Design considerations for sustainable spacecraft water management systems

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Abstract

It is well recognized that water handling systems used in a spacecraft are prone to failure caused by biofouling and mineral scaling, which can clog mechanical systems and degrade the performance of capillary-based technologies. Long duration spaceflight applications, such as extended stays at a Lunar Outpost or during a Mars transit mission, will increasingly benefit from hardware that is generally more robust and operationally sustainable over time.

This paper presents design strategies and testing considerations for improving the reliability of water handling technologies. Our application of interest is to devise a spacecraft wastewater management system wherein fouling can be accommodated by design attributes of the management hardware, rather than implementing some means of preventing its occurrence. Two representative boundary applications are presented. The first is a short term application where reduced gravity flight tests demonstrated a static phase separator prototype that achieved nearly 100% separation of gas from liquids under widely varying wetting conditions correlated to anticipated ranges of wastewater fouling. The second is a design concept for a lunar outpost water recovery system where wastewater is allowed to age and form biofilms and precipitates that can be filtered through lunar regolith media as the water is reclaimed. Both applications are supported by similar underlying principles of facilitating sustainable fluid handling in the presence of fouled surfaces.

Keywords: Sustainable; Life support; Wastewater; Fouling

1. Introduction

Development of spacecraft life support hardware over the past few decades has focused primarily on microgravity applications, with sophisticated designs usually constrained by limitations of volume, mass and power. In particular, for 2-phase gas/liquid separation in microgravity, centripetal acceleration or capillary action is used to remove liquids without the aid of gravity-driven buoyancy. These systems have often been prone to failure due to surface fouling caused by biological reactions or mineral scaling, which can clog mechanical systems. In turn, these failures can cause increased maintenance cost and overall crew labor burden.

Long duration space missions, such as expected for a Lunar Outpost or a Mars transit, will drive the need for hardware that is less prone to fouling failure and generally more robust and sustainable. One application that would benefit from innovation is wastewater management, wherein biologically mediated wastewater degradation can be accommodated by the design of the fluid management hardware as opposed to its occurrence being detrimental to the desired process.

This paper presents challenges associated with spacecraft water system biological and mineral fouling and suggests alternative approaches that move toward increased...
sustainability. Design considerations are presented wherein systems may be capable of accommodating, or potentially even benefiting from, fluid/surface fouling. Suggestions for a shift in the method of testing and evaluating spacecraft management system prototypes are offered to better bound expected operational conditions, providing more realistic performance data. Two examples of sustainable spacecraft fluid management systems that incorporate these design considerations are presented herein as case studies. One system is conceived for short duration microgravity flight, and the other for long duration planetary use. They are unified by accommodating fluid fouling, rather than preventing it, to achieve more sustainable and robust performance.

2. Background

2.1. Spacecraft fluid management

In a microgravity environment, separation of immiscible fluids (i.e. gas and liquid) does not occur naturally, as it does on Earth due to buoyancy. In such situations, surface tension and wetting forces become the dominant influence on the liquid behavior. The Space Shuttle and the International Space Station (ISS) both use rotary fans for water separation from an airstream, which are known to be susceptible to failure due to fouling, since the tight tolerances and small orifices do not readily accommodate the resultant blockage that can occur from biological or inorganic mass buildup. This potential for clogging adds another concern in addition to the already generally increased likelihood of failure due to moving parts needed for rotating equipment (Johnson, 2002; Puttkamer, 2008).

Capillary action is regularly used for the control of liquids in various spacecraft systems, such as propellant and cryogen management or in thermal fluid loops for temperature control (Weislogel et al., 2009; Thomas et al., 2009). Large length-scale capillary systems such as these tend to exploit container geometry and fluid properties to passively transport fluids to desired positions for a variety of purposes. Thus, the shape of the container can serve as a pumping mechanism that does not rely on moving parts. Unfortunately, such methods have only been confidently established for well characterized systems with favorable wetting conditions, where there is a high degree of affinity of the liquid for the solid surface. Generally, these systems work best when the advancing contact angle $\theta_{adv}$ is reliably low (Fig. 1), yielding a high degree of capillary pumping. This key design parameter, which is the angle formed between the advancing liquid interface and the solid surface as it moves along, is governed by the various surface energies and the geometry of the solid surface (Quere, 2008). The lower $\theta_{adv}$ the greater the degree of affinity the liquid has for the surface, leading to an increased spontaneous wicking potential. Any changes to the surface properties, including fouling, can affect this process.

