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Membrane contactor processes for wastewater reclamation in space II. Combined direct osmosis, osmotic distillation, and membrane distillation for treatment of metabolic wastewater

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Abstract

The improvement of an innovative dual membrane contactor process for treatment of combined hygiene and metabolic wastewater was investigated. Flux and solute rejection in the combined direct osmosis/osmotic distillation (DO/OD) process were enhanced by incorporating membrane distillation (MD) concepts into the process. Two new configurations were investigated: DO/MD, in which the driving force was temperature gradient only, and DO/membrane osmotic distillation (DO/MOD) in which the driving forces were temperature gradient and concentration gradient. Development of a temperature gradient across the membranes substantially enhances the flux of the dual membrane process. It was demonstrated that water flux could be increased by up to 25 times with only a 3–5 °C temperature difference across the membranes. Solutes in the feed wastewater, including urea, were completely rejected. It was demonstrated that complex wastewaters that cannot be treated by one process only could be well treated using a dual membrane process.

Keywords: Forward osmosis; Osmotic distillation; Membrane distillation; Reverse osmosis; Wastewater reclamation

1. Introduction

Negative public perception and recently developing concerns regarding the presence of harmful contaminants (e.g., pharmaceuticals and personal care products) in treated wastewater have resulted in reclaimed water not yet finding acceptance for terrestrial direct potable reuse [1]. For these reasons, reclamation of wastewater for direct potable reuse in space applications is a revolutionary concept. Today, potable water is transported to astronauts serving on low earth orbital missions in space; wastewater generated aboard the spacecraft is treated and stored for disposal upon return to Earth. On the International Space Station (ISS), for example, potable water is provided from Shuttle fuel cells during resupply missions because the fuel cells produce more water than is required by the Shuttle [2]. For more advanced missions, it will be necessary to recover and repeatedly reuse both hygiene and metabolic liquid wastes.

Waste streams on board spacecrafts, including hygiene wastewater, humidity condensate, and urine, are collected separately – making it possible to match the most efficient treatment process with the unique characteristics of each stream. The waste streams generated in space are often very different from their terrestrial equivalents. For example, the hygiene wastewater and urine streams tend to be much more concentrated than domestic wastewater [3].

Among advanced wastewater treatment processes, membrane applications have clearly emerged as a promising alternative to conventional physical–chemical treatment processes [1,4–7]. Due to their compact configuration and high quality product, membrane processes, and especially reverse osmosis (RO) processes, are well suited for applications in space where weight, volume, and use of consumable materials should be minimized.

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1.1. Membrane contactor processes for advanced wastewater pretreatment

Pretreatment is an essential step before membrane treatment of wastewater, especially when RO is involved. An innovative combination of membrane processes is used for RO pretreatment in the Direct Osmotic Concentration (DOC) system developed for NASA by Osmotek Inc. (Corvallis, OR) [8]. The DOC system is one of several advanced wastewater reclamation systems being evaluated by NASA for future use in long distance/long duration human space missions [9].

The NASA DOC test unit, a membrane-only wastewater treatment system, was recently refurbished and upgraded and was found to be capable of achieving high water recoveries (over 95%) with relatively low specific energy consumption (15–50 kWh/m^3), and with very minimal resupply [10]. In the DOC test unit (Fig. 1), two membrane contactors are used for the pretreatment of two streams of wastewater before treatment with RO. The stream of hygiene wastewater mixed with humidity condensate (greater than 80% of the total wastewater) is pretreated by direct osmosis (DO) in DOC#1; the stream of concentrated wastewater from DOC#1 is mixed with urine (less than 20% of the total wastewater) and is treated with a unique dual membrane process involving DO and osmotic distillation (OD) (dual DO/OD) in DOC#2. An RO subsystem is then used to produce two liquid streams: highly purified water and a concentrated osmotic agent (OA) for repeated use in extraction of water from the wastewater in the DO and DO/OD membrane contactors.

1.1.1. Direct osmosis

DO (or osmosis or forward osmosis) is the diffusion of water through a semi-permeable membrane from a stream of higher water concentration to a stream of OA [11]. When used with an appropriate semi-permeable membrane, DO can efficiently treat liquids with high concentrations of dissolved organic matter and suspended solids, including leachates, greywater, foods, and beverages [12–15]. DO requires low operating pressures (less than 170 kPa (10 psig)), and therefore, membrane support, membrane compaction, and pressure-driven membrane fouling are not of significant concern.

1.1.2. Osmotic distillation

OD is an evaporative membrane contactor process that involves the contact of two streams of liquid with a hydrophobic microporous membrane. As in DO, the driving force for mass transport is the concentration difference across the membrane. However, in OD, the concentration difference results in a vapor pressure gradient across the membrane. OD is most suitable for concentrating aqueous solutions containing non-volatile solutes. The primary advantage of OD is its ability to concentrate solutes to very high levels at low temperature and pressure. The capability of OD to reject urea (a molecule with a low vapor pressure that is a major constituent of urine) makes it more applicable than either RO or DO to wastewater reclamation for potable reuse. Additionally, in special cases (e.g., in the DOC system), when the OA is an available stream from another process, OD may be a cost effective separation process.

