Advanced Water Recovery Technologies for Long Duration Space Exploration Missions

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ABSTRACT

Extended-duration space travel and habitation require recovering water from wastewater generated in spacecrafts and extraterrestrial outposts since the largest consumable for human life support is water. Many wastewater treatment technologies used for terrestrial applications are adoptable to extraterrestrial situations but challenges remain as constraints of space flights and habitation impose severe limitations of these technologies. Membrane-based technologies, particularly membrane filtration, have been widely studied by NASA and NASA-funded research groups for possible applications in space wastewater treatment. The advantages of membrane filtration are apparent: it is energy-efficient and compact, needs little consumable other than replacement membranes and cleaning agents, and doesn't involve multiphase flow, which is big plus for operations under microgravity environment. However, membrane lifespan and performance are affected by the phenomena of concentration polarization and membrane fouling. This article attempts to survey current status of membrane technologies related to wastewater treatment and desalination in the context of space exploration and quantify them in terms of readiness level for space exploration. This paper also makes specific recommendations and predictions on how scientist and engineers involving designing, testing, and developing space-certified membrane-based advanced water recovery technologies can improve the likelihood of successful development of an effective regenerative human life support system for long-duration space missions.

INTRODUCTION

Water is essential to all lives. Currently, potable water has been provided fully for the entire duration of the mission to all manned low orbit space missions including Space Shuttle and International Space Station (ISS) missions. The wastewaters generated in current space-related missions, including urine, hygiene water, and condensate water, are either discharged into space or brought back to the earth (although there is limited water recovery of certain streams of space wastewater in ISS, the recovered water is not used as potable water). This arrangement of water supply for long-duration manned space missions would be, of course, unattainable. And wastewater recycling becomes an essential part of Environmental Control and Life Support Systems (ECLSS) for all long-duration space exploration missions. Many terrestrial wastewater treatment technologies can be potentially adopted for extraterrestrial applications. However, many challenges need to be overcome in order to converting wastewaters to potable water as required by extended duration space exploration.

The main challenge of human presence in space is to duplicate the critical functions of intricate, interdependent processes that occur and sustain lives on earth. The water aspect of this challenge is to completely recover potable water from wastewater generated in the outer space with no need of water replenishment and substantial amount of consumables in a restricted and confined microgravity environment. Outer space is an unforgiving and daunting place, far away from any help from the earth, and this puts a huge premium on reliability and easiness of maintenance of water recovery systems. Microgravity introduces another dimension to an already-difficult problem in wastewater treatment in space exploration. Forces that are small in terrestrial flow situations such as surface tension become dominant while buoyancy is absent in a weightless environment. Flotation and sedimentation, for example, two common and inexpensive wastewater treatment processes, have no use in a microgravity environment. Some of other common wastewater treatment unit operations have to be modified to address solid/liquid, gas/liquid, and gas/solid separations in the form of additional equipment or/and processes. The difficulty of wastewater treatment associated with microgravity is also extended to the issues of process scale-up and modeling/simulation. All process models, past or current, theoretical or empirical, are subject to validation in space because of microgravity factor. The cost of doing that is so prohibitive that there have been few attempts made to field-test the equipment or design.

The labeling of "microgravity compatible" technologies for water treatment are often based on whether the technology in question is mono-phased and/or whether gravity plays any significant role in driving process performance. This approach is imprecise and sometimes questionable since it ignores the forces such as surface tension that are insignificant under normal gravity but are important in the microgravity environment. The uniqueness of microgravity environment has unsettling implications on various water treatment processes where the bulk fluid is mono-phased but involved solid-fluid interfaces between the fluid and the material of the equipment. One such a sample is membrane filtration that is being used in ISS for water recovery from hygiene water and humidity condensate. There is no evidence yet to suspect that microgravity has adverse effect on operability of the reverse osmosis unit, however, no one can rule out the possibility of adverse effect of surface tension on membrane filtration at the membrane surface and/or in the boundary layer since surface tension is manifested at interfaces, where concentration polarization and membrane fouling occur.

