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Humidity Condensate Stabilization Using an Engineered Biologically Active Storage Tank

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Water recovery on the International Space Station (ISS) reduces resupply costs. Humidity Condensate (HC) is a major source of available water on ISS but contains both organic and inorganic contaminants. Organic carbon and nitrogen in the HC can support microbial growth. Microbial growth in the HC storage tank has been documented and this growth has caused operational issues in the past. One possible solution to prevent excess growth and stabilize the HC to prevent downstream growth is to engineer a storage tank that will facilitate the oxidation of carbon (C) and nitrogen (N), but prevent biomass shedding and growth downstream. A micro-gravity compatible Membrane Aerated Bioreactor (MABR) could serve as the HC feed tank and support waste stabilization. The stabilization would not only prevent downstream operational issues but would also reduce the loading on the mixed beds and catalytic oxidizer. We evaluated the performance of a gravity independent MABR treating HC over seven months of operation. A range of loading rates from 2 C/d (crew member per day) to 15 C/d, corresponding to organic carbon loadings from 800-6200 mg/d and organic nitrogen loadings from 130-1300 mg/d. Results indicated that the MABR was able to significantly remove organic carbon (>80%), oxidize organic N, and lower the pH with only minimal consumables (O_2).

Nomenclature

C = Carbon
C/d = Crew member per day
DO = Dissolve Oxygen
DOC = Dissolved Organic Carbon
EPB = Early Planetary Base
HC = Humidity Condensate
HRT = Hydraulic Retention Time
ID = Inner Diameter
ISS = International Space Station
L/d = Liter per day
L/min = Liter per minute
MABR = Membrane Aerated Bioreactors
N = Nitrogen
NASA = National Aeronautics and Space Administration
NH3 = Ammonia (Aqueous)
NO_2^- & NO_3^- = Nitrate and Nitrite species (Aqueous)

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OD = Outer Diameter
ON = Organic Nitrogen
RO = Reverse Osmosis
TDS = Total Dissolved Solids
TN = Total Nitrogen

I. Introduction

One of the applications of treating and reusing wastewater is to facilitate human habitation off Earth's surface. The National Aeronautics and Space Administration (NASA) is expanding the presence of humans in space and development of life support systems to provide the requirements for space habitation is necessary[1]. Water accounts for 65% of the daily mass input per crew member and is a critical factor in these systems[2]. As such, much effort and research has been employed in order to provide technologies capable of producing reliable reused water by reclaiming wastewater (e.g. crew members' urine, or humidity condensate) and also allow mission duration and sustainability to be independent of initial water resources or resupply scenarios.

Humidity is a key component in spacecraft by providing physical comfort for astronauts[3]. The main source of increasing humidity in a closed cabin spacecraft is the metabolic moisture generation by crew members. The International Space Station (ISS) has been maintained at pressure and humidity levels very close to Earth (temperature of 22 ^{0}C, and humidity level of 60%) [4]. However, humidity levels higher than ~60% can cause negative impacts on thermal comfort, damage the electronic devices, allow corrosion, and cause bacterial growth[5]. There is evidence indicating that bacterial growth in spacecraft was mainly due to water covering internal surfaces and life support systems [6]. Several water quality analyses have been done on pre-flight and post-flight water samples which indicated biological contamination in humidity condensate (post-flight sample104 cells/ml) [7]. Therefore, humidity condensate (HC) is considered a significant cause of microbial growth in storage tanks. Previous studies have shown HC tanks are biologically active, and biofilms could contribute to downstream biofouling[8, 9, 10.]

Biological treatment is a possible solution to stabilize the HC by engineering a storage system to allow bacteria to remove biodegradable organic carbon but prevent biofilm transport to downstream systems. This would prevent downstream growth reducing consumables and increasing mixed bed filters bed life. Biological treatment systems are regenerable and only consume small amounts of oxygen (O_2). Compared to systems that only inhibit microbial growth, biological systems eliminate growth potential by consuming growth substrates.

Past studies have operated full scale Membrane Aerated Bioreactors (MABR) as feed tanks for habitation wastewaters and evaluated their treatment over long-term operation [11, 12, 13]. Their findings revealed that theses MABRs can achieve high carbon (C) removal (~80-90%) and high nitrogen (N) oxidation efficiency (~50-60%), while maintaining pH below 7. In this study, we operated a full scale MABR over 7 months to treat HC. The gravity independent MABR was challenged with a range of loading rates from 2 C/d (crew member per day) to 15 C/d.