2.2. Fouling

Biofouling is a phenomenon through which microbial growth in a water solution attaches to wetted surfaces within the system. Due to the self-contained and continuous functionality typical of spacecraft water management systems in particular, the detrimental effects of biofouling pose well recognized design and operational challenges. Testing conducted at NASA-Marshall Space Flight Center indicated that microbiology contributed to corrosion of an aluminum alloy used in spacecraft water recovery systems (Obenhuber et al., 1991). The study also concluded that once biofilms form in a water recovery system they are “extremely difficult to remove” without methods that are destructive to the hardware. If iodine is added to the potable water system to prevent microbial growth, it must subsequently be removed before drinking due to crew health concerns – a unit operation that further increases system complexity (NASA-JSC, 2000). Designing systems that are less susceptible to biofouling offers only one potential solution to these concerns.

Another form of wastewater fouling is mineral scaling. Scaling occurs as inorganic precipitates form when certain ion concentrations in solutions exceed their solubility limits and create solid salts. These salts then precipitate onto surfaces. Because water management systems are often exposed to fluids with high salt concentrations (i.e. urine), the prevention of scaling must be addressed. Scaling can be avoided by pretreatment or by careful design and operation of the water management system.

3. Technology development considerations

3.1. Geometry

In contrast to state-of-the-art mechanical approaches, it is anticipated that passive capillary driven liquid phase
separation is feasible directly in place of active rotary separators for wastewater applications, where the wetting and fouling characteristics can vary widely. Thomas and Muirhead (2009) observed that certain aspects of wastewater fouling can improve wetting characteristics. They found that although vacuum drying and large defects tended to increase $\theta_{adv}$, crystal growth and biofilm growth actually lowered $\theta_{adv}$. They also noted that the use of pretreatments generally increased $\theta_{adv}$. These trends indicate that promotion of wastewater fouling may be exploited to significantly decrease $\theta_{adv}$ and thereby improve performance of capillary-based fluid management systems.

In a related study, a passive capillary-driven ‘static phase separator’ (SPS) was developed and tested in a reduced-gravity environment to demonstrate successful air/liquid separation under highly variable wetting conditions, wherein capillary conditions varied from highly wetting to non-wetting (Weislogel et al., 2008). When the system was operated within design specifications, it achieved 100% separation in nearly 100% of the tests performed, and with fluids of widely varying contact angles. The sub-scale prototype demonstrated several key design features:

- Centrifugal motive gas flow when available from upstream fans that are not directly exposed to the wastewater can be used effectively to force droplet coalescence.
- The bulk fluid flow may be controlled by either wicking in the case of favorable wetting ($\theta_{adv} \approx 90^\circ$) or air drag in the case of poor wetting ($\theta_{adv} \approx 30^\circ$) – the same geometry can serve both limits.
- Capillary forces act to ‘contain’ the liquid in both cases.
- Liquid carryover is minimized by ‘pinning edges’ in the case of favorable wetting or tortuous paths in the case of poor wetting. These pinning edges are sharp features that present an unfavorable geometry for capillary pumping, and instead encourage fluid to follow an adjacent, more favorable capillary path.

When contact angles are large, capillary wicking rates are reduced below the input liquid flow rate and the capillary force actually resists fluid motion. In this case the bulk liquid will accumulate locally until air drag provided by upstream fans overwhelms the capillary force and dynamic pressure is sufficient to direct the liquid to its desired storage location. Capillary pinning effects, wherein the fluid is retained in a desired location by the unfavorable capillary pumping geometry, then serve to contain the liquid for further processing. In general, geometry-based design considerations based on this principle can be used to improve the operational reliability of capillary-based microgravity fluid management systems. Potentially, such a capillary based technology can be directly used in place of mechanical, rotary fan separators for microgravity fluid management, and may be less prone to failure caused by surface fouling. A design strategy begins to emerge when complemented by the following additional considerations.