Recognizing the gap between a basic process of a particular water processing technology and an on-board water treatment module for extended-duration space missions, NASA has devised a systematic assessment scheme, called Technology Readiness Level (TRL), to assess the maturity of a technology for all space-bound technologies, making comparison of sophistication levels among different technologies designed for a particular application of space exploration. For each technology, the larger the number of TRL, the closer the technology is eligible for being used for space missions. The definitions of TRL are can be found in many NASA documents (White, 1995).

MEMBRANE SEPARATION TECHNOLOGIES FOR WATER RECOVERY

Membrane Filtration

Membrane filtration is a technology that utilizes semi-permeable materials in a specific arrangement (configuration) to exclude most organic or inorganic maters in wastewaters based on size or molecular weight while allowing water and, for some variations of membrane filtration systems, small molecules to permeate through. The most common variations of membrane filtration are based on the ability of a membrane to reject materials of certain range of size and/or molecular weight (Liu, 2003). Membrane filtration technology for water treatment has advanced rapidly as demand for potable water worldwide increases. The last two decades have witnessed new reverse osmosis membrane materials that can be operated at ever lower pressure and with increasing salt rejection. Current commercial membranes for reverse osmosis have been claimed to have 97% - 99.5% salt rejection rate (usually obtained from lab-scale membrane units with NaCl solution) and 7 bar operating net driving pressure (Nicolaisen, 2002). Realistically, many reverse osmosis water treatment plants operate at much lower salt rejection rate (about 50 % - 75%) as concentration polarization and fouling take their tolls. The effect of the "evil twin," concentration polarization and fouling, on potable water production from brackish water and seawater is significant and has limited the wide acceptance in the U.S. as a main water treatment technology because of high energy cost and disposal issue related to the concentrated brine from reverse osmosis plants. In long-duration space missions, however, the requirement for water recovery from space wastewater is ideally 100% (not accounting for additional water from foods). This would require either the development of low-pressure and less prone to fouling membranes situated in a membrane module that has minimal concentration polarization in operation or incorporation and optimization of several membrane processes or/and other separation technologies into water recovery systems. Various membrane separation types in common uses have different possible TRL rating with microfiltration (MF) at the high end, and ultrafiltration (UF) and reverse osmosis (RO) in the middle range of the TRL spectrum.

MF is a pressure-driven membrane filtration process that has a membrane with a pore size typically of 0.01-2 μm and able to retain particles with molecular weights equal or larger than 200 kDa and is used in a number of applications, as either a pre-filtration step or as a process to separate a fluid from a process stream. MF membranes are symmetric with characteristic sponge-like network of interconnecting pores. Cartridge filters are typically composed of microfiltration media. Multi-units of MF have been used in spacecrafts and habitats including MIR and ISS as a pretreatment unit for subsequent water processors such as vapor-compression distillation. MF as pretreatment process could be considered as TRL 8 or 9 technologies.

UF involves the use membrane with a pore size less than 0.1 μm (500 – 100 kDa). Ultrafiltration is not as fine a filtration process as reverse osmosis, but it also does not require the same energy to perform the separation. Applications of ultrafiltration in water recovery for space adventures can mostly likely be found in situations where pretreatment is needed for reducing or removing certain compounds from the feed stream of a reverse osmosis unit in order to alleviate the energy demand and fouling. In UF, the chemical nature of membrane materials has only little effect upon the separation (but not fouling) since ultrafiltration separation like microfiltration is based upon sieving mechanisms thus ultrafiltration is only somewhat dependent upon the charge of the particle and is much more concerned with the size of the particle.