II. Methods

A. Reactor characteristics

The biological reactor characteristics have been published previously[12], but are also described here briefly. The rectangular MABR in this study had overall dimensions of L=82 cm, W=53 cm, H=40 cm and a total volume of 173 L (Figure 1). The MABR contained 1755 siloxane membranes with OD=0.55 and ID=0.245 cm. Total liquid volume of the reactor was 104 L. There were two air plenums on the opposite sides of the reactor which supplied air or oxygen into the membranes. The liquid flow was perpendicular to the membranes. There was a recycle line, connected to a centrifugal pump (22 L/min) to provide mixing in the reactor. The wastewater was pumped into the reactor using a peristaltic pump, while the effluent was discharged by displacement from the outlet zone. There was a HACH multi probe Sonde placed in the recycle line for online monitoring of pH, Total Dissolve Solids (TDS), Dissolve Oxygen (DO), and temperature. The gas (O_2 or air) flowrate (0.6-1 L/min) was controlled by a gas mass flow controller.

B. General Operation and Test Points

The operation of the MABR was evaluated over seven months. The feed recipe is detailed in Table 1. The waste streamcontained organic and inorganic HC solutions which were made using published ersatz recipes[14, 15]. The HC wastewater was pumped into the reactor continuously. The loading rate increased from 2 C/d to 15 C/d with the

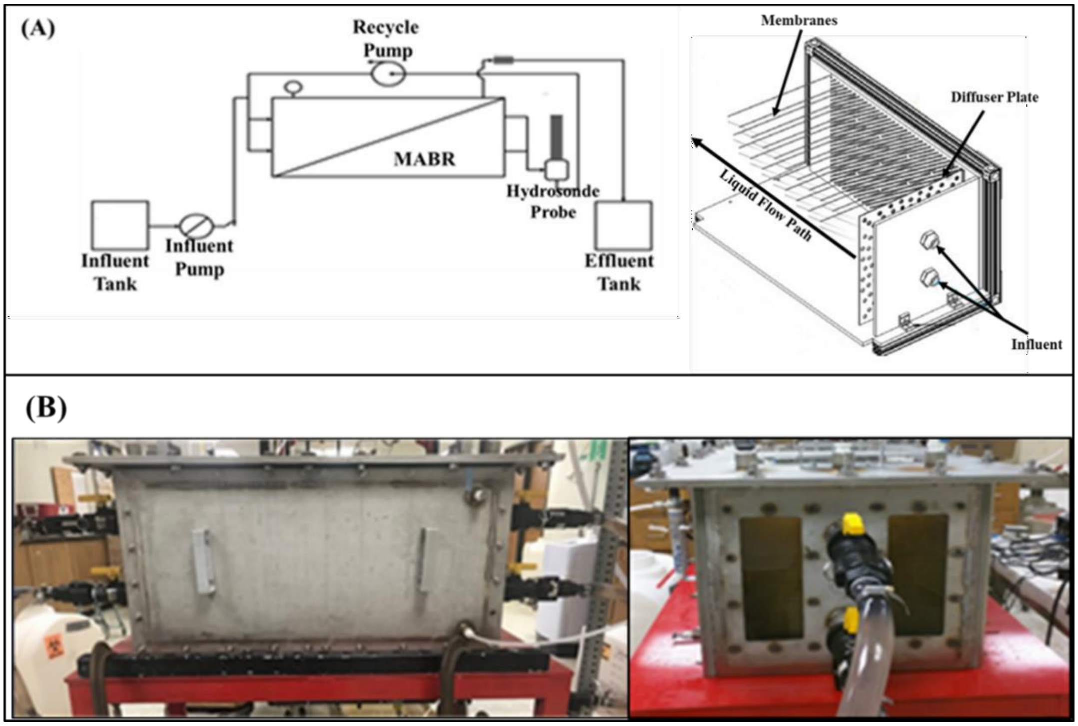

Figure 1. Two-stage MABR system, "(A) Flow diagram of system," "(B) system operation in the lab"

Hydraulic Retention Time (HRT) ranging from 3.7 to 28.2 days. Details of conducted test points and volume treated are represented in Table 2.

