Design, Development, and Testing of a Water Vapor Exchanger for Spacecraft Life Support Systems

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Thermal and environmental control systems for future exploration spacecraft must meet challenging requirements for efficient operation and conservation of resources. Maximizing the use of regenerative systems and conserving water are critical considerations. This paper describes the design, development, and testing of an innovative water vapor exchanger (WVX) that can minimize the amount of water absorbed in, and vented from, regenerative CO_2 removal systems. Key design requirements for the WVX are high air flow capacity (suitable for a crew of six), very high water recovery, and very low pressure losses. We developed fabrication and assembly methods that enable high-efficiency mass transfer in a uniform and stable array of Nafion tubes. We also developed analysis and design methods to compute mass transfer and pressure losses. We built and tested subscale units sized for flow rates of 2 and 5 ft^3/min (3.4–8.5 m^3/hr). Durability testing demonstrated that a stable core geometry was sustained over many humid/dry cycles. Pressure losses were very low (< 0.5 in. H_2O (125 Pa) total) and met requirements at prototypical flow rates. We measured water recovery efficiency across a range of flow rates and humidity levels that simulate the range of possible cabin conditions. We measured water recovery efficiencies in the range of 80 to 90%, with the best efficiency at lower flow rates and higher cabin humidity levels. We compared performance of the WVX with similar units built using an unstructured Nafion tube bundle. The WVX achieves higher water recovery efficiency with nearly an order of magnitude lower pressure drop than unstructured tube bundles. These results show that the WVX provides uniform flow through flow channels for both the humid and dry streams and can meet requirements for service on future exploration spacecraft. The WVX technology will be best suited for long-duration exploration vehicles that require regenerative CO_2 removal systems while needing to conserve water.

Nomenclature

ECLSS	=	environmental control and life support system
F_1	=	convective mass transfer coefficient, stream 1 (kg/m²-s-Pa)
F_2	=	convective mass transfer coefficient, stream 2 (kg/m²-s-Pa)
h_1	=	convective heat transfer coefficient, stream 1 (W/m²-K)
h_2	=	convective heat transfer coefficient, stream 2 (W/m²-K)
k_{mem}	=	thermal conductivity of membrane (W/m-K)
LPCOR	=	low pressure CO_2 removal
M_a	=	molecular weight of air (28.97 kg/kmol)
M_w	=	molecular weight of water (18.015 kg/kmol)

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$m''_{conv,1}$ = convective mass flux, stream 1 (kg/m²-s)
$m''_{conv,2}$ = convective mass flux, stream 2 (kg/m²-s)
m''_{diff} = diffusive mass flux, through membrane (kg/m²-s)
$\dot{m}_{dry,out}$ = mass flow rate of air leaving the dry/tube side of the WVX (kg/s)
$\dot{m}_{humid,in}$ = mass flow rate of air entering the humid/shell side of the WVX (kg/s)
p_a = partial pressure of air (Pa)
$p_{sat,w}$ = saturation pressure of water (Pa)
p_{tot} = total pressure (Pa)
p_{wj} = water vapor pressure at point *j* (Pa)
p_{wi1} = water vapor pressure at membrane interface, stream 1 (Pa)
p_{wi2} = water vapor pressure at membrane interface, stream 2 (Pa)
RCA = rapid cycle amine
R_{m1} = convective mass transfer resistance, stream 1 (Pa-s-m²/kg)
R_{m2} = convective mass transfer resistance, stream 2 (Pa-s-m²/kg)
$Q''_{sens,1}$ = convective flux of sensible heat, stream 1 (W/m²)
$Q''_{sens,2}$ = convective flux of sensible heat, stream 2 (W/m²)
R_1 = convective heat transfer resistance, stream 1 (K-m²/W)
R_2 = convective heat transfer resistance, stream 2 (K-m²/W)
R_{mem} = thermal resistance of membrane (K-m²/W)
RH_i = relative humidity at point *i*
T_j = temperature at location *j* (K)
T_{i1} = temperature at membrane interface, stream 1 (K)
T_{i2} = temperature at membrane interface, stream 2 (K)
t_{mem} = membrane thickness (m)
W_i = absolute humidity level of the flow through port "i" (g H_2O / g dry gas)
WVX = water vapor exchanger