The presence of large quantity of mixed surfactants in space wastewater poses a unique problem for ultrafiltration. On the one hand, micellar-enhanced ultrafitration is widely credited for removing certain particulates and solutes that would be impossible to be removed without the assistance of surfactant aggregates, micelles; on the other hand, surfactant monomers are believed to be responsible for membrane fouling by adhering to the membrane surface. The susceptibility of UF membranes to fouling by proteins has generated interests in fundamental studies in membrane fouling. It is no surprising to see prevalence of fouling in these applications since polymeric UF membranes (polysulfone, for instance) are more or less hydrophobic and proteins have tendency to adhere their hydrophobic cores to the membrane surface thus forming a strong bond – irreversible fouling. In space wastewater treatment, however, membrane fouling is mainly caused by deposition of minerals on the surface and blockage of the pores in addition to adsorption of surfactant monomers, and biofouling. The extent of mineral fouling in relation to surfactant fouling is yet to be determined. Biofouling of UF and other membranes is another important subject that is not adequately studied. In addition to composition of wastewater feed stream, the membrane surface characteristics are the most important factors that determine the extent of biofouling. One recent paper (Vrijenhoek et al., 2001) suggested that the smoothness of the RO membrane surface had a lot to do with whether biofilms would form on the membrane because, they argued, without crevices or holes or folds, it is difficult to for microorganisms to establish their colonies. This conclusion obviously needs to be further studied. But even the above argument is accurate; one has to wonder if it is also applicable to ultrafiltration since UF membranes contain relatively large-sized pores.

RO, also known as hyperfiltration, is the finest filtration known. This process will allow the removal of particles as small as ions from a solution. Reverse osmosis is used to purify water and remove salts and other impurities in order to improve the color, taste or properties of the fluid. Most reverse osmosis technology uses a process known as cross-flow to allow the membrane to continually clean itself. As some of the fluid passes through the membrane the rest continues downstream, sweeping the rejected species away from the membrane. The process of reverse osmosis requires a driving force to push the fluid through the membrane, and the most common force is pressure from a pump. A reverse osmosis process involves pressures 5-10 times higher than those used in ultrafiltration. As the concentration of the fluid being rejected increases, the driving force required continuing concentrating the fluid increases. Reverse osmosis is capable of rejecting bacteria, salts, sugars, proteins, particles, fats, and other constituents that have a molecular weight of greater than 0.15-0.25 kDa. The separation of ions with reverse osmosis is aided by charged particles. This means that dissolved ions that carry a charge, such as salts, are more likely to be rejected by the membrane than those that are not charged, such as organics. The larger the charge and the larger the particle, the more likely it will be rejected. The transport mechanism of RO is now believed to be the solution diffusion mechanism.

Other Membrane Processes

There are several other membrane processes that involve separate dissolved species from water. Among them are pervaporation and membrane distillation. Pervaporation is defined as a separation process in which a liquid feed mixture is separated by means of partial diffusion-vaporization through a non-porous polymeric membrane while vacuum or a sweep gas is applied to the downstream side of the membrane. Membrane pervaporation has been used in removal of VOC from groundwater and wastewater (for example, Peng et al., 2003; Peng and Liu, 2003ab) and in removal of water from highly-concentrated alcohol (for example, Verkerk et al., 2001). The strength of pervaporation technology lies in its ability to separate trace amount of component(s) from the remaining components in the bulk liquid with less energy requirement and high recovery rate than other separation technologies including other membrane processes. The potential application of pervaporation and its cousin processes such as temperature swing adsorption and thick film absorption in space wastewater treatment is limited to dehydration of the high concentrated brine discharged from an RO unit. It should be noted that the issues such as concentration polarization and membrane fouling also affect pervaporation. Scaling of minerals is a potentially worrisome problem since many pervaporation units operate at 30 – 50 °C to be most effective.

Membrane distillation is another membrane technology that can be used as a part of water recovery system. Membrane distillation (MD) is a type of low temperature, reduced pressure distillation using porous hydrophobic polymer materials. It is a process that separates two aqueous solutions at different temperatures and has been developed for the production of high-purity water, and for the separation of volatile solvents such as acetone and ethanol. MD can achieve higher concentration than RO. In MD, the membrane must be hydrophobic and microporous. The hydrophobic nature of the material prevents the membrane from being wetted by the liquid feed and hence liquid penetration and transport across the membrane is avoided, provided the feed side pressure does not exceed the minimum entry pressure for the pore size distribution of the membrane. The driving force of MD is temperature gradient and the two different temperatures produce two different partial vapor pressures at the solution-membrane interface, which propels consequent penetration of the vapor through the pores of the membrane. The vapor is condensed on the chilled wall by cooling water, producing a distillate. This process usually takes place at atmospheric pressure and temperature that may be much lower than the boiling point of water. Membrane could be used to compliment a hybrid membrane process such as UF-RO unit in space missions. The effect of microgravity on MD operations needs further research.