Table 1. Humidity Condensate Recipe[15]

Waste stream	Ersatz organic humidity (mL)	Ersatz inorganic humidity (mL)	Reverse Osmosis (RO) water (mL)	Total volume (mL per crew)
Humidity condensate	100	100	1,930	1,950

Table 2. Overview of Test Points Conducted and Volume Treated

Date	Waste Stream	Feeding Mode	Days Operated	Loading	Volume Treated (L)
6/18/2019	Humidity Condensate	Continuous	48	2 C/d* (3.9 L/d)	187.2
8/6/2019			16	3 C/d (5.9 L/d)	94.4
8/23/2019			31	4 C/d (7.8 L/d)	241.8
9/25/2019			32	5 C/d (9.9 L/d)	316.8
10/28/2019			17	10 C/d (19.8 L/d)	336.6
11/15/2019			61	15 C/d (30 L/d)	1830

*C/d: Crew member per day

C. Data Analysis

Online monitoring measured pH, DO, TDS, and temperature continuously (one reading per minute) using a multiprobe water quality hydrosonde. The influent and effluent samples were collected three times per week. Samples were filtered (pore size of 0.45 µm) and stored at 4°C. The influent samples were analyzed for Dissolve Organic

Carbon (DOC) and Total Nitrogen (TN), and the effluent samples were analyzed for DOC, TN, NO_2^-, NO_3^-, and NH_3/NH_4^+. DOC samples were acidified to remove inorganic carbon. DOC and TN samples were evaluated using a Shimadzu analyzer. NO_2^- and NO_3^- were analyzed using a Dionex Ion Chromatograph instrument, and samples were analyzed for NH_3 using ammonia reagent set (AmVer™ high range ammonia) and HACH spectrophotometry.

III. Results

The operation of the reactor was evaluated over seven months. Over this time, the reactor treated HC across six test points. The loading rate of influent increased over the operation time and ranged from 2 to 15 C/d, corresponding to liquid flowrates from 3.9 to 30 L/d. The reactor treated almost 3,000 L (1,500 crew-days) of HC waste stream over seven months of operation. The average pH of the reactor across all test points was in the range of 5.6-6.1 (Figure 2). The pH was independent of variations in HRT (Figure 2). Oxygen was always supplied as pure oxygen and the system remained fully aerobic. DO was generally above 20 mg/l although there was a reduction in DO concentrations when HRT was below 10 days (Figure 2).

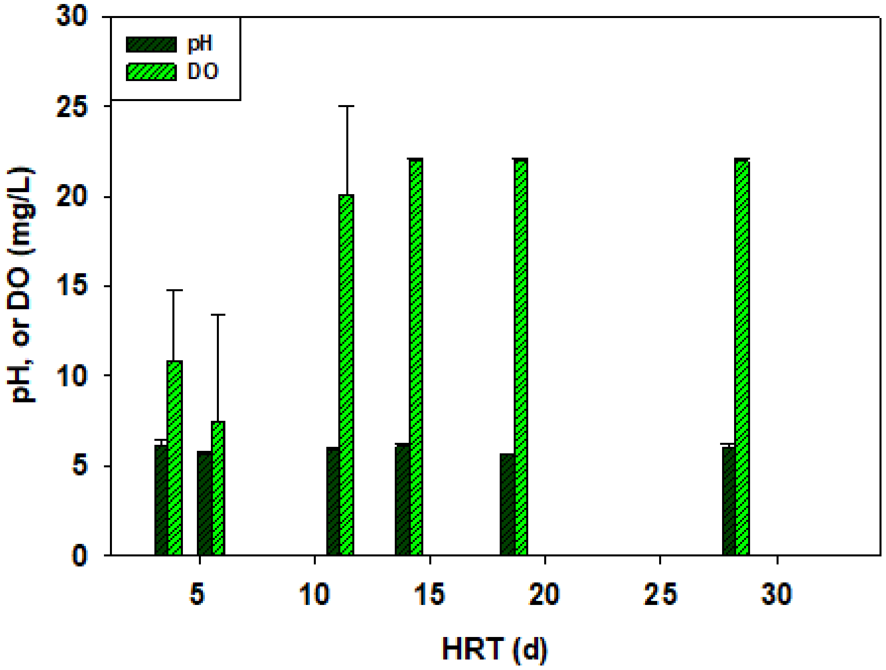

Figure 2. Impact of HRT on pH and DO for HC wastewater

DOC concentrations and loading- The influent DOC concentrations ranged from 207-270 mg/l (Figure 3). The effluent DOC concentration was much lower than the influent DOC concentration and ranged from 15-59 mg/l (Figure3). This resulted in a range of C removals from 80 to 94 % (Figure 3). Reductions in effluent DOC concentration were generally related to increases in HRT (Figure 3). Influent and effluent DOC loading ranged from 0.8-6.9 g/d, and 0.07-1.7 g/d, respectively (Figure 4). Effluent DOC loading increased linearly with influent DOC loading (r^2=0.96) (Figure 4-A). In addition, decreases in effluent DOC loading corresponded to increases in HRT (r^2=0.6) (Figure 5).

