NASA Zero-Gravity Space Flight Experiment
Proposal; Not Published

Investigating the Role of Microgravity on the Properties of Air-Trapping Membranes used in Water Recycling Systems

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1. Abstract

This proposal seeks to investigate the impact of a microgravity environment on the properties and behavior of air-trapping membranes and their performance in pressure-driven distillation (PD) for water recycling in space. The primary objective is to analyze changes in water flux and salt rejection—two key metrics for assessing membrane performance and purification efficiency—compared to an Earth-based control. By varying feed and permeate pressures, the experiment will explore membrane behavior under different operating conditions, ensuring successful purification while adapting to the unique challenges of microgravity. The findings could provide critical insights into the viability of air-trapping membranes for water purification in spaceflight, uncovering unique behaviors that may be leveraged to enhance existing membrane technologies. Additionally, this research may offer invaluable information for applying such membrane systems in space and other low-gravity environments, supporting the development of more efficient water recovery systems for long-term space missions and planetary bases.

2. Purpose

The purpose of these experiments is to investigate how microgravity influences the performance of air-trapping membranes used in PD. The research will focus on two key metrics: water flux, which measures the rate at which water passes through the membranes, and salt rejection, which evaluates the efficiency of PD in preventing dissolved species from contaminating the permeate. By addressing the central question of how the near absence of gravitational forces affects these processes, the study aims to provide fundamental insights that could lead to the development of more effective water purification systems for spaceflight, long-term space missions, and planetary bases.

3. Background

Recycling urine, hygiene wash water, and humidity condensate is critical for sustaining long-term space missions and establishing extraterrestrial settlements, where transporting large volumes of potable water from Earth is impractical, as discussed by [Lopez, et al.]. At the International Space Station (ISS), water recycling systems are essential for providing the crew with water for drinking, bathing, conducting experiments, and producing oxygen. As NASA shifts its focus from human missions in low Earth orbit on the ISS to orbiting and land-based habitats, the need for more efficient and lightweight wastewater recycling methods becomes increasingly important.

This challenge is exacerbated by the growing global demand for freshwater, driven by rising populations, increasing standards of living, and anthropogenic climate change. These factors have placed unprecedented stress on the world's freshwater resources, necessitating advanced technologies to treat nontraditional water sources like wastewater or seawater. Membrane technologies, particularly reverse osmosis (RO), have become the gold standard for water desalination and rehabilitation due to their energy efficiency, compact design, and effectiveness in removing dissolved salts. However, despite their success, these technologies have limitations, especially in handling low-molecular-weight solutes and resisting the chemical oxidants commonly used in water treatment.

To overcome these limitations, researchers have developed air-trapping membranes that utilize an entrapped air layer to achieve a unique combination of high-water permeability and selectivity. Traditionally, membrane distillation techniques that rely on thermal energy have been highly effective but inefficient due to significant heat loss. The innovation of PD with air-trapped membranes offers a novel approach, combining the benefits of gas-liquid phase change separation with improved energy efficiency and a safer, simpler purification process. PD drives vapor through the membrane without the need for thermal energy, achieving near-complete rejection of dissolved solutes while maintaining superior water permeability. The hydrophobic coating on the inner surface of these membranes selectively permits water vapor to pass while blocking liquid water and dissolved chemicals. Additionally, these membranes exhibit robust chemical resistance against oxidative damage, addressing a significant limitation of traditional membrane technologies.

However, as a newly emerging technology, PD and its air-trapped membranes have not been extensively studied in varied environments. Their viability in both large-scale and specialized applications, such as spaceflight, remains under investigation. Studying their performance in microgravity environments is particularly important, as gravity significantly influences fluid dynamics on Earth. In microgravity, the stability of the air layer within the membrane pores might be affected, potentially altering water flux, vapor transport, and condensation processes. Understanding these dynamics is crucial for optimizing these technologies for space and Earth-based applications.

This experiment is being conducted to explore these uncertainties and challenges, particularly in the context of long-term space missions and the development of planetary bases like those in NASA’s Artemis Missions. Current water recovery systems on the ISS, including the urine and water processor assemblies face issues such as mechanical failures, biofouling, and the accumulation of harmful compounds such as dimethylsilanediol in water streams. These challenges are further intensified by the unique environmental conditions in space, such as microgravity and heightened ionizing radiation.

The PD process under study represents a promising alternative that could replace or complement existing technologies like RO and thermal distillation, which have certain limitations in space environments. By leveraging the advanced properties of air-trapped membranes, this experiment aims to assess the efficacy of PD in removing contaminants while maintaining resistance to the harsh chemical and physical conditions of space. The findings from this study could pave the way for more efficient and reliable water recovery systems in spaceflight, supporting NASA’s goals for future lunar and planetary missions.

Related Research

1. [Lopez et al., *International Conference on Environmental Systems*, 2024] demonstrates the potential application of pressure-driven distillation in spaceflight water recovery systems. Rejection of challenging contaminants seen in the

wastewater on the International Space Station are tested through a pressure-driven distillation membrane.