Yet, it should be noted that the concentration driving force in OD is much weaker than the concentration driving force in DO because OD involves evaporation and vapor diffusion steps that are heat and mass transport limited, respectively. Despite being an isothermal process, heat in OD is transported with the vapors across the membrane—requiring

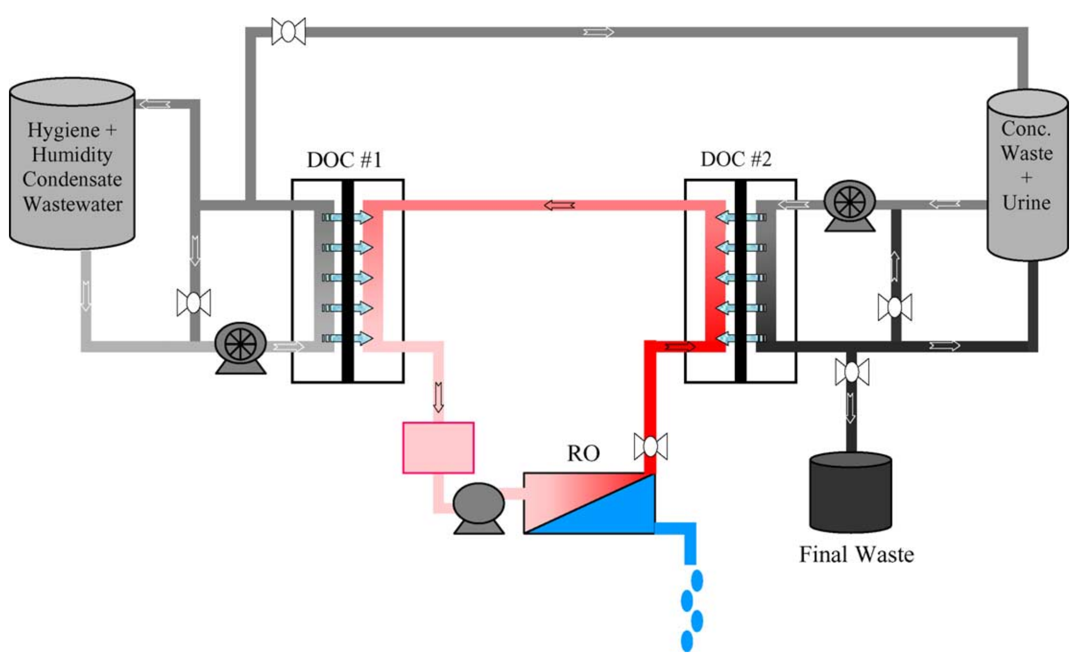

Fig. 1. Flow diagram of the NASA DOC wastewater treatment process.

continuous resupply of heat to the feed–membrane interface. But because of being isothermal and because of the slow mass transport across the membrane, little exchange of heat occurs in the system and the temperature change on the feed side is negligible—requiring a very slow resupply of heat to the membrane interface. Furthermore, even at relatively high concentrations, salt only minimally reduces the vapor pressure of water in the OA solution—making OD a very slow process.

1.2. The dual DO/OD process

In the dual DO/OD membrane contactor (Fig. 2), two membranes, one semi-permeable and one microporous, are laid on each other. The active layer of the semi-permeable membrane faces the wastewater stream and the support side of the microporous membrane faces the OA. Mass transport is carried out in three steps: water diffuses from the wastewater stream through the semi-permeable membrane, evaporates through the hydrophobic microporous membrane, and then condenses in the OA. The driving forces throughout the process are the osmotic pressure and partial vapor pressure gradients across the two membranes. These are induced by the concentration difference between the feed wastewater and the OA. The dual process aims to overcome the drawbacks of the individual processes and to enhance their advantages. For example, OD can reject urea (a major constituent in urine) but DO, like RO, cannot; DO can reject surfactants but OD fails in their presence [16]. However, in the current design of DOC#2, the slow mass transport of the OD process prevents the full treatment of the daily volume of wastewater generated in a future mission scenario.

A thorough investigation of mass and heat transfer in the dual DO/OD process was previously conducted on the NASA DOC test unit [10]. Problems encountered included membrane flooding, leakage across the membranes and outside of the module, and insufficient membrane support. While these problems were relatively simple to overcome, the most critical shortcoming was low mass transport across the two membranes in DOC#2. In order to demonstrate this, results from a previous investigation [10] are shown in Fig. 3. The feed stream was triply concentrated synthetic wastewater at 20 °C and flowing at 0.6 l/min. The OA concentration was varied from 60 to 100 g/l NaCl. Results indicate that fluxes are very low and that with 1.3 m^2 of membrane surface area in DOC#2, treatment of 18 l/day is not feasible.