Membrane Materials

A membrane is undoubted the center of membrane technology. It is no surprise there are many efforts devoted to this area. Many companies have developed and manufactured a variety of membrane materials and configurations for water purification. Current commercial membranes for membrane filtration are mainly made from synthetic polymers and inorganic materials with varied durability under harsh and prolonged operating conditions. Table 2 lists several typical membrane materials and their respective properties (Cheryan, 1998; Peng and Liu, 2003; Cortalezzi et al., 2003):

Table 2. Properties of selective membrane filtration materials

Materials	Maximum temperature (C)	pH range	Solvent resistance
Cellulose acetate	30/65	2-2.75	Low
Fluoropolymer	60	1.5-12	High
Polyamide	60	2-10	High*
Polyethersulfone	80	1.5-9.5	Medium
Polysulfone	80	1.5-12	Medium
PVDF	80	1.5-12	Medium
Polyacrylonitrile	80	1.5-12	High
Alumina oxide	300	0-14	High†
Zirconia oxide	300	0.5-13.5	High†
Iron oxide	300	0-14	High

* susceptible to chlorine attack.
† not recommended for phosphorus.

The first-generation RO membrane materials such as cellulose acetate, though less prone to fouling, has seen its market share declining in desalination and wastewater treatment operations due to newly arrived composite RO membranes. The fragility of this type of membranes has ruled itself out in applications in space missions. Currently, the second-generation RO membranes such as composite membranes made from thin polyamide active layer on top of UF or MF substrates made from polysulfone has been adopted for seawater desalination. However, owing to different components in space wastewater, the applicability of this type of materials remains unclear and needs further long-term studies. Inorganic membranes represented by alumina oxide and zirconia oxide (third-generation) are very resistant to high temperature, organic solvents and acids. However, the processability and cost issues related to inorganic membranes are main road blocks to successful commercial applications. The potential applications of inorganic membranes for space missions are not very encouraging now due to the processability issue. This situation could change with the improvements in processing techniques. A current trend in membrane development is modification of membrane surface characteristics to achieve certain operational goals. Improvement in hydrophilicity by copolymerizing another monomer or functional group is a common technique to reduce membrane fouling by proteins or organic colloids. Another emerging area of membrane materials is nanocomposite membrane. This type of membrane materials involve the use of polymeric materials as substrate embedded with nano-sized property-enhancers such as carbon nanotubes.

Membrane Modules

Spiral wound

In spiral wound modules, a flat membrane envelope or set of envelopes is rolled into a cylinder as shown in Figure 1. The envelope is constructed from two sheets of membrane, sealed on three edges and each sheet is sandwiched between two turbulent-promoting spacers. The open end of envelope is sealed to a perforated tube (the permeate tube) with a proper glue so that the permeate can pass through the perforations. Another spacer is laid on top of the envelope before it is rolled, creating the flow path for the feed liquid. This feed spacer generates turbulence, thereby enhancing the feed side mass transfer rate. The spiral wrapped envelopes and spacers are then wrapped again with tape or glass or net-like sieve before fitting into a pressure vessel. In this way, a reasonable membrane area can be housed in a convenient module, resulting in a very high surface area to volume ratio. One noticeable drawback lies in the permeate path length. A permeating component that enters the permeate envelope farthest from the permeate tube must spiral inward several feet. Depending upon the path length, permeate spacer design, gel layer, and permeate flux, significant permeate side pressure drops can be encountered. The other disadvantage of this module is that it is a poor choice for treating fluids containing particulate matters. This configuration is widely used in desalination plants with RO and generally is well-suited for space wastewater treatment.