TN concentrations and loading- Total influent N concentrations were low (30-39 mg/l) (Figure 3). The effluent N concentrations (19-32 mg/l) across all test points were similar to influent N concentrations (Figure 3). There was no strong relationship between HRT and effluent N concentration, however it seemed that shorter HRT resulted in higher effluent N concentrations (Figure 3). Influent N loading increased with HRT and ranged from 0.12-1.2 g/d (Figure 4-B). Effluent N loading was in the range of 0.09-0.96 g/d across all test points and increased linearly with influent N loading (r^2=0.98) (Figure 4-B). Generally, increases in effluent N loading was related to reduction in HRT (r^2= 0.7) (Figure 5).

NO_x^- (NO_2^- or NO_3^-) production- Total NO_x^- production was generally low across all test points and ranged from 1.9-15 mg/l (Figure 3). Overall, higher effluent N concentrations corresponded to lower NO_x^- concentrations (Figure 3). However, it seemed that NO_x^- concentration was mostly related to HRT and increased linearly with respect to HRT (r^2=0.9) (Figure 3). The most dominant compound of NO_x^- was always NO_3^-. NO_2^- concentrations across all conducted test points were 3-30% of total NO_x^-.

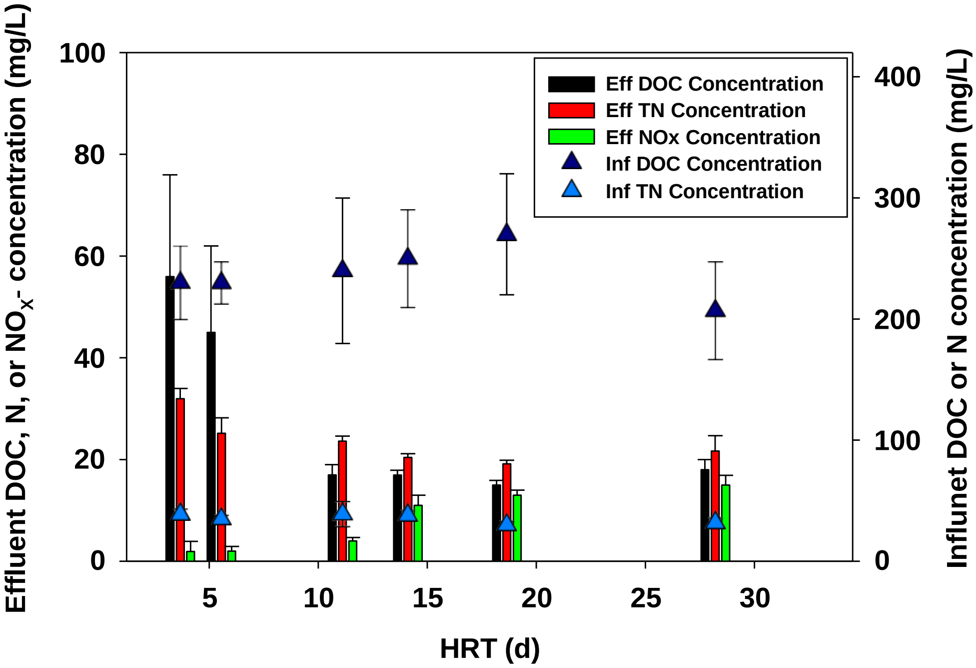

Figure 3. Impact of HRT on influent and effluent DOC, N, and NO_x^- concentration for HC wastewater over 7 months