2. [Park et al ., *Science*, 2017] discuss the trade-off between membrane permeability and selectivity, highlighting the challenges and advancements in designing membranes that can overcome this trade-off.
3. [Nguyen et al., *Science Advances*, 2023] present a proof-of-concept for a pressure-driven distillation process using air-trapping membranes that achieve high water permeability and near-complete rejection of dissolved solutes, including challenging contaminants like sodium chloride, boron, and urea, suggesting their potential for advanced water purification applications, including space-based water recycling.

This proposal aims to study the impacts of microgravity on water vapor transport in distillation membranes. As far as we are aware, this would be the first time a distillation membrane has been studied under the effects of microgravity. While air-trapping membrane technologies have been extensively studied on Earth, the impact of microgravity on their performance, particularly on PD, remains largely unexplored. This study directly addresses the challenges of developing sustainable water purification technologies for spaceflight applications. By understanding how these membranes perform in microgravity, the research can inform the design of systems for long-duration space missions, where water recycling and efficiency are crucial.

4. Variables

Independent Variables

The first and most obvious independent variable in this investigation is the gravitational force. The results of these experiments will be compared to the performance of the same system in Earthly conditions, with the fundamental goal being to identify key differences between operation under Earth's gravity and a microgravity environment. Beyond this, the independent variables include the feed pressure, or the pressure placed on the impure water supply used to force water vapor across the membrane, and permeate pressure, which is the pressure of purified water collected on the other side of the membrane. These two pressures are responsible for driving the movement of water vapor across the membrane, thereby influencing the overall efficiency of the distillation process. Varying the feed and permeate pressures will allow us to understand how operational conditions in microgravity differ from Earth-based conditions, potentially revealing unique behaviors of the membrane that could be harnessed for specialized applications.

Dependent Variables

The dependent variables include the water flux and salt rejection rates of the membrane. Water flux will be measured visually, as well as with the help of a sensor to quantify results for comparison with the Earth-based control. The degree of salt rejection will be measured using a conductivity meter, revealing the concentration of dissolved species in the permeate; a foundational measure for the performance of the system. Together, the rate of water purification and the quality of the purified water will inform how effectively the membranes and distillation system operates under microgravity.

5. Hypothesis with Justification

Hypothesis 1: The water flux through air-trapping membranes will increase in a microgravity environment compared to operation under Earth's gravity.

Justification: On Earth, gravity plays a significant role in the movement of fluids, including within membrane systems. The near absence of a gravitational force is expected to reduce the pressure of the air layer in the pore, decreasing mass transfer resistance for vapor transport through the membrane, , thereby leading to an increase in the water flux. Previous studies have shown that fluid dynamics are significantly altered in microgravity, which supports the hypothesis that water flux will increase.

Hypothesis 2: Salt rejection efficiency of the air-trapping membranes will remain the same in microgravity as under Earth's gravitation and exceed 98%.

Justification: Air-trapping membranes rely on a gas-liquid phase change to separate dissolved solutes from water; this phase change is not affected by gravitational forces, as supported by Nguyen et al., Science Advances, 2023.

6. Experiment Design

Technical Specifications: The membrane that will be used in the proposed experiment is made of polycarbonate with a hydrophobic modification consisting of long-chain carbon functional groups. The membrane module will be less than 5 kg, operate at a maximum pressure of 200 psi, and have an active membrane area of 0.01 m^2. The membrane module, pump, and feed reservoir will be secured to the floor of the aircraft using appropriate rigging equipment, including shackles, eye bolts, and aircraft cable.

Setup and Data Collection: Water flux and salt rejection will be measured continuously throughout the duration of the flight. Water flux will be measured using a flowmeter while salt rejection will be measured using a conductivity sensor. Data will be collected and stored electronically to be analyzed after the flight. Data analysis will involve looking for any variations in water flux and salt rejection upon exposure to microgravity. Pressure will be varied throughout the 25-30 parabolas, starting at 20 psi and increasing to 200 psi.

One of the potential challenges in this experiment is the fluctuation of microgravity during parabolic flight. These fluctuations could impact the consistency of data collected. To address this, we plan to implement real-time monitoring and data logging, allowing us to correlate specific data points with the exact microgravity conditions at that moment. This will help in isolating the effects of microgravity on the membrane performance. Additionally, we will conduct a sensitivity analysis to evaluate the impact of various parameters on water flux and salt rejection. This will include examining how changes in pressure, membrane characteristics, and other design variables affect fluctuations in our dependent variables.

