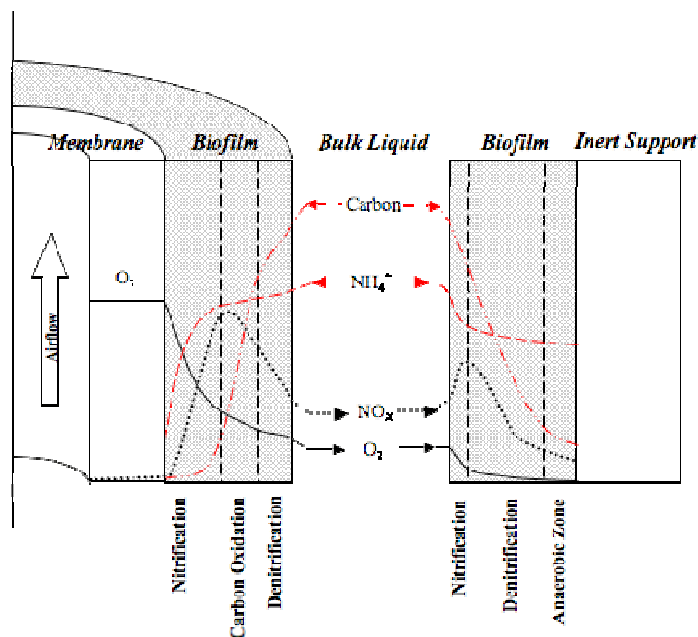


Figure 1. Comparison of substrate diffusion in a counter-diffusion membrane-aerated biofilm (left) and a co-diffusion traditional biofilm (right)

concurrently (Smith et al. 2006). Furthermore, terrestrial application of MABRs are becoming more commonplace. Downing and Nerenberg (2007) propose the use of membrane-aerated biofilms in an activated sludge basin architecture for the treatment of a municipal waste. Terada et al. (2007) investigated the feasibility of a MABR performing autotrophic nitrogen removal, which is oftentimes used in source separated waste treatment.

The primary operating parameters impacting SND in a MABR are surface area, C:N ratio, and partial oxygen pressure. Brindle et al. (1998) and Satho et al. (2004) determined that increased surface area positively impacted MABR treatment performance. Matsumoto et al. (2007) and La Para et al. (2006) determined that nitrogen removal efficiency is optimal at approximately C:N of 4. Although theoretically plausible, the narrow operating range required for SND in a MABR limits their application to high C:N ratio waste streams whereas the EPB waste stream has a C:N ratio of approximately 0.7.

In light of the research conducted on MABRs, a modified MABR (mMABR) was proposed in which oxygen-permeable membranes and high surface area inert bio-

media were implemented in tandem, effectively taking advantage of traditional and membrane-aerated biofilm ecologies in a single system. Hypothetically, the increased surface area provided by the inert bio-media would accommodate the conditions necessary for denitrifying bacteria that would not otherwise grow in waste streams with low C:N ratios.

The objectives of this research were to determine the impact of liquid loading rate on water quality performance and to understand the relationship between reactor hydrodynamics and water quality performance. In order to accomplish these goals, the reactor was challenged with three loading rates of 0.15 mL/min, 0.30 mL/min, and 0.45 mL/min. Other parameters that potentially impact water quality performance such as available surface area, airflow rate, and recycle ratio remained constant. At the duration of each loading point, a tracer study was conducted in order to characterize hydrodynamic properties. Water quality performance at these loading rates was evaluated and compared.

EXPERIMENTAL

The mMABR bioreactor has been operated continuously at Texas Tech University since January 2006. Previous research on the mMABR involved determining the impact of intramembrane airflow rate on water quality performance and effluent air quality (Landes et al. 2007a, Landes et al. 2007b). The current research aims to evaluate the ability of the reactor to handle varying liquid loading rates. As detailed in Table 1, three influent flow rates were analyzed. The hydraulic residence time, θ , was defined as the clean bed effective volume divided by the respective influent flow rate.

SYSTEM CONFIGURATION

The system consists of two pumps, a gas-liquid separator, influent and effluent tanks, and the main reactor vessel (Figure 2). Physical dimensions are detailed in Table 2. Oxygen is conveyed to the biofilm through 100 semi-permeable Silastic® silicon membranes (Dow Corning Co.) that are approximately 2.4 times the length of the reactor. In order to increase the ability of the reactor to achieve denitrification, additional surface area was allowed for by the addition of inert Coralife® Bio-Balls. Accounting for the majority of surface area, the microbiological species existing on the Bio-Balls should have the ability to perform anoxic denitrification due to the depleted oxygen levels within the bulk liquid.