Furthermore, the flux is very sensitive to OA concentration—decreasing with decreasing OA concentration. Because it is desired that the DOC process be operated at the lowest OA concentration possible (e.g., 40–60 g/l NaCl) for economic and operational reasons [10], it is apparent that the DO/OD process must be improved or replaced.

1.3. Enhancement of the dual DO/OD process

The current DOC#2 membrane contactor is a plate-and-frame module designed to hold four plates with eight pairs of membranes having a total surface area of approximately 1.3 m^2. The flow pattern in DOC#2 is illustrated in Fig. 4. The OA is flowing upward inside the plates (designated by the thin diagonal arrows) and the wastewater is flowing in the space formed by the gaskets (designated by the thick vertical arrows). The wastewater changes flow direction between neighboring plates. Two pairs of membranes are installed between every two plates. Each plate has one transferring slot cut at one end to allow wastewater to flow into the next channel between the neighboring plates.

To increase mass transfer in DOC#2, two process modifications are being considered. The first option is to increase the surface area of membranes in DOC#2 by adding more plates and membranes to the plate-and-frame module. This solution is less favorable because it requires redesign of the module, resizing of the pumps, and rebuild of the RO subsystem. It would also increase the system weight. The second option is to increase the flux in DOC#2 by incorporating membrane distillation (MD) concepts. This solution only requires the installation of a heat exchanger and a source of cooling or heating.

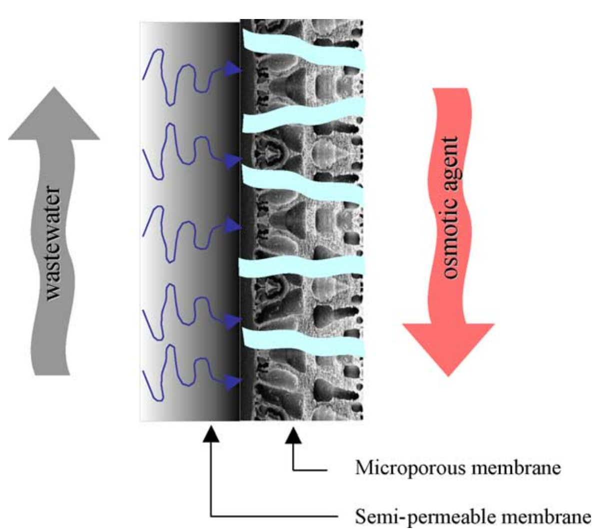

Fig. 2. Mass transport in the dual DO/OD membrane process in DOC#2.

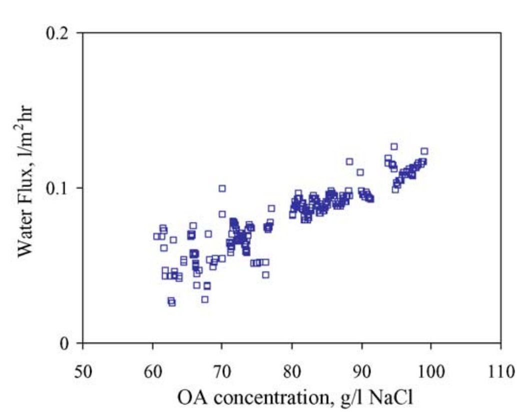

Fig. 3. Flux vs. OA concentration in the dual DO/OD process.

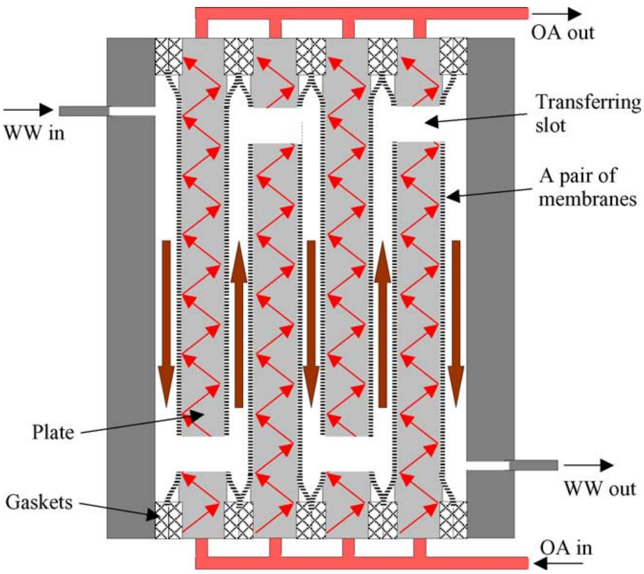

Fig. 4. Cross-section of the DOC#2 plate-and-frame design.

MD is a low-temperature distillation process that takes place through the pores of a microporous membrane. In MD, the temperature gradient, rather than the concentration gradient, is the source of the vapor pressure gradient driving force for separation. MD, like OD, depends on dry pores to allow for evaporation and transport of vapors (only) across a microporous membrane. MD can be incorporated in DOC#2 by either increasing the feed temperature or decreasing the OA temperature. Because heat is continuously generated in the DOC system by pumps and pipe friction, it is preferable to chill the permeate (OA) stream rather than heat the feed wastewater stream. Two MD-enhanced configurations are being evaluated, DO/MD and DO/membrane osmotic distillation (DO/MOD).