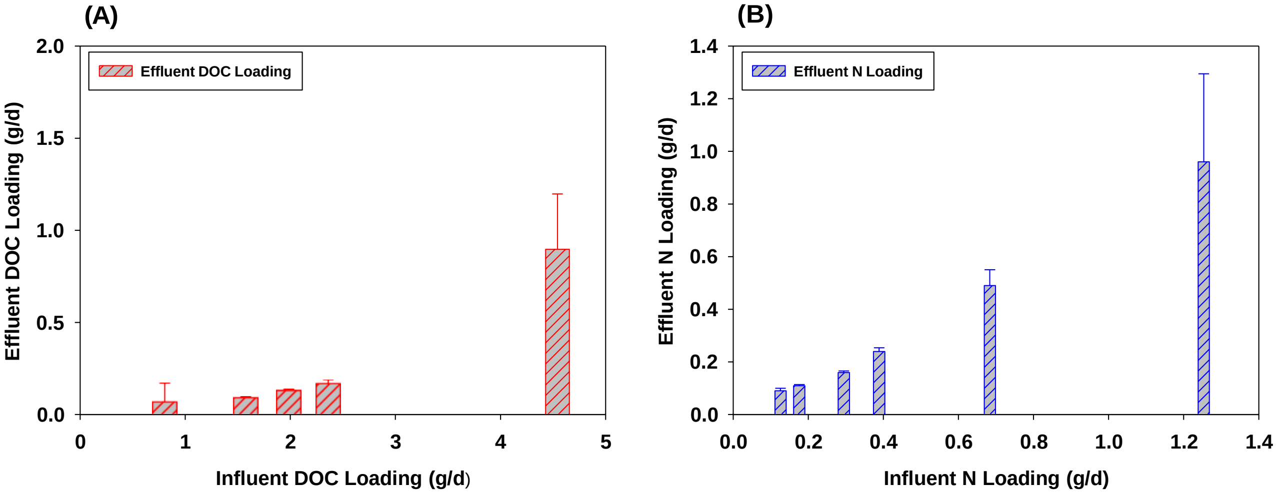

Figure 4. Impact of (A) influent DOC loading on effluent DOC loading (B) influent N loading on effluent N loading over 7 months

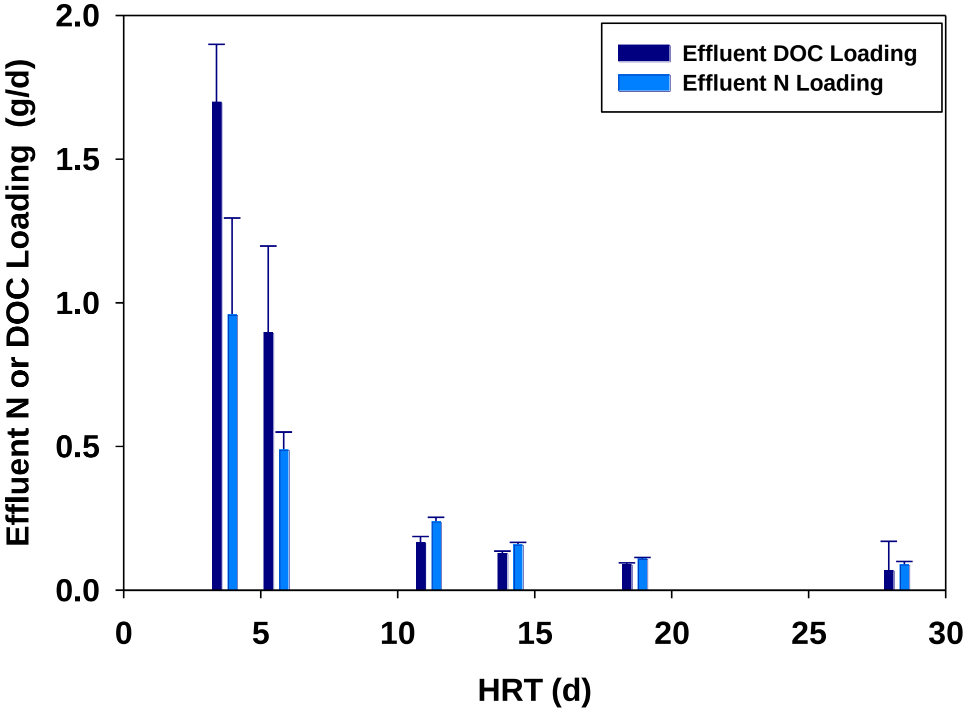

Figure 5. Impact of HRT on effluent N or DOC loading over seven months

IV. Conclusion

Overall, the MABR was able to treat HC wastewater over seven months with no failure. This system treated wastewater with loading rates ranging from 2 C/d to 15 C/d and HRT of 3.7 d to 28.2 d, which caused a range of influent N and C loading. Across all test point, the average pH and DO concentration ranged from 5.6-6.1 and 7.5-22 mg/l, respectively. Generally, the effluent C concentration was >80 % lower than influent C concentration demonstrating the ability of the reactors to reduce downstream growth potential. The MABR modestly reduced Organic Nitrogen (ON) concentrations. These findings support the use of a MABR as the HC collection vessel in order to stabilize the wastewater and prevent downstream growth. The system was able to reliably operate with high efficiency, low oxygenconsumption, and no maintenance.

Acknowledgments

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