3.2. Pretreatment

The use of oxidizing pretreatment chemicals for spacecraft wastewater is intended to prevent urea hydrolysis and the subsequent biofilm and precipitate formation that tends to foul and clog hardware such as rotary fan separators, vacuum orifice, or water recovery systems. In contrast, the absence of pretreatment chemicals likely results in an increased prevalence of biofilm formation and small crystalline growth, which has been shown to significantly lower the contact angle by up to 44° with 95% confidence (Thomas and Muirhead, 2009). This response can be utilized by design to increase the performance of a capillary-based wastewater management system. Consequently, an alternate design strategy coinciding with the use of a capillary-based system might be to eliminate the need for pretreatment chemicals intended to prevent fouling, and deliberately allow wastewater fouling to occur in the liquid management system. The operational implications of employing this approach are discussed below. Typical surface features caused by biofouling and crystalline growth are shown in Fig. 2.

While incorporating a wastewater management system that does not require pretreatment chemicals would undoubtedly be beneficial from an operational and logistics perspective, the effect of intentionally allowing biofilm formation on associated systems that are prone to clogging would still need to be considered. As a case study, the Space Shuttle currently uses a 0.87 cm internal diameter pipeline linking the wastewater storage tank to the vacuum dump orifice, approximately 0.14 cm in diameter. Between the wastewater tank and the vacuum orifice is a composite foam filter, with the smallest layer having a mean pore size of 300 µm, yielding a clean filter pressure drop of 0.1 psid. During at least one flight anomaly, decreased flow was observed through the wastewater dump line. A subsequent investigation suggested that either bubble formation or precipitate fouling caused the decreased flow rate (Muirhead and Verostko, 2007). If this conclusion is correct, it
is certainly important to consider the likelihood of the intentional fouling layer resulting in clogging of other parts in the system. Part of this concern arises from the potential for biomass to break off and into the liquid stream. As the example of a surface with relatively deep features in figure illustrates, however, the thickness of waste water fouling layers is generally less than 300 μm, and these results suggest that the fouling layer is unlikely to grow to a depth that would slough off and clog downstream hardware (Thomas and Muirhead, 2009).

To partially characterize which elements of a fouling layer would indeed pass through a capillary management system, particles greater than 100 μm were filtered during a 21-day test (Thomas and Muirhead, 2009). The largest particles anticipated are ~1 mm, although amorphous deposits can be even larger. Thus, while clogging of the wastewater dump line and wastewater storage tank is unlikely, care should be taken to appropriately size the dump line filter to avoid clogging it or any small downstream component such as a vacuum orifice. The foam filter is specifically designed to filter particulates that arise in spite of pretreatment chemicals, i.e. clothing fibers or hair. Amorphous deposits are likely a consequence the amorphous crystalline or biofilm formations and must be collected by the filter. It seems feasible to modify the foam filter to include a lower density stage to trap and remove sticky amorphous deposits, without causing a dramatic increase in the pressure loss across the filter or allowing breakthrough of the contaminants.

The Space Shuttle air return line includes both an odor and a bacterial filter. The air flow returned from a capillary-based liquid–air separator would likely have a higher odor and bacterial burden, but could likewise be filtered before returning to the cabin. Of greater concern is the probable odor and bacteria emitted from a wastewater input funnel caused by biofouling in the absence of pretreatment. However, simple operational rules could be put in place to minimize these undesirable effects as well. For example, simply capping the interface when not in use would trap odors, similar to how the Apollo crew capsule urine dump line was used. When operated, the air fan assist would draw cabin air through the system and minimize the potential for contaminants to escape. Additionally, the urine funnel would be interchangeable and cleaned between uses, as current operational protocols specify. Within these imposed constraints, the absence of pretreatment chemicals should not create an added odor and bacterial burden in the spacecraft.