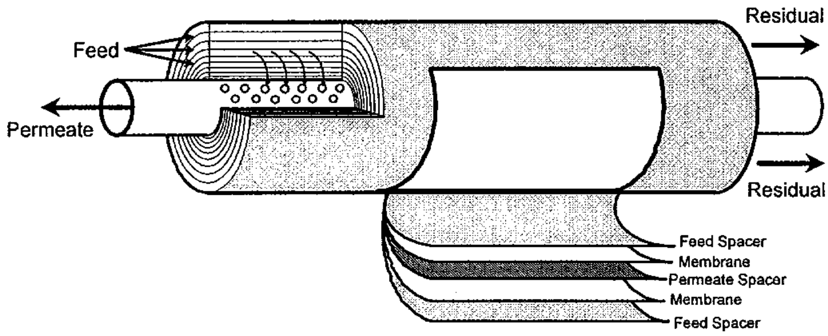

Figure 1. A schematic illustration of a spiral wound module
(Liu, 2003)

Hollow fiber

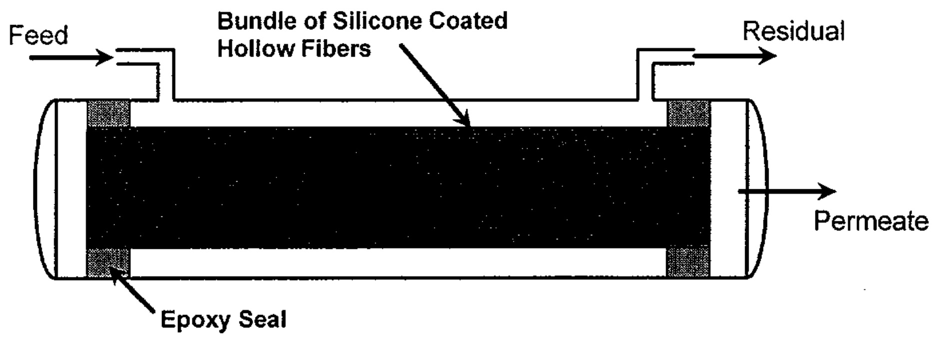

Figure 2. A schematic illustration of a hollow fiber module
(Liu, 2003)

In a hollow fiber configuration, small diameter polymer tubes are bundled together to form a hollow fiber module like a shell and tube heat exchanger (Figure 2). These modules can be configured for liquid flow on the tube side, or lumen side. These tubes have diameters on the order of 100 microns. As a result, they have a very high surface area to module volume ratio. The drawback is that the liquid flow inside the hollow fibers is normally within the range of laminar flow regime due to its low hydraulic diameter. The consequence of prevalent laminar flows is high mass transfer resistance on the liquid feed side. However, because of laminar flow regime, the modeling of mass transfer in a hollow fiber module is relatively easy and the scale-up behavior is more predictable than that in other modules. One noticeable problem with a hollow fiber module is that a whole unit has to be replaced if failure occurs.

Plate & frame

Plate-and-frame configuration is a migration from filtration technology, and is formed by the layering of flat sheets of membrane between spacers. The feed and permeate channels are isolated from one another using flat membranes and rigid frames (Figure 3). A single plate and frame unit can be used to test different membranes by swapping out the flat sheets of membrane. Further it allows for the use for membrane materials (e.g., inorganic membranes) that cannot be conveniently produced as hollow fibers or spiral wound elements. The disadvantages are that the ratio of membrane area to module volume is low compared to spiral wound or hollow fiber modules, dismounting is time-consuming and labor-intensive, and higher capital costs associated with the frame structures. Although a lot of tests related to membrane characterization or optimization in NASA or elsewhere use variations of this type of membrane modules, it is highly unlikely that any of this type of membrane configuration would end up in a spacecraft or space habitat.