Figure 1: Diagram of the membrane test system

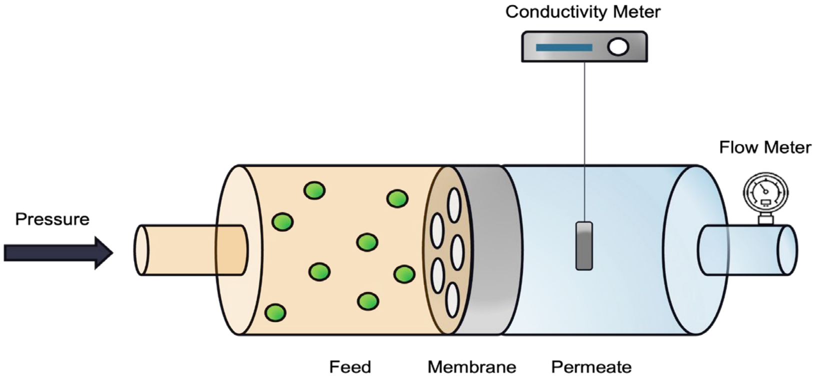
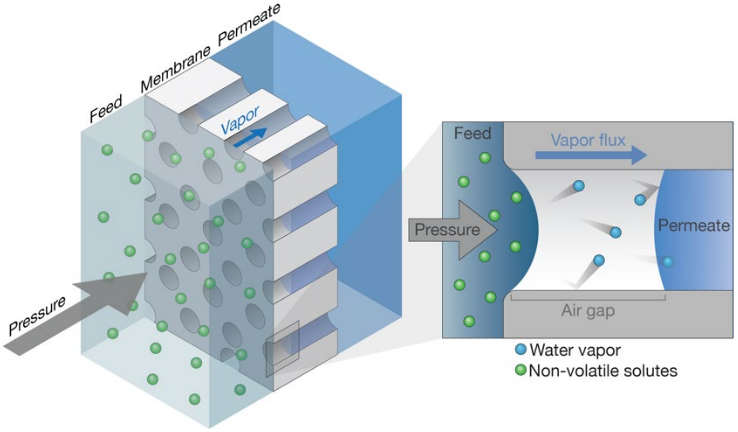


Figure 2: Schematic of the mechanism underlying the proposed pressure-driven distillation (PD) membrane



7. Safety

For safe and effective use in parabolic flight, the experimental setup is designed with no significant safety hazards like open flames, high voltages, or corrosive chemicals. The module will be housed in a compact, rounded enclosure with no sharp edges or protrusions to minimize the risk of injury to personnel or damage to the aircraft as a consequence of impact with the module. The experiments use low-voltage electronics, which include the pumps, flow sensors, and conductivity meters. A simple salt solution will be used as the feedstock, and there are no hazardous chemicals used in any of the experiments. These solutions will be contained within sealed, shatterproof containers to prevent spills and leaks, and these containers will be further enclosed in a secondary containment system to ensure that no liquids escape into the aircraft regardless in any event.

The experimental setup includes pressure relief valves to prevent any pressure buildup that could lead to system leaks or ruptures. Additionally, Dr. Straub's research group has thoroughly tested the membranes and membrane module up to 500 psi, which is significantly higher than the 200 psi pressure used in the experiment. This ensured the robustness and reliability of the membrane under the experimental conditions, providing an added layer of safety against pressure-relates issues.

8. Outreach and Collaboration

Outreach: The primary objective of our outreach is to enhance public understanding of water desalination technologies especially its potential for space flights and long-term space missions. We aim to engage a broad audience, including high school students, industry professionals and NASA researchers interested in environmental sustainability.

Collaboration: Dr. Anthony Straub and Kian Lopez of the Civil and Environmental Engineering Department at the University of Colorado – Boulder will leverage their expertise in membrane technology and fluid dynamics to provide critical insights into the experimental design and data analysis, contributing to the success of this experiment.

Dr. Anthony Straub has more than 12 years of experience working on membrane technology research. Currently, Dr. Straub is an assistant professor of Civil, Environmental, and Architectural Engineering at the University of Colorado Boulder. He also holds appointments in the Environmental Engineering Program and the Materials Science and Engineering Program. Dr. Straub conducted his postdoctoral studies at Massachusetts Institute of Technology in the Department of Materials Science and

Engineering. He completed his Ph.D. at Yale University in Chemical and Environmental Engineering. His current research focuses on the development of advanced membranes and materials for separations and water treatment. He is PI on several sponsored project from agencies including the National Science Foundation, Department of Interior, and Department of Defense.

Kian Lopez is a PhD student at CU Boulder and a NASA Graduate Research Fellow. He has been working with NASA engineers on the development of this technology and application in space flight systems since receiving the fellowship in 2022. Kian spent the summer of 2023 working at NASA's Ames Research Center on the testing and implementation of PD membranes in spaceflight systems and published this work in the International Conference on Environmental Systems in July 2024.

Om Sanan is a senior at Scarsdale High School in Scarsdale, New York and a water treatment researcher and computer/AI/ML programmer for 7 years. Since Fall 2022, he has been interning with The National Renewable Energy Laboratory writing research on decarbonization of the water desalination process, water security and reuse, and energy independence. Om interned with NASA SEES Space Research during summer 2024 working with the GRACE - Weighing Where the Water Goes team. He is also working on research on community water desalination with MIT and publishing research on digital twins and large language models with Colorado State University. Om is also the founder and CEO of Day Zero Water (https://dzwater.org), a student-led non-profit, which he founded in 2018 to implement water filtration projects in schools locally in the U.S. and water-stressed areas in India and Africa and help raise water conservation awareness.

References

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