3.3. Materials and surface treatments

Surface treatments also offer a means of improving material wetting characteristics. Based on the results of the wastewater fouling studies described above, several previous assumptions regarding surface treatments can be reconsidered. Specifically, the presumed need for a biocidal surface treatment and long-term mechanical durability may not be applicable. As one feasible strategy, a hydrophilic treatment could be applied to the capillary system in absence of a biocidal treatment to improve initial wetting. As the system is used, the surface treatment will wear off while crystalline and biofilm fouling layers form. This approach would potentially allow for favorable wetting conditions within both new and used capillary systems.

Another option would be to simulate the ultimate outcome of wastewater fouling conditions in the new design. Since it has been shown that small crystalline growth improves wetting conditions, while large crystals as well as dried and cracked surface features worsen wetting, simulating favorable fouling conditions offers an attractive alternate design strategy for capillary based systems. Specifically, by roughening a surface such that the largest defect height \( d \) and capillary length \( l \) are in ratio satisfying \( d/l < 0.04 \), a partially wetted surface will be wetted more favorably (Thomas and Muirhead, 2009). With such a capillary-based wastewater system, designers could consider integrating exposure to wastewater prior to use in flight to promote fouling layer growth to improve initial system performance. This might be considered an unusual procedure, and care would have to be taken to ensure that any pathogenic constituents are confined to the wastewater system. Alternatively, a sterile wastewater ersatz could be developed that would deposit fouling layers on the surface in a similarly beneficial way.

3.4. High fidelity environmental technology testing

In addition to the technical design considerations, it is possible that more sustainable spacecraft fluid management technologies might also be developed by reconsidering the methods in which they are typically tested under highly controlled conditions. The goal is generally to conduct defined tests that produce predictable and reproducible results akin to how basic scientific research is carried out. Once these systems are in space, however, they often fail in complex, unforeseen ways leaving the engineers frustrated and the systems in disuse.

Designing, testing and evaluating spacecraft fluid management systems is an engineering challenge more than it is a basic science research challenge. Rather than examining fundamental processes, engineers are generally more interested in how well a given system meets operational requirements. Testing protocols, therefore, should be adjusted to reflect this goal. Systems should not need to be fully characterized under precise and controlled environments; rather results from complex and compounded conditions within defined boundaries should be compared to stated performance requirements. Suggested basic elements of this approach are:

1. Set performance requirements and evaluation criteria for desired technology.
2. Define reasonable envelope of expected operational environmental conditions.
3. Evaluate multiple technologies within this expected operational envelope.
4. Escalate, expand and compound the envelope as technologies mature.
5. Evaluate the results against performance requirements and technology capabilities.

While this approach may seem like standard engineering practice, it is in fact a departure from the methods in which most spacecraft fluid management systems are tested, perhaps a consequence of the rarity and expense of ‘in-space’ field testing. Specifically, the typical approach today is to control the testing environment in such a way that any particular requirement is evaluated in relative isolation. For example, ground tests with fluid systems often use ersatz with over-simplified conditions that do not fully represent the actual environment that produces the appropriate complex surface conditions in which the fouling occurs. Engineering performance tests consequently should be less concerned with fully characterizing a single parameter in favor of gaining confidence in the system’s overall robustness and sustainability across a range of expected conditions. In this manner, the resultant designs will necessarily be capable of accommodating, if not exploiting, fluid fouling, making the next generation of spacecraft life support and fluid handling systems more robust and sustainable.

4. Applications

The design and testing considerations presented can be applied to a wide spectrum of spacecraft fluid management systems. Presented here are two examples, one for intermittent, short-term microgravity fluid management; and another for long duration, continuous lunar outpost use. Both of these applications represent departures from the state-of-the-art technologies and current system development plans.