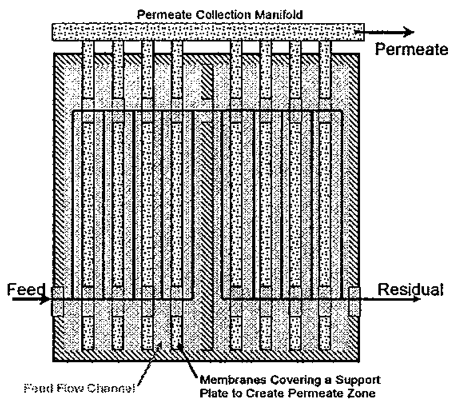

Figure 3. A schematic illustration of a plate & frame module (Liu, 2003)

Tubular

Polymeric tubular membranes are usually made by casting a membrane onto the inside of a pre-formed tube, which is referred to as the substrate tube. The tube is generally made from one or two piles of non-woven fabric such as polyester or polypropylene. The diameters of tubes range from 5-25 mm (Figure 4). The advantage of the tubular membrane is its mechanical strength if the membrane is supported by porous stainless steel or plastic tubes. Tubular arrangements often provide good control of flow to the operators and are easy to clean. Additionally it is the only membrane format for inorganic membranes, particularly ceramics. The disadvantage of this type of modules is mainly higher costs in investment and operation. The arrangement of tubular membranes in a housing vessel is similar to that of hollow fiber element. Tubular membranes sometimes are arranged helically to enhance mass transfer by creating a second flow (Dean vortex) inside the substrate tube (Moulin et al., 1999).

Other Configurations

Several membrane configurations were developed in response to concentration polarization issue in water treatment. The main thrust of these membrane unit designs is to induce high shear on the membrane surfaces (Murase et al., 1991; Engler and Wiesner, 2000; Al-Akoum et al., 2002; Lee and Lueptow, 2002). Vane and Alvarez (2002) used a VSEP (Figure 5) to improve mass transfer at the interface for pervaporation of VOCs.

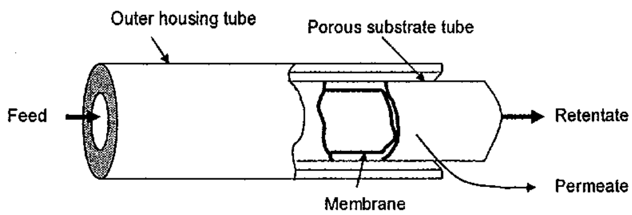

Figure 4. A schematic illustration of a tubular module (Liu, 2003)

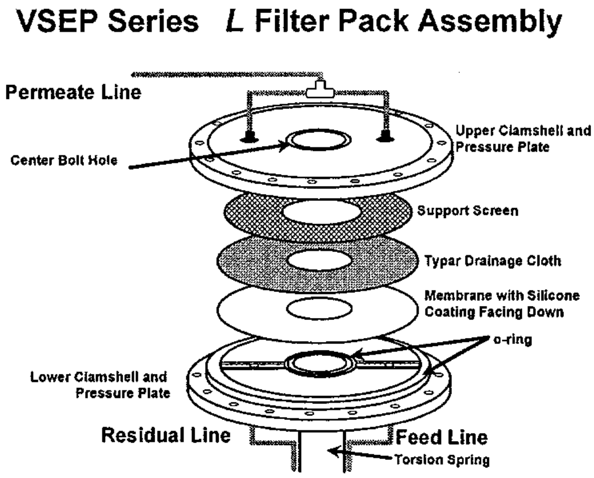

Figure 5. A Vibrating Membrane Module (Courtesy of New Logic, Inc.)

Concentration Polarization

Concentration polarization is an adverse process phenomenon that affects almost all membrane systems and types. In membrane filtration, it builds up retained components to such an extent that the retained components begin to back-diffuse to the bulk. Concentration polarization is also partially responsible for causing membrane fouling because of certain sparsely soluble minerals often reach saturation concentration at the membrane surface and precipitate on the membrane forming a layer of irreversible bonded minerals. Concentration polarization, however, is considered reversible and can often be alleviated by introduce mixing-promoting spacers and increasing flow rate in a cross-flow membrane configuration. Some innovative design of membrane systems such as rotating RO (Lee and Lueptow, 2000), vibrating membrane module (Vane and Alvarez, 2002; Al-Akoum et al., 2002) have been demonstrated to be effective in the systems involved. Beyond increasing shear to counter concentration polarization, there are several other possibilities utilizing other external forces/fields to reduce concentration gradients and enhance trans-membrane mass transfer. One of such forces utilized is electrical force. Huotari and others were able to increase the limiting flux of a cross-flow ultrafiltration unit dealing with oily wastewater by applying electric field (Huotari et al., 1999). However, direct application of the set-up from the above-mentioned authors to space wastewater is very difficult since there are too many components including surfactants, ions, microorganisms, and urea with diverse electrophoretic motilities. The other possibilities of using non-shear forces are acoustic separation or ultrasound in the boundary layer (Athaide and Govind, 1987) and the use of magnetic force. These new areas are promising and need to be further studied.