α_1 = activity of water on membrane surface, stream 1
α_2 = activity of water on membrane surface, stream 2
β = bypass fraction used to model a WVX core with non-uniform geometry
η = water recovery efficiency
η_{shell} = water recovery efficiency calculated based on shell-side exit conditions
η_{tube} = water recovery efficiency calculated from tube-side exit conditions
σ_{mem} = membrane diffusion coefficient (m²/s)

I. Introduction

Thermal and environmental control systems for future exploration spacecraft must meet challenging requirements for efficient operation and conservation of resources. Regenerative CO_2 removal systems such as the amine swing bed technology planned for use in Orion are attractive for these spacecraft because they do not use consumable CO_2 absorbers. However, these systems also vent water to space along with the carbon dioxide, which can be very costly for long-duration missions. Use of conventional condensing heat exchangers alone to conserve water is also not feasible, since to save most of the water they would need to operate below 0°C and would add a significant challenge to a spacecraft's thermal control system to achieve such a low set point. We propose to develop an innovative water vapor exchanger (WVX) that minimizes water loss without placing additional demands on the thermal control system (Figure 1). This design uses highly water-permeable membranes in a compact, microtube core that enables high water recovery efficiency with very low pressure drop and no need for external cooling. The microtube WVX addresses the need for water conservation in long-duration missions, reduces the need for consumables by enabling use of state-of-the-art regenerative CO_2 removal systems, and minimizes demands on the spacecraft thermal control system. The innovative microtube core design is a highly uniform array of Nafion tubes (Figure 2). The unique design enables higher water-transfer effectiveness and lower pressure losses than conventional hollow fiber gas dryers. For a spacecraft with a crew of six, the WVX can save over 23 lb_m of water per day.

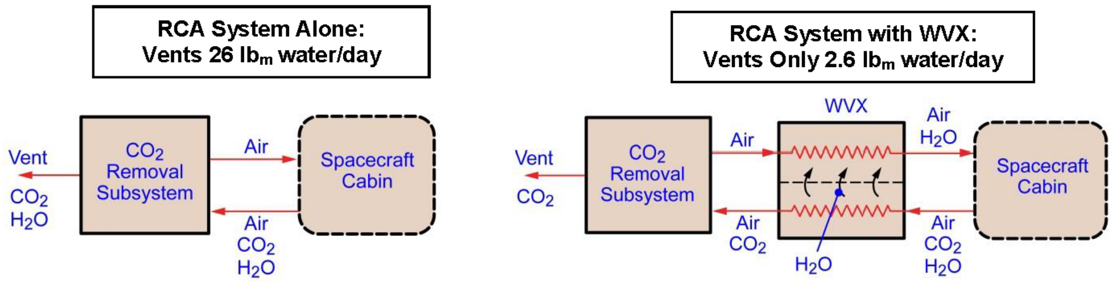


Figure 1. Water Vapor Exchanger for water conservation without additional spacecraft heat rejection. *The compact microchannel membrane WVX prevents nearly all the water vapor in the cabin air from reaching the CO_2 absorber without the need for low-temperature cooling. For a spacecraft with a crew of six, the WVX will save over 23 lb_m of water per day.*

An earlier paper[1] describes proof-of-concept tests, trade-off studies, and a prototype conceptual design that showed the feasibility of achieving high water recovery efficiency using a Nafion tube array. This paper discusses design and fabrication of the WVX prototypes, separate effects tests that demonstrated durability of the core under conditions that simulate operation in a spacecraft life support system, performance testing and results in open-loop water recovery tests, comparisons of the WVX technology with commercial, unstructured tube bundles, and an assessment of the technology for use in future exploration spacecraft. A separate paper[2] discusses demonstration of the WVX in a solid amine bed test loop.

(a) Conventional Nafion Air Dryer

(b) Uniform Nafion Tube Array in Creare WVX

Figure 2. Innovative mechanical design produces a highly uniform array of Nafion tubes that form the core of the Water Vapor Exchanger. *Photo shows a single module from the prototype WVX.*

II. Background

Environmental and Thermal Control for Future Exploration Spacecraft. The spacecraft life support system must control CO_2 concentration and maintain a comfortable and safe level of relative humidity in the cabin. Typical missions may call for up to six crew members, with mission durations that could be months long. Table 1 shows the rates of CO_2 and H_2O production by a crew of six that must be controlled by the spacecraft's ECLSS.[3] The average load for a crew this size is roughly 0.6 lb_m/hr CO_2 and 1.1 lb_m/hr water.

Conventional CO_2 control methods are based on absorption in LiOH or zeolite compounds, and water vapor has typically been collected by condensing heat exchangers. However, these CO_2 absorbers are large and heavy, and condensing heat exchangers require a low-temperature cooling system with high capacity. These characteristics are not attractive for exploration spacecraft.

Table 1. Metabolic production rates for crew of six.

	g/min	lb_m/hr
CO_2	3.8–5.3	0.5–0.7
H_2O	7.6–9.1	1.0–1.2

To overcome these limitations, NASA and its contractors have worked for many years to develop improved techniques for CO_2 and humidity control. UTC Aerospace Systems has developed an amine-based, pressure-swing absorption system for CO_2 removal that has many attractive characteristics. The amine absorbs CO_2 from cabin air, then vents CO_2 to space when exposed to vacuum. The basic technology for a Regenerative CO_2 Removal System was flight tested on the space shuttle in the early 1990s. The sorbent system has evolved since then and is now known as SA9T, which comprises plastic beads coated with amine and packed into a porous metal foam. The system is assembled from multiple beds, with absorbing beds interleaved with desorbing beds. In this way the heat generated by CO_2 and water absorption in one set of beds can maintain the temperature of the desorbing beds and the system does not need external heating or cooling. The system, now known as the CO_2 And Moisture Removal Amine Swingbed (CAMRAS), was selected as the baseline primary CO_2 and H_2O vapor removal device for the Orion spacecraft.[4]

The amine used in SA9T is also a very strong absorber of water vapor and will effectively dehumidify the spacecraft cabin. This characteristic is attractive for short-duration missions where water lost to space is not a concern, since the absorbed water vents to space along with the CO_2. However, long-duration exploration missions cannot afford to vent 25 lb_m of water overboard every day. A practical CO_2 removal system for long-duration space flight must conserve water.

CO_2 Removal and Water Conservation Effects on Thermal Control. The International Space Station uses a condensing heat exchanger (CHX) to remove moisture from the cabin air. Cooling water chills the HX surface to the desired dew point for the cabin air, which condenses to liquid phase and flows into a condensate collection system. This approach could be used to remove moisture from the cabin ventilation stream before it reaches the RCA unit, similar to the schematic shown in Figure 1. However, condensing the moisture from the cabin air to prevent absorption in the RCA beds would be very costly. Typical design conditions for a spacecraft call for a cabin dew point of 7.5°C, which is comfortable for the crew and prevents condensation on cooling lines. A dew point of 7.5°C corresponds to a water vapor pressure of 1.037 kPa. To prevent 90% of the cabin water vapor from entering the RCA beds, the water vapor pressure must be reduced to 0.1037 kPa, which is below the triple point of water. A conventional CHX cannot operate under these conditions, since the water must be frozen to achieve these low vapor pressures. Furthermore, cooling the gas stream to ~0°C will require the thermal management system to provide substantial refrigeration. Condensation and freezing of 9 g/min (Table 1) would require roughly 50 W of cooling at sub-freezing temperatures in a complex condensing/freezing heat exchanger.

The Amine Swingbed Payload Demonstrator on the International Space Station (ISS) uses a desiccant wheel to reduce water loss.[5] The desiccant wheel provides a function similar to the WVX, but requires more elaborate thermal control because absorption of water vapor in the desiccant releases heat, and proper operation relies on controlling the absorption isotherms in the absorbing and desorbing sections of the wheel. The desiccant wheel therefore uses two non-condensing heat exchangers to cool air before it enters the swingbed, plus an electric heater block at the inlet to the regenerating side of the desiccant wheel to heat the dry air so it will absorb water on the way back to the cabin.

Development of the membrane WVX is motivated by the need to develop a technology for water conservation that enables use of state-of-the-art CO_2 removal technologies without adding large loads to the thermal management system.

III. Design and Fabrication of High-Efficiency Nafion Tube Arrays

Creare's membrane water vapor exchanger (WVX) will prevent most of the water in the cabin air from reaching the CO_2 removal beds and requires no additional thermal control. The unique design of the WVX core enables small size, light weight, and low pressure losses.

Principle of Operation. The core of the membrane WVX is an array of water-permeable microtubes arranged in a counterflow, shell-and-tube configuration (Figure 3). An array of tubes made from water-permeable membranes is contained in a flow housing, or "shell." For the WVX, humid ventilation gas from the cabin enters the shell side, flows through the space outside the tubes from left to right in the figure, and then exits the shell. Dry gas from the amine beds enters the header on the right and then flows right to left through the tubes. The streams transfer water vapor through the tube walls, so the dry gas becomes increasingly more humid as it nears the tube exits. The humidified gas then flows into the exit header, then exhausts into the cabin.

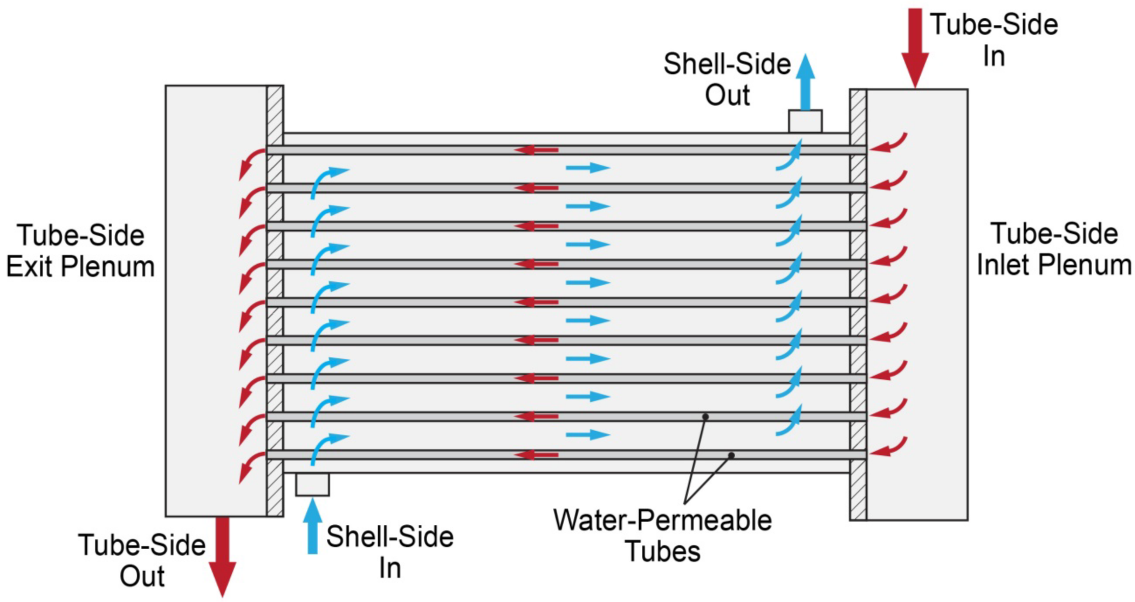
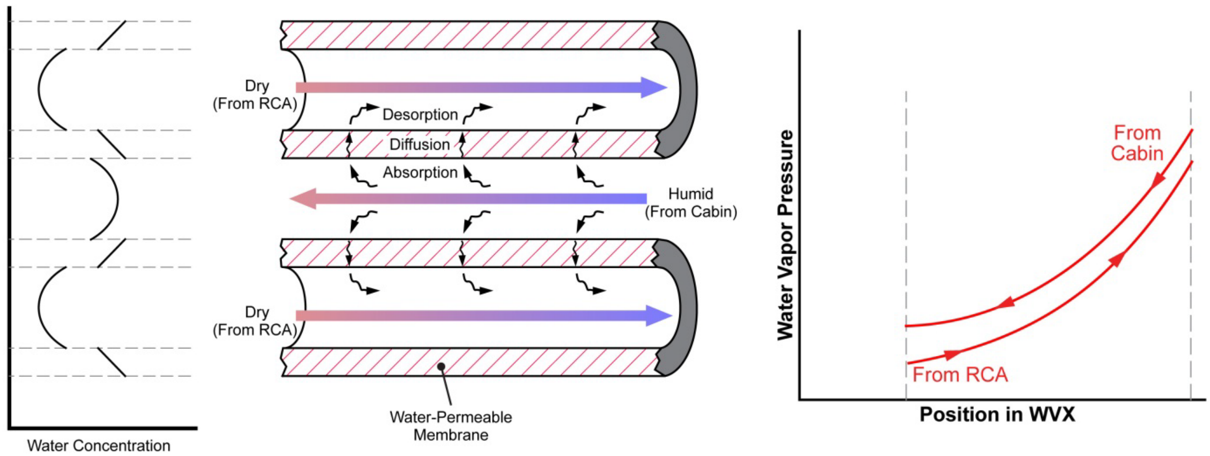


Figure 3. Basic WVX configuration.

Figure 4a illustrates the water transfer process. Water diffuses through the tube walls from the humid to the dry stream. Water transfer is driven by the chemical potential gradient that arises due to the difference in water vapor pressure. Water vapor transfer through a solid membrane has three steps: (1) Water from the humid stream is absorbed into the membrane. The membrane surface equilibrates with the local vapor concentration according to Henry's Law or other empirical relations developed for specific materials. (2) The absorbed water diffuses from the humid to the dry side of the membrane. This process is typically modeled using Fick's Law with a diffusion coefficient that depends on the water concentration. (3) Water from the dry side of the membrane desorbs and enters the dry stream. As on the humid side, the membrane surface equilibrates with the local vapor concentration. The net result is a continuous transport of water from the humid to the dry stream. Typically the membrane resistance controls the overall rate of mass transfer, and it is important to select a membrane with maximum water permeability. Our previous testing has shown that Nafion membranes are highly water-permeable and result in the most compact WVX core.



(a) Water Vapor Transfer from Humid to Dry Streams

(b) Overall Water Vapor Pressure Profiles

Figure 4. Water vapor transport in the WVX core.

Figure 4b illustrates the overall end-to-end profile of water vapor concentration in the exchanger. As long as the resistances to mass transfer are small and the surface area for mass transfer is large enough, the water vapor pressures in the humid and dry streams will be close. As a result, most of the water will leave the humid stream before it exits the exchanger, minimizing the amount that will be absorbed in the RCA bed. The dry stream absorbs most of the water and reenters the cabin with nearly the same humidity level as the incoming ventilation stream. Therefore a water vapor exchanger that functions as intended will necessarily operate with small concentration differences between the two streams. To minimize the size of the unit under these conditions, it is important to minimize the mass transfer resistance. Our design incorporates small-diameter Nafion tubes that provide a small convective mass transfer resistance in the flow streams themselves and enables a very high membrane surface-area density for a compact core. Small channel size also results in laminar gas flow through the core, resulting in the minimum pressure drop per unit mass transfer.[6]

Design Methods. We designed the Phase II prototype WVX using an analysis model that accounts for mass, momentum, and heat transfer in the WVX core. These models agree well with earlier data and have been further validated by comparison with results from tests of the prototype reported later in this paper (Section V). The analysis model for mass and heat transfer is a 1-D numerical model that uses a finite control volume method to calculate heat and mass transfer in the exchanger. Figure 5 illustrates the phenomenological models used to compute water vapor and heat transfer in each finite volume element, which is an axial section of the core that includes shell side flow, the water-permeable membrane, and the tube side flow. The mass transfer calculation is illustrated schematically on the left-hand side of Figure 5, and the heat transfer calculation is illustrated on the right. Each path has three resistances in series: convection in the humid stream, diffusion or heat conduction across the membrane, and convection in the dry stream. The water concentration on the membrane surfaces are assumed to equilibrate with the wall concentration of the flowing vapor, which is computed based on the convective mass transfer coefficient and an equilibrium concentration relationship for Nafion and humid air by Motupally.[7] Diffusion through the Nafion membrane is computed using Fick's law and a concentration-dependent diffusion coefficient computed using methods also described by Motupally. Heat transfer is computed using standard relationships for convection in the flowing gas and heat conduction through the membrane.

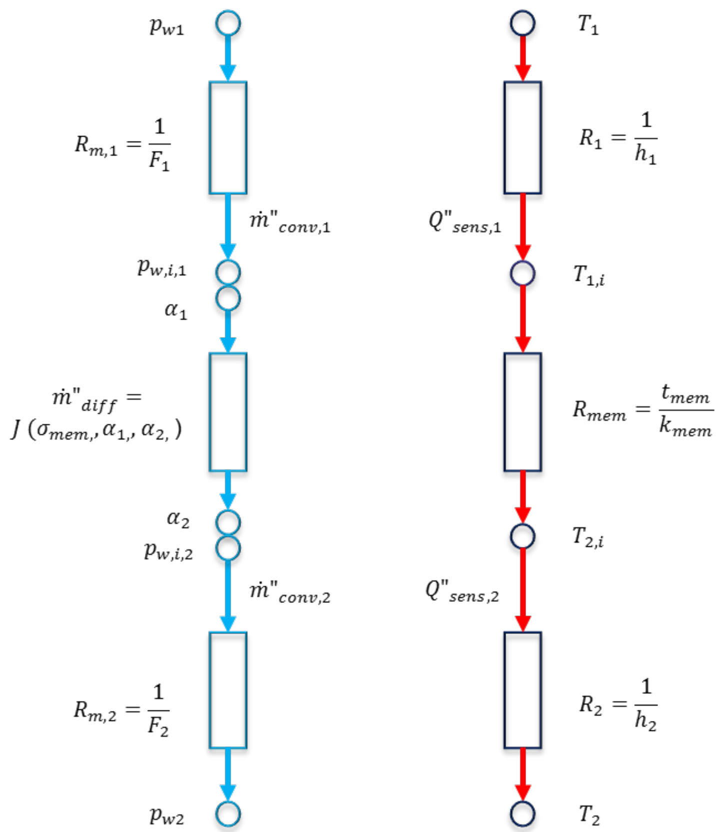


Figure 5. Elements of design model for the WVX.

Core Design and Assembly. The main challenge to overcome in designing a high-efficiency WVX using Nafion membranes is the very large dimensional change (10 to 13%) of the membranes in response to varying water content. High efficiency demands a highly uniform array of tubes in the WVX core, but these large changes in tube length make it impossible to maintain a uniform tube array in a conventional shell-and-tube design. The WVX overcomes this difficulty by ensuring that all the Nafion tubes are held in tension under all operating conditions.

Figure 6 illustrates key elements of the WVX. The left-hand photo shows the core assembled with inlet and exit headers, and the right-hand photo shows the core alone. The WVX core comprises ten modules (stacked vertically in the right-hand photo) that are assembled using metal frames, O-ring seals, and mechanical fasteners. Side walls are made from polycarbonate, providing a view of the Nafion tube array. The central eight inches of the core is the active water transfer region. The tube side inlet and exit plena distribute the tube side flow across the Nafion tube array and provide space for the Nafion tensioning elements.

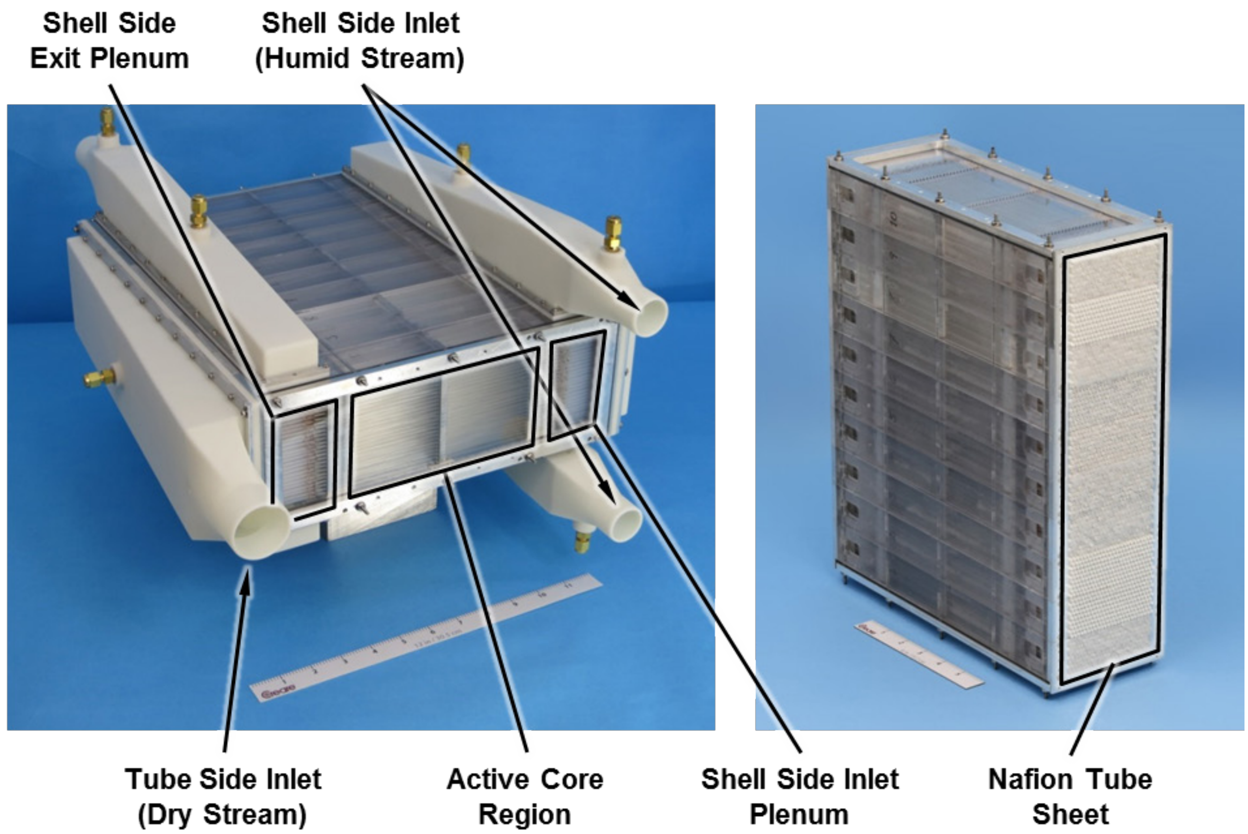


Figure 6. Key features of the WVX.

IV. Humidity Cycling Tests

We demonstrated that the WVX design maintains a uniform array of tubes by cycling a single module repeatedly from low to high relative humidity and back. This process cycled the length of the Nafion tubes and repeatedly loaded and unloaded the critical Nafion tube connections. To perform this test we placed the module in a test chamber with flowing air at a controllable relative humidity. We cycled the relative humidity from low (RH < 10%) to high (RH > 60%) and back 20 times over a one-month period. We observed no joint failures during the test and this module was subsequently used in the ten-module WVX assembly with verified low leakage.

Figure 7 shows the WVX module in the test chamber with dry air (4% RH) and 70% RH air. This figure shows that the core geometry remains uniform over this wide range of conditions and corresponding Nafion tube lengths. Although the polycarbonate walls of the module make it difficult to obtain very clear images of the tube array, it is clearly much more uniform under all conditions than a typical, unstructured tube bundle (see Figure 2).

Additional separate-effects tests measured the effects of trace quantities of ammonia on water permeability. These results are reported in a companion paper (ICES-2016-228).

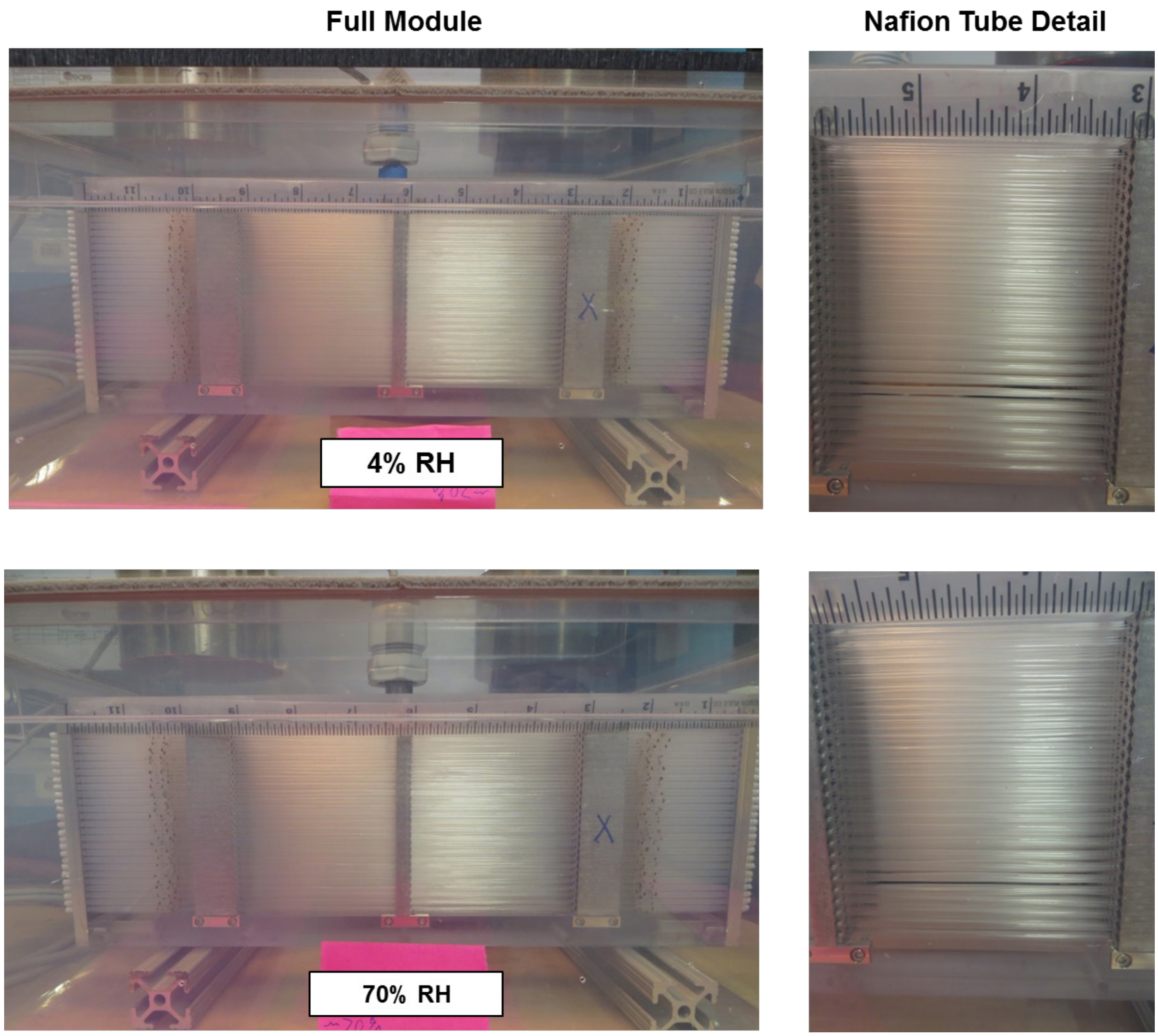


Figure 7. 225-tube WVX module in the variable humidity test chamber at 4% RH (top) and 70% RH (bottom). *The core geometry remains uniform over this range of conditions (compare with conventional Nafion tube bundle shown in Figure 2).*

V. Performance Demonstrations

Detailed performance measurements were made in Creare's laboratories using a once-through test setup. Each side of the WVX was supplied with a separate stream of conditioned air that simulated the ventilation streams in a spacecraft life support system. We first measured the performance of a four-module WVX, followed by the complete ten-module prototype. We found that both units achieve very high water transfer efficiency (85 to 90%) with very low pressure losses (< 0.5 in. H_2O (125 Pa) total under nominal operating conditions). This performance agreed well with the predictions of our design models. A companion paper[2] presents data from tests of the WVX in conjunction with an amine bed, with very similar results.

A. Water Vapor Transfer Efficiency

We measured the water recovery performance of the WVX across a range of flow and RH conditions (Table 2). All tests were conducted at normal ambient temperature (20 to 22°C). RH test points were selected to span the range of relative humidity values expected in a spacecraft cabin based on the ISS atmosphere temperature/humidity envelope. We tested at three flow rates: nominal (5 std ft^3/min = 170 g/min), 50% of nominal, and 150% of nominal.

The inlet RH ranged up to 70%. The nominal flow rate is based on projected flows through an amine-bed CO_2 removal system sized for a single crew member. Note that the amine bed flow loop is expected to operate in parallel with the spacecraft main ventilation loop, and the flow rate through the amine bed is much lower than the overall ventilation flow rate.

Table 2. WVX test matrix.

	Vary Inlet RH% Tests		**Vary Flow Rate Tests**	
	4-Module WVX	**10-Module WVX**	**4-Module WVX**	**10-Module WVX**
Mass Flow (g/min)	68	170	34, 68, 102	85, 170, 255
Inlet RH	30%, 50%, 70%	30%, 50%, 60–70%	50%, 70%	50%, 60–70%
Air Temperature (°C)	Ambient (20–22°C)	Ambient (20–22°C)	Ambient (20–22°C)	Ambient (20–22°C)

Figure 8 shows