The three dual membrane processes being evaluated in this investigation are shown in Fig. 5. The DO/OD process (Fig. 5a) is isothermal and the only driving force stems from the concentration gradient across the two membranes. In the DO/MD configuration (Fig. 5b) the permeate stream is cold water with negligible solute concentration. The driving force for mass transport is the vapor pressure gradient across the membranes, which originates from the temperature gradient. In this configuration the concentration driving force (due to the presence of solutes in the wastewater) opposes the temperature driving force. But because the temperature driving force is much stronger than the concentration driving force, this opposition slightly reduces the flux but does not stop the process. In order to reverse the concentration gradient and create a concentration driving force, the permeate stream could be switched from ultrapure water to an OA. The result is a process that will be referred to as MOD. The DO/MOD process is shown in Fig. 5c. The concentration and temperature driving forces are shown to operate in the same direction.

MOD is a process that has not been studied much; only two previous investigations on MOD could be found in the literature. Wang et al. [17,18] investigated mass and heat transfer in MOD and, when compared with MD, found MOD to not only have higher mass transport of vapors but also improved heat transfer efficiency (defined as the ratio between heat of evaporation and total heat transfer). In that regard, combining MOD with DO has the additional benefit of using MOD for separation of complex feed solutions (e.g., solutions containing surfactants) that otherwise could not be separated with either OD, MD, or MOD alone.

1.4. Objectives

The main goal of the current investigation is to evaluate the feasibility of incorporating MD concepts into the DOC#2 membrane contactor and to study the impact on water flux and process integrity. The effects of transmembrane temperature, OA composition, and wastewater chemistry on water flux and solute rejection (with emphasis on urea), will be evaluated for several potential membranes in three operating modes: DO/OD, DO/MD and DO/MOD. Long-term membrane and process integrity will be monitored and evaluated. It is expected that a very small temperature difference across the two membranes will provide enough flux enhancement to enable DOC#2 to treat the daily volume of wastewater

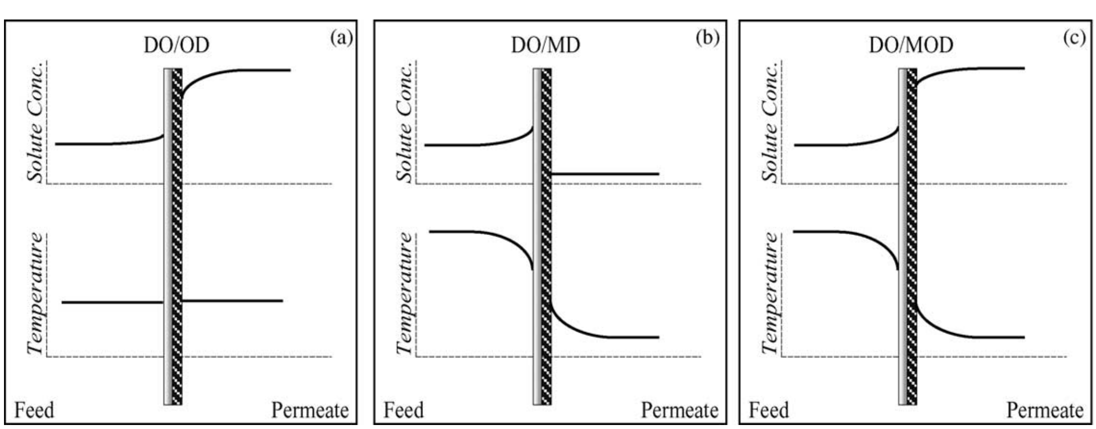

Fig. 5. Concentration and temperature profiles in (a) DO/OD, (b) DO/MD, and (c) DO/MOD.

generated in a space mission scenario. Results will confirm whether the MD-enhanced processes are viable for treatment of complex feed solutions that cannot be treated by the individual processes (i.e., DO, MD, or OD) alone. Results will also provide information to assist with the redesign of critical components in the NASA DOC test unit.

2. Materials and methods

2.1. Membranes

A cellulose triacetate (CTA) semi-permeable membrane was used for the DO process in all dual membrane configurations. The CTA membrane was acquired from Osmotek Inc. and has been found to be very efficient in flux and solute rejection for the DO process [10]. The original microporous membrane for the OD process in DOC#2 was a water-repelling fabric (Ultrex–Supplex, Burlington Industries, Greensboro, NC). Results from membrane analysis [10] indicated that the properties of this material were not the most suitable for OD. The optimal OD membrane would be a thin membrane with high porosity and uniform pores with a nominal pore size of 0.2–0.5 μm. Both sides of the membrane would also be strongly hydrophobic with a contact angle greater than 100°. The Ultrex–Supplex membrane had very low porosity, pores exceeding 1 μm in diameter, and a contact angle of 95°. Also, the support material was easily wetted. In terms of performance, bench-scale test results revealed that, when combined with the CTA membrane in the dual DO/OD configuration, the material was easily flooded and the separation process failed [10].