Table 1. Summary of Test Conditions

Date	Sample Size, n	Influent Flow Rate, mL/min	θ , d
10/25/06 - 01/02/07	23	0.30	8.2
07/26/07 - 11/10/07	38	0.45	5.5
12/28/07 - 02/23/08	21	0.15	16.4

Table 2. mMABR Reactor Dimensions

Properties	Value
Length of Reactor, cm	35.5
Diameter of Reactor – ID, cm	15.2
Total Volume, mL	6450
Working Volume, mL	3550
Number of Tubes	100
Tube Diameter – (ID, OD), cm	0.08, 0.17
Tube Surface Area, cm ²	4550
Bio-Balls Surface Area, cm ²	7100

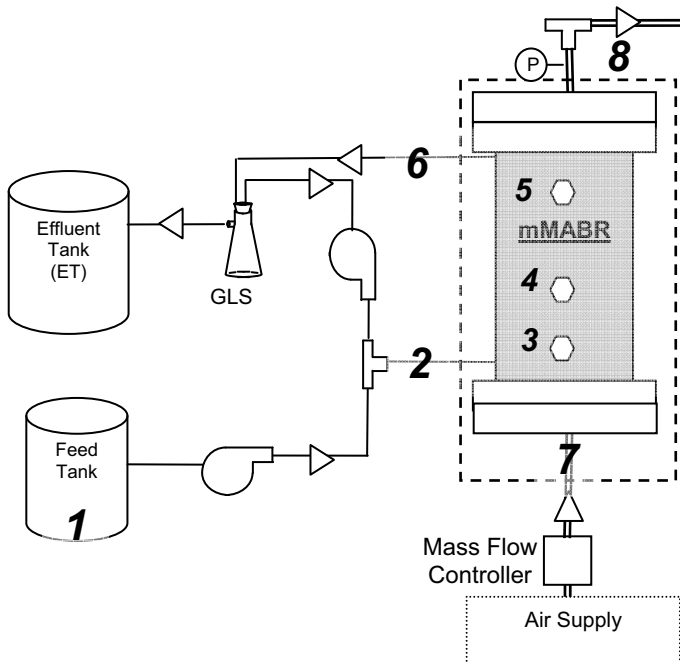


Figure 2. mMABR bioreactor system: 1 is the influent, 2 is the mixed recycle/feed line, 3 is 10 cm from the bottom of the reactor, 4 is 18 cm from the bottom of the reactor, 5 is 26.5 cm from the bottom of the reactor, 6 is the effluent line, 7 is the influent air line, and 8 is the effluent air line

SYSTEM OPERATION

The recycle ratio was maintained at 10 and influent feed was continuously supplied via two peristaltic pumps (Cole Parmer, 7550-50). Pump tubing and the gas liquid separator were cleaned or exchanged every week in order to prevent excess biological growth in regions

outside of the mMABR reactor. In response to previous research (Landes et al. 2007a), the airflow rate was set at 10 L/min and controlled via a differential pressure mass flow controller (Cole Parmer, 32907-67). Influent feed was made on days that samples were collected. The feed solution is a chemical ersatz recipe that replicates the waste stream of an EPB. It is composed of urine, hygiene water, and humidity condensates. Verostko et al. (2004) detail the makeup of the ersatz wastewater solution.

LIQUID LOADING STUDY

Sampling

Samples were collected approximately three times a week from the influent tank, mixed recycle/feed line, three bulk liquid points along the length of the reactor, and the effluent line (Figure 2). The bulk liquid sample collection required employing a 4-inch needle connected to the syringe in order to collect a representative sample. The effects of aeration were minimized during collection of the bulk liquid samples (points 3, 4, & 5 in Figure 2) by using a syringe, and immediately after collection, all trapped air in the syringe was removed. The liquid sample was subsequently emptied into a vial, and the DO concentration was analyzed using a Hach LDO probe and meter (LDO101 and HQ40d).

Analysis

Samples were analyzed for pH, DO, anions, cations, organic carbon, and total nitrogen (TN). A Thermo Orion meter attached with a pH electrode was employed to analyze the hydrogen ion concentration. Dissolved organic carbon (DOC) and TN samples were filtered with 0.47 μ m membranes, diluted, acidified, and analyzed using a combustion technique Shimadzu TOC/TN analyzer (TOCvch and TNM1). Anions and cations of interest, nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+) were filtered with 0.47 μ m membranes, diluted, and analyzed using a Dionex ion chromatograph (DX-600).

For this study, DOC reduction, nitrification, and denitrification were used to assess the water quality performance of the mMABR bioreactor. For the following equations, all subscripts refer to the corresponding location in Figure 2. Assuming all