Membrane Fouling

Fouling is a phenomenon of irreversible loss of membrane permeability leading to reduction in permeation flux. Fouling is caused by adsorption of feed components, clogging of the pores (UF and MF), chemical bonding reaction between the solutes and the membrane, gel formation, and microbial growth and biofilm formation (Koltuniewicz and Noworyta, 1994). The major factors that influence membrane fouling are the hydrodynamics of the process, and the physicochemical properties of the membrane and the feed solution (Huisman et al., 2000). Membrane fouling is a direct result of interaction between solutes in the feed stream and the membrane. As such, the properties of the membrane and solutes in the feed stream as well as operating parameters have strong bearing on fouling. For a UF/MF membrane, the hydrophilicity, surface topography, charge on the membrane, and pore size contribute individually or in several of combinations, to the fouling while organic colloids, pH, soluble minerals, and surfactants appear to be the contributing factors from solutes in feed streams (Cheryan, 1998). As alluded previously, proper selection or modification of membrane surface, pretreatment of membranes with certain surfactants and enzymes, and use of biocides can reduce fouling. The measures used to fight concentration polarization can also mitigate fouling since concentration polarization is partially responsible for fouling. Temperature also affects the extent of fouling (Goosen et al., 2002).

In addition to hydrophilicity, membrane surface topography and pore size also affect the interaction between foulant molecules and the membrane thus membrane fouling. Membrane surface morphology can influence the membrane fouling in two ways: the rough surface tends to trap macromolecules and the surface area of a rough membrane is larger than that of a smooth membrane, which increases likelihood and number of protein adsorption sites. Additionally, in a cross-flow mode operation, a foulant molecule that deposits on a rough membrane surface is less likely to tear off from the surface. Pore size role in membrane fouling seems to be obvious. However, large pore size only gives initial high flux. Once foulants deposit onto the surface of the pore and aggregates are formed in the pore, the pore becomes constricted and lower flux ensues. If pore size is in the same magnitude as size of the molecules, the chance of the molecules clogging some of pores increases. Cheryan (1998) suggests a ratio of pore size to particle size of 1:10.

CONCLUDING REMARKS

Membrane separation technologies are the logic choice for space water recovery. Membrane filtration is a physical process that requires no additional chemicals and less energy than a typical thermal process, and is compact, modular, and perceivably insensitive to microgravity. Great leap has been made in many areas of membrane filtration technology ranging from materials to new module/unit designs. A lot of this advancement will ultimately be migrated to space wastewater treatment, resulting in better and reliable space water recovery systems. The most challenging task that NASA scientists and engineers face is the difficulty of quickly bringing the existing technology to TRL 7 or higher. The lack of experimental data regarding long-term membrane performance under microgravity environment is the major obstacle for this implementation. Additional critical areas that need further studies include biofouling mechanism and removal strategies, fouling by mixed surfactants, novel fouling resistant membranes and innovative countermeasures to concentration polarization.

The future of membrane technologies for space missions will be no doubt very bright and it is highly likely there will be a membrane subsystem in the ECLSS of a spacecraft or space habitat. The water recovery systems for various mission scenarios need to be tailored and fully integrated into the ECLSS of the space living environment. The decision of which water treatment component should be included in a water recovery system ought to be based on a variety of important factors including energy consumption and energy sources, equivalent system mass, reliability, and simplicity in operation and maintenance.

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