Among the hydrophobic microporous membranes that were tested to replace the original membrane, a composite polytetrafluoroethylene (PTFE) membrane (TefSep 0.22 μm (TS22)) (GE Osmonics, Minnetonka, MN) was the most promising [10]. It provided high urea rejection and a relatively high flux in both OD and DO/OD modes. However, the TS22 membrane is a very delicate membrane, and integrity problems (mainly delamination) were often observed in the dual DO/OD process.

Among other microporous membranes, the most structurally suitable membrane was the PolySep 0.22 μm (PP22) membrane, also acquired from GE Osmonics. The PP22 is a symmetric, isotropic membrane made from polypropylene. It has a nominal pore size of 0.22 μm, a porosity of approximately 70%, and a thickness of 150 μm. The PP22 membrane has been observed to have high mechanical strength and durability, and in term of performance, it showed high urea rejection but very low vapor flux in OD and DO/OD modes [10]. Also, it should be noted that the PP22 membrane has been tested in a membrane distillation (MD) study [19] and showed high water flux (i.e., 3–28 l/m^2 h for temperature differences of 10–40 °C, respectively) and more than 99.8% salt rejection.

2.2. Solution chemistries

Three wastewater simulants, corresponding to the main sources of wastewater on board a spacecraft, were used in this study. These include hygiene wastewater, humidity condensate, and urine. The average daily volume of wastewater generated in a space mission for DOC#2 to treat is approximately 18 l. The chemical compositions of the synthetic hygiene wastewater and humidity condensate are presented in Table 1 [20]. In all experiments involving feed wastewater, triply concentrated synthetic wastewater was used. This concentration represents the average wastewater concentration transferred from the DOC#1 subsystem to the dual membrane process in DOC#2. The DOC#2 contactor was specifically designed to treat wastewater containing urea and therefore, ACS grade urea (Fisher Scientific, Pittsburgh, PA) was used as the urine simulant in the current study. DO/MD was performed with ultrapure water recirculated on the permeate side and DO/OD and DO/MOD were performed with an ACS grade NaCl solution (Fisher Scientific).

2.3. Bench-scale test unit

Bench-scale tests of the three dual membrane configurations (i.e., DO/OD, DO/MD, and DO/MOD) were performed on a vertically-oriented, modified, acrylic SEPA-CF membrane cell (Osmonics, Minnetonka, MN) that utilizes a flat sheet membrane 139 cm^2 in surface area (Fig. 6). In the modified cell, the permeate stream (either OA or water) flows tangential to the membrane—similar to the feed stream. The feed and permeate streams were recirculated using two peristaltic pumps (Masterflex L/S, Cole-Parmer, Vernon Hills, IL), capable of delivering up to 1.0 l/min. Feed flow was adjusted to generate a cross flow velocity of 0.1 m/s. The temperature of the permeate stream was maintained at 20 ± 1 °C using a heat

Table 1
Synthetic wastewater components [20].

Wastewater component	Quantity
Hygiene wastewater	
NASA whole body shower soap (Ecolab Inc., St. Paul, MN)	1.2 g/l wastewater
Humidity condensate	0.618 ml/l wastewater
Ethanol	117.98 g/l
2-Propanol	31.87 g/l
1,2-Propanediol	65.04 g/l
Caprolactam	23.74 g/l
2-(2-Butoxyethoxy) ethanol	3.43 g/l
4-Ethylmorpholine	3.85 g/l
Methanol	6.82 g/l
Formaldehyde	14.02 g/l
Formic acid	19.95 g/l
Propionic acid	6.53 g/l
Zinc acetate dihydrate	39.96 g/l
Ammonium bicarbonate	29.87 g/l
Ammonium carbonate	29.37 g/l
Urine	
Urea	5 g/l wastewater

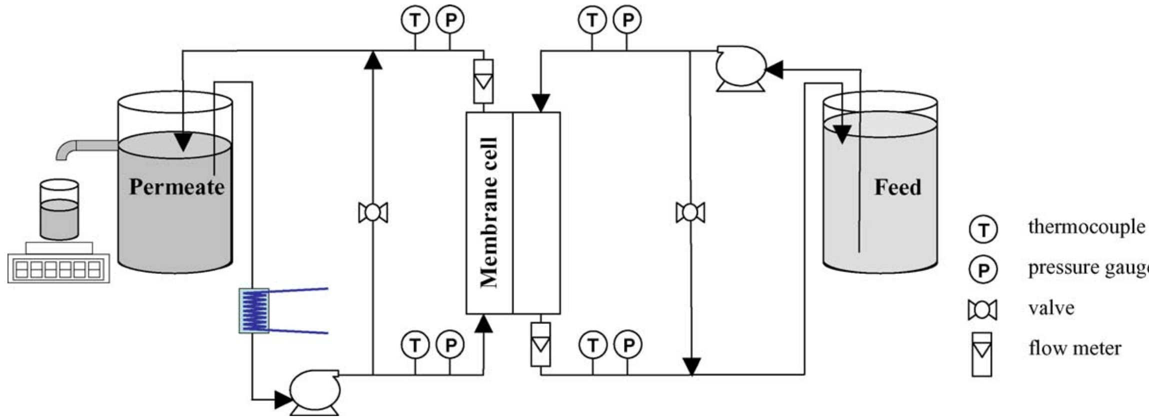

Fig. 6. Flow diagram of the bench-scale test unit.

exchanger fed by a water chiller (ISOTEMP 1023S, Fisher Scientific, Pittsburgh, PA). Temperature on the feed side was controlled by a hot bath (Model 284, Precision Scientific, Winchester, VA) in which the feed tank was immersed. The conductivity of the permeate stream was continuously monitored. Urea analysis was performed on the permeate stream at the end of each experiment. Water flux was calculated by measuring the change in the weight of water overflowing the permeate tank.

3. Results and discussion

3.1. DO/MD

Extrapolation on results from preliminary MD tests [19] (Fig. 7) indicated that approximately 4 °C temperature difference across the microporous membrane is required to generate flux on the order of 2 l/m^2 h. In the dual DO/MD configuration, the additional resistance to mass transfer generated by the semi-permeable membrane reduces the water flux to approximately 1 l/m^2 h. Also, results from the DOC test unit [10] indicated that the steady-state temperature of the DOC#2 feed wastewater is approximately 25 °C. Thus, in order to treat at least 18 l/day, the feed and OA temperatures in the bench-scale DO/MD configuration were selected to be 25 and 21 °C, respectively.

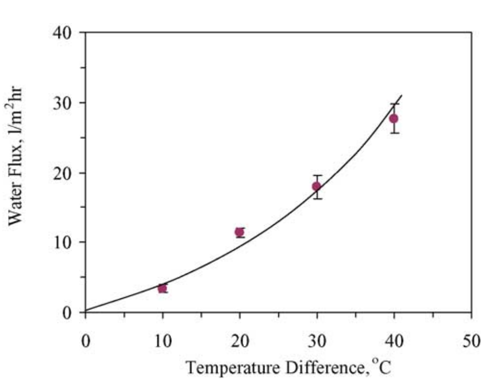

Fig. 7. Water flux as a function of temperature difference in MD with PP22 membrane.

DO/MD bench scale tests were performed on two feed wastewater streams: a solution of urea in deionized water and a triply concentrated synthetic wastewater. Deionized water was recirculated on the permeate side of the membranes. The flow velocity of both the feed and permeate streams was 0.1 m/s—similar to flows in DOC#2. Water fluxes as a function of time for the urea solution and the concentrated synthetic wastewater are shown in Fig. 8a and b, respectively. For both feed solutions, water flux is constant in time at approximately 0.8 l/m^2 h. This flux is 7–20 times higher than fluxes observed in the DO/OD process with 60–100 g/l NaCl in the OA (Fig. 3). Comparison between Fig. 8a and b reveals that flux of water through the pair of membranes essentially does not change when surfactants are present. It is also important to note that after the first 30 h, the concentrated synthetic wastewater was allowed to further concentrate. At the end of the experiment the feed wastewater was approximately 9 times concentrated, and still, no effect on flux was observed. No traces of urea or surfactant were detected in the permeate stream throughout the experiments.

Results in the DO/MD configuration at low temperature differences further confirm that flux in the dual membrane process is controlled by the resistance to mass transfer of vapors in the microporous membrane. Results from early study [10] have shown that under similar solution chemistry (both feed and OA concentrations) the resistance to mass transfer in DO, with the CTA membrane, is much lower than the resistance in OD. Therefore, even at high feed wastewater concentrations, which significantly impaired water flux in DO only, the resistance to mass transfer in DO/MD is still controlled by the evaporation through the microporous membrane—thus, increase in the resistance to mass transport through the semi-permeable membrane would only affect flux through this membrane and not the microporous membrane. The vapor pressure driving force, due to temperature gradient across the membranes, is therefore the main force that contributes to flux enhancement in the DO/MD configuration. Yet, it is not ignored that above a certain temperature difference the

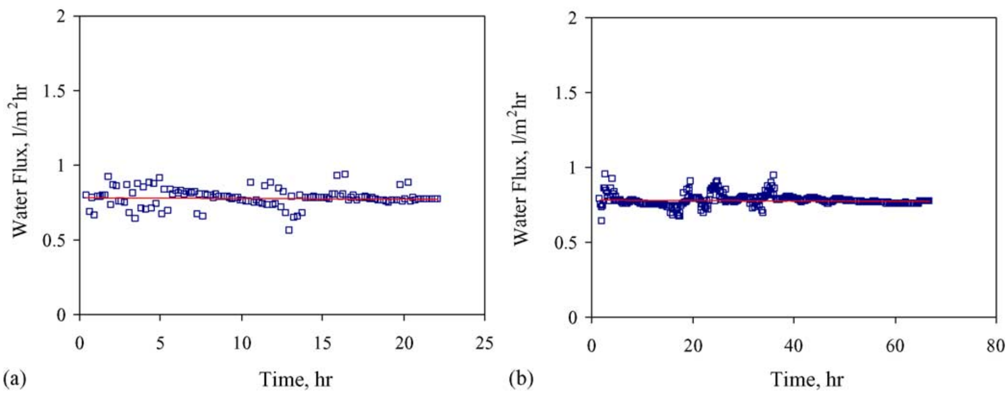

Fig. 8. Flux vs. time in the dual DO/MD process. For (a) urea solution feed and (b) concentrated synthetic feed.

semi-permeable membrane might become a limiting factor in mass transport of water across the two membranes—a trend that should be further investigated.

Compared to results with deionized feed water in MD mode only (at the same temperature difference) [19], flux was 30% lower in the presence of the CTA membrane. This is most likely due to an increase in thermal resistance across the membranes that makes temperature polarization in the DO/MD process more profound than in MD only and due to the reduced vapor pressure in the synthetic feed wastewater. Yet, the loss of flux due to the presence of a semi-permeable membrane is inevitable in the current application: in the absence of the CTA membrane, wastewater would flood the microporous membrane and the separation process would terminate.

Though the osmotic pressure driving force is absent in the DO/MD configuration, it is hypothesized that the mechanism of mass transport in DO/MD is similar to that in DO/OD. In both configurations, water evaporates through the microporous membrane and leaves the zone in between the membranes at low water concentration—generating a concentration driving force for water to diffuse through the semi-permeable membrane.

To evaluate the sensitivity of the MD-enhanced configurations to small temperature changes, the DO/MD configuration was tested for 15 days (350 h) without controlling the feed temperature—allowing it to adjust to ambient temperature in the laboratory. The temperature difference across the membrane varied between 3 and 5 °C, depending on the time of day. A repetitive pattern of flux increase and decrease was observed corresponding to the cyclic change of ambient temperature in the laboratory. Results confirm that flux is very sensitive to temperature gradient—almost doubling with a 2 °C increase in temperature difference across the membranes. Urea analysis on the permeate samples were below the detection level for the entire 15-day period. Fig. 9 is a magnification of the results on the 14th day. The 324th hour is noon time and the transmembrane temperature gradient is 2.8 °C. As time progresses, ΔT increases up to a maximum of 4 °C and flux increases until reaching a maximum just before midnight, when the ambient temperature in the laboratory reaches a maximum. From midnight, flux declines with decreasing ambient temperature. Though it is not expected that temperature changes will be significant in closed life-support systems, the results illustrate the significant effect of small temperature differences on flux in the dual membrane processes.

3.2. DO/MOD

The effect of OA concentration on water flux in the dual DO/MOD configuration is illustrated in Fig. 10. Feed and OA temperatures were set to 25 and 21 °C, respectively. The flow velocity of both the feed wastewater and OA was 0.1 m/s. The results are scattered due to the high sensitivity of the measuring procedure, however, results show very low dependence of flux on OA concentration in the tested range of 60–100 g/l NaCl. These results correspond to results obtained in DO/OD (Fig. 3) and OD only and they further reveal the weak vapor pressure driving force generated by the OA.

When comparing the results in Fig. 10 with those in Fig. 8, an average flux increase of 0.1–0.2 l/m^2 h can be observed. This is due to the concentration driving force that is added in the transition from DO/MD to DO/MOD. This difference corresponds to the flux in the DO/OD process when

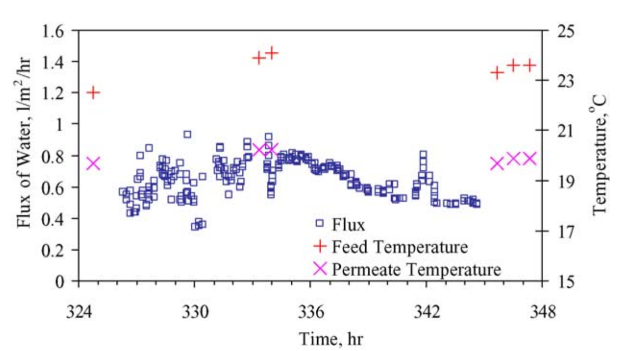

Fig. 9. A 24 h frame of bench-scale results in dual DO/MD membrane configuration.

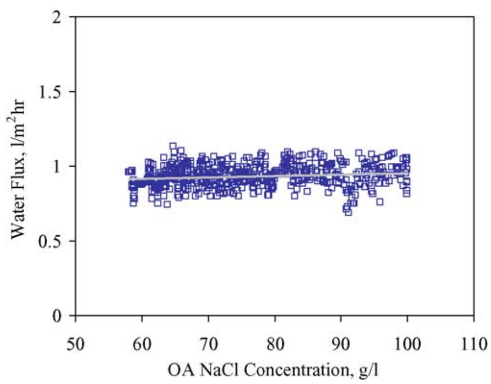

Fig. 10. Flux vs. OA concentration in the dual DO/MOD process.

the OA is 100 g/l NaCl (Fig. 3). Moreover, extrapolation on the very mild slope of flux versus OA concentration in the DO/MOD process (Fig. 10) predicts that at very low OA concentration (i.e., approaching DO/MD) water flux will approach 0.8 l/m^2 h. This flux is exactly the flux observed in the DO/MD experiments. When comparing the results in Fig. 10 with those in Fig. 3, flux in the DO/MOD process is 8–25 times higher than in the DO/OD process with only 4 °C difference across the two membranes. These results clearly show that the partial vapor pressure driving force in the OD process is much weaker and less efficient than the thermal driving force in MD. Urea analysis was performed on the OA at the end of the investigation. Concentrations were below detection limit—indicating 100% urea rejection.

3.3. Comparison of the three dual membrane processes

The dual membrane configuration in DOC#2 is essential to achieve separation of water from the complex wastewater in the DOC system. The initial design of the dual DO/OD process provided low water flux and suffered from acute membrane integrity setbacks. Compared to other microporous membranes, the PP22 membrane provided the necessary protection to the dual DO/OD process; however, it also provided low water flux. Incorporation of MD into the dual membrane process resulted in flux improvement in both configurations—DO/MD and DO/MOD. Both modifications provide enough flux to allow treatment of the daily load of wastewater in a long-term space mission scenario with the existing DOC#2 membrane contactor.

Although from the flux results it would appear that DO/MOD is preferable to DO/MD, using DO/MD in DOC#2 has the benefit of providing greater protection against surfactant contamination. If the OA in DO/OD or DO/MOD becomes contaminated with surfactant through a breach of integrity in any of the membranes, surfactants are most likely to become concentrated in the OA produced by the RO subsystem. This in turn will most certainly cause flooding of the microporous membrane in DOC#2 from its support side. If DO/MD is implemented, the water stream flowing on the permeate side of DOC#2 would be the product of some of the RO elements in the RO subsystem. This water would be free of surfactants and other contaminants.

To incorporate the new DO/MOD configuration in the NASA DOC test unit, modifications to the DOC#2 contactor and its hydraulic system will be required. These include increasing the RO concentrate flowrate through DOC#2 to overcome its heat exchanger characteristics and adding a heat exchanger to reduce the OA temperature prior to entering the contactor. If DO/MD is chosen as the alternative process for DOC#2, the RO subsystem will be utilized to produce an OA for DOC#1 and the product streams of the RO subsystem will be combined and rerouted to DOC#2. The rerouted streams will be chilled with a new heat exchanger—similar to the alternative DO/MOD configuration.

For both configurations, the RO subsystem will have to be retrofitted. The flowrates of both the RO permeate and concentrate (OA) streams will have to be increased to enhance the heat transfer efficiency in DOC#2. However, for DO/MD, only minor modifications of the RO flow capacities will be required because the combined permeate flowrate of the available RO elements is much higher than the flowrate of the currently generated OA.

From the energetic standpoint, cooling the permeate stream to create 4 °C temperature difference across the membranes in DOC#2 is much less energy intensive than utilizing high-pressure RO pumps (at 6–7 MPa) to generate a concentrated OA. In the current design of the DOC system, the OA is required to be very concentrated to provide the maximal driving force for mass transport in the DO/OD process in DOC#2. In the new configurations, the RO subsystem would be required to generate OA at much lower concentration (e.g., 40–60 g/l NaCl). Results in an early investigation [10] have shown that the DO process in DOC#1, with the CTA membrane, has a sufficient treatment capacity in these low OA concentrations. Moreover, if DO/MOD is implemented, the concentration driving force is not critical to achieve the required treatment capacity in DOC#2 and therefore, OA concentration is not a concern.

4. Conclusions

Dual DO/MD and DO/MOD processes were investigated to replace the DO/OD process for wastewater pretreatment and urea removal in the NASA DOC test unit. Both configurations were successful in achieving higher flux and complete urea rejection in bench-scale tests. Over a period of 15 days, the flux in DO/MD was 4–20 times greater than in the DO/OD process and urea was fully rejected. The flux was shown to increase with an increased temperature gradient and no sign of flux reduction due to fouling was observed. Having additional driving force, DO/MOD provided better flux enhancement; 8–25 times higher flux compared to the DO/OD process.

This investigation confirmed that MD and/or OD processes can be combined with DO in a dual membrane configuration to treat complex liquid streams that cannot be treated with either individual process. This is not only pertinent to NASA's DOC system but it also has implications for many terrestrial industrial and wastewater treatment applications, especially where MD or OD cannot be used alone due to the low surface tension of the feed solution or where RO or DO cannot be used alone due to the presence of small polar molecules that easily diffuse through semi-permeable membranes.

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