4.1. Contingency wastewater disposal

A direct application of the static phase separator (SPS) design considerations was initiated to develop a contingency wastewater disposal system for NASA’s Crew Exploration Vehicle (CEV) called the Personal Body-Attached Liquid Liquidator, or PBALL. In this contingency scenario, the airflow system was assumed to have failed, leaving only passive hardware and vacuum vent to dispose of the wastewater. To meet these needs, the PBALL was conceived to rely on capillary action and urine wetting design considerations. The design challenges inherent in the SPS are similar in some ways to the PBALL, with the key difference being the lack of air flow provided by an external source. The PBALL was designed to accommodate a range of wetting conditions, from $0^\circ < \Theta_{\text{adv}} \sim 90^\circ$, be adaptable for both male and female use, collect and retain up to a liter of urine, minimize splash-back, and allow continuous drain of the wastewater to vacuum while minimizing cabin air loss.

The PBALL device is composed of a crew interface, a void volume to retain the bulk liquid, and a capillary vane structure that serves to draw the urine away from the void volume and towards the vacuum drain port. The vane structure (resembling a tapering stack of ‘waving fans’) utilizes capillary wedge geometry to collect, contain and dispose of the wastewater. Fig. 3 shows the vane structure design for PBALL, wherein a large void volume is presented to the incoming wastewater stream to minimize pinning events. The vane structure becomes denser downstream and reduces the interior angle of the vanes. This provides capillary pumping for wetting conditions and generally allows for concentration of the bulk liquid with passive displacement of the air. In poor-wetting conditions, the momentum of the liquid stream forces the liquid downstream. Spurious perturbations to the system promote capillary pumping. Only a single vane continues to the liquid exit port providing capillary communication to the bulk liquid without extensive viscous and pinning forces.

The PBALL design demonstrates application of a number of fundamental capillary-driven principles described above, namely:

- Collection of bulk fluid via capillary geometries (for favorable wetting the capillary uptake rate exceeds the input rate) and liquid momentum (for unfavorable wetting, when the capillary uptake rate is lower than the input rate the device relies on liquid inertia and capillary containment to capture and separate the fluid phases).
- Containment of bulk fluid by capillary force.
- Minimization of carryover or splash by pinning edges.
- Promotion of beneficial fouling by avoiding pretreatment chemicals.

Using a linear model to describe the relationship between surface fouling and contact angle (Thomas and Muirhead, 2009), the impact of surface fouling on capillary
pumping can likewise be predicted. For illustrative purposes in Fig. 4, this semi-empirical approach is applied to expected conditions for the full scale PBALL and shows the correlation of surface fouling on capillary pumping along a plane representing an average wastewater input flow rate of 20 ml/s (NASA-JSC, 2008). The region below this plane represents where the input liquid flow rate exceeds the capillary pumping rate, resulting in a buildup of bulk liquid. As indicated, highly fouled surfaces with small surface defects produce the highest capillary pumping rates. This illustrates the likely outcome of intentional wastewater fouling and demonstrates its positive impact on capillary pumping action.

4.2. Lunar outpost water recovery

As missions become extended in duration and move toward more self-reliant operations, new demands are placed on the life support system design. Thus far, all indications have suggested that the lunar outpost water recovery systems will be evolved from current spacecraft technologies, including urine pretreatment, distillation, and brine dewatering (NASA, 2005). However, these technologies were developed for microgravity compatibility, and may carry undesirable fouling and failure mode heritage from this environment.

Unlike orbiting spacecraft, a lunar outpost will exist in a fractional Earth gravity environment (~0.166g_0) with abundant natural resources including lunar regolith, vast open surfaces, and plentiful sunlight. Sunlight can provide a direct source of energy for solar distillation, while gravity can at the very least make complex microgravity compatible technologies fluid separation technologies unnecessary, and at best be advantageously utilized in a wastewater recovery process. Meanwhile, the outpost may not have ready access to Earth resupply, making consumables and maintenance of greater concern when conducting design trade studies. Lunar surface conditions are perhaps more analogous to the terrestrial environment than to microgravity space flight.

For these reasons, the appropriate technology development approach for lunar outpost hardware may likely be adapting terrestrial technologies for use in a hypogravity environment, rather than modifying microgravity space flight technologies.

