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Journal of Membrane Science 255 (2005) 117–124

journal of MEMBRANE SCIENCE

www.elsevier.com/locate/memsci

Integrated evaluation of a sequential membrane filtration system for recovery of bioreactor effluent during long space missions

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Received 27 August 2004; received in revised form 18 January 2005; accepted 22 January 2005
Available online 25 February 2005

Abstract

Performance of an integrated membrane filtration system was investigated for treatment of the effluent from an aerated rotating membrane bioreactor system (ARMS). The ARMS is developed and operated at the Kennedy Space Center (KSC) as a potential technology for water recovery and recycling during long space missions. The 3 L bioreactor utilizes a rotating membrane module consisting of silastic hollow fibers for aeration and biofilm growth. Effluent from the ARMS contains high levels of dissolved inorganic solids. A sequential membrane filtration system consisting of prefiltration and reverse osmosis (RO) membranes was evaluated for treatment of the bioreactor effluent. To select an appropriate prefiltration membrane, a series of membrane screening experiments were conducted with two UF membranes (MWCO 10,000 and 50,000 Da) and a nanofiltration (NF) membrane using stirred filtration cells. In addition, integrated membrane filtration tests were conducted with the NF and RO membranes using a cross-flow membrane filtration unit. Effectiveness of the integrated membrane filtration system was evaluated in terms of flux and total solids rejection of the individual filtration steps as well as the overall system performance.

Keywords: Nanofiltration; Reverse osmosis; Membrane bioreactor; Space craft wastewater; Water reclamation

1. Introduction

Water recovery and recycling is an important consideration for reducing payload during long space missions. It is estimated that the water needs in space would be about 11.5 L/day-person as shown in Table 1. Although this quantity is less than 4% of the water used in the United States per person per day, it would not be possible to transport the amount of water needed to space during extended missions.

The wastewater generated during space missions is estimated to be about 13 times more concentrated with relatively low BOD/solids ratio in comparison to the typical municipal wastewater quality in the United States. Table 2 presents the composition of the simulated space wastewater based on the anticipated water use during space missions. The development of a closed loop water recovery and recycling system would require integration of multiple technologies to bring the wastewater to drinking water quality. One of the water recovery and recycling processes currently being evaluated for water recovery and recycling during long space missions incorporates the aerobic rotational membrane system (ARMS) which is currently tested at the Kennedy Space Center, Florida. The ARMS is a novel compact membrane bioreactor which converts ammonia to nitrates. The rotating hollow fiber membrane module provides mixing to maintain high mass transfer rates between the bulk liquid and the biofilm resulting in high bioconversion rates and reduce the volume requirements [2,3]. The reactor effluent contains

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doi:10.1016/j.memsci.2005.01.028

Table 1
Two-person crew water use in space [1]

Source	Quantity
Shower water (L/d)	5.44
Hand wash water (L/d)	8.16
Urinal flush water (L/d)	1.00
Average urine donation (L/d)	3.00
Humidity condensate (L/d)	4.54
Oral hygiene water (L/d)	0.73
Total (for two) (L/d)	22.87

significant amounts of dissolved inorganic salts as well as soluble products from the bioreactor which need to be removed for development of a closed loop water recovery and recycling system.

Membrane processes can be integrated to biological treatment processes for down stream treatment. However, the use of an RO treatment requires pretreatment to improve the performance of the RO membrane in terms of flux as well as solids removal [4–7]. Integration of membrane processes with different separation characteristics can improve the final product water quality and allow the subsequent membrane system to operate at lower pressures [8–12].

The purpose of this study was to investigate the performance of an integrated membrane filtration system for treatment of the ARMS effluent. Experiments were conducted to evaluate the overall performance of an integrated filtration system incorporating two different membranes. A series of membrane screening experiments were conducted with two UF membranes (MWCO 10,000 and 50,000 Da) and a NF membrane for use as a prefilter for the RO membrane using stirred dead end filtration cells. The membranes were evaluated in terms of solids removal and flux characteristics of the individual filtration steps as well as the overall system. After selecting a prefilter, an integrated membrane filtration system consisting of NF and RO membranes was evaluated using a cross-flow filtration system.

Table 2
Composition of synthetic waste formulation [1]

Compound	Concentration (mg/L)
Urea	1640
KH_2PO_4	580
NaCl	900
K_2SO_4	590
NH_4Cl	120
$(NH_4)_2SO_4$	360
$CaCl_2$	88
$MgSO_4$	71
$NaHCO_3$	520
Miranol C2M Conc.-NP (surfactant)	558
STEOL CS-330 (surfactant)	854
Total	6281

2. Suitability of membranes technologies for bioreactor effluent

The low-pressure membrane filtration processes such as microfiltration (MF) and ultrafiltration (UF) remove particulates, colloids, and high-molecular-weight soluble species by a size exclusion mechanism [13,14]. The MF and UF membranes generally allow most inorganic species to pass and retain discrete particulate matter such as particle, bacteria, and some viruses.

The NF membranes are designed to selectively remove multivalent ions and large organic contaminants while allowing other compounds to pass. Therefore, NF units can be operated at lower pressures since the compounds that pass through the membrane do not add to the osmotic pressure of the system [15–17]. Both the NF and RO can be described as diffusion-controlled processes since diffusion plays a significant role in the mass transport. The ability of RO membranes to reject inorganic species while passing relatively pure water has lead to the widespread use of membrane processes for drinking water applications. The ultra-low-pressure reverse osmosis (ULPRO), and nanofiltration (NF) offer significant operational advantages for water treatment and wastewater reclamation/reuse applications where a high product quality is desired.

Processes that involve coupling of membrane technologies could significantly improve the effluent quality [18–20]. An integrated membrane system utilizing multiple membranes with different characteristics can also lower the membrane fouling rates and results in more stable operation [21,22]. The key operational and design considerations for integration of the membrane processes include flux, solids rejection, pressure requirements, and long-term performance.

3. Experimental

Experiments were conducted to evaluate the integration of a membrane filtration system for treatment of the effluent from the ARMS bioreactor.

3.1. ARMS bioreactor

The ARMS is developed and evaluated at the Kennedy Space Center (KSC), Florida, as a potential technology for wastewater recovery and recycling applications during space missions since biological treatment may be an important component for recycling wastewater into potable water. The ARMS is a gravity independent attached growth bioreactor. The 3 L bioreactor is operated on a continuous mode with simulated wastewater representing the output of a 1/2-person crew during space missions. The system is aerated through the rotating hollow fiber membrane module consisting of 115 silastic hollow fibers which are 35.6 cm long, with 0.155 cm i.d. and 0.318 cm o.d. [3]. Silastic tubing (500-008 Dow, Corning, Midland, Michigan) was used for the mem-