As part of a wastewater management system for a planetary base, an alternative filtering method is suggested. The aforementioned fouling studies indicated that wastewater can be expected to form biofilms, amorphous crystalline deposits, and large crystals on solid surfaces. These constituents are similar to those found in terrestrial water treatment systems, and can easily be filtered out. For example, wastewater in a lunar outpost could be encouraged to form biological and mineral precipitates in a roughing filter, and then these fouling constituents could then be removed by filtering. Potentially, lunar regolith could be used as a media filter.

The aforementioned wastewater fouling study indicated that fouled surfaces contain crystals on the order of 10–100 μm, while the fouling layers are generally less than 200 μm. A commonly used lunar regolith simulant has a mean particle size of about 200 μm. Based on these approximate sizes, it is feasible to design a lunar regolith filter that will effectively remove wastewater precipitates and biofilms, as a granular filter can have an effective media diameter up to approximately 25 times the diameter of the targeted contaminants, and can be designed to be a purely physical filtering process.

Filtered wastewater is then delivered to the primary downstream processors. By precipitating crystalline constituents, it is feasible to expect a higher recovery rate and lower energy cost for the primary processors, which are limited by the solubility of the ionic concentrations. These filters could be located outside of the habitable spacecraft volume, and can be prevented from freezing by using direct solar energy and albedo effects.

This concept addresses several important challenges to implementing a water recovery system for a lunar outpost, as well as raises several other concerns that must be addressed, as summarized below.

- **Sustainability** – this concept uses simple unit processes that are proven and robust, with minimal electrical energy required, and a likely low maintenance burden.
- **In situ** resource utilization – as suggested by many studies, a lunar outpost will likely benefit from use of local resources, such as direct solar energy and lunar regolith proposed here as the primary resources supporting water, recovery, and additionally, takes advantage of the presence of lunar gravity.
- **Pretreatment** – this concept eliminates the need for toxic pretreatment chemicals used for urine stabilization. Instead of trying to prevent urea hydrolysis, this concept promotes biologically mediated urine degradation, taking ions out of solutions and then filtering the subsequent minerals and biology.

![Fig. 4. Capillary pumping to input liquid flowrate based on fraction fouled and defect height.](image-url)
Integration – this concept can be directly integrated with existing water recovery system technologies, including brine dewatering systems that could result in improved performance with the elimination of mineral fouling.

A primary NASA Exploration Life Support technology activity is “reducing life support consumables and improving system performance and robustness” (Barta and Ewert, 2009). This sustainable water recovery concept addresses this gap through the innovative use of partial gravity, solar energy and lunar regolith in place of pretreatment chemicals and primary processors (Thomas et al., 2009).

5. Conclusion

Rather than attempting to prevent or reduce fouling, which can result in wastewater system failures, sustainable fluid management concepts can be designed to accommodate, perhaps even benefit from, biofouling and mineral scaling. Design considerations including geometry guidelines for capillary-based fluid separators capable of handling highly variable wetting conditions, discontinued need for pretreatment chemicals, and wastewater fouling filtration offer feasible approaches.

Two example applications are presented herein, one for short-duration microgravity flight, and the other for long-duration planetary outpost use. Reduced-gravity flight tests demonstrated a static phase separator that achieved nearly 100% separation of gas from fluids over a range of widely varying wetting conditions that might realistically be expected from wastewater fouling that would occur during actual use. In another example, a lunar outpost water recovery system could benefit by being encouraged to foul regolith media and form biofilms and precipitates that can then be filtered and the water reclaimed using downstream treatment processes.

Additionally, rather than evaluating technologies within narrowly controlled experimental conditions that might not accurately reflect actual complex operational environments, water handling systems can be operationally verified over a reasonable envelope of expected conditions to better ensure their reliability. These considerations can be applied to myriad terrestrial and spacecraft sustainable fluid management technologies.

Collectively, the design considerations and application examples presented here are unified by the approach of accommodating fluid fouling to achieve more sustainable and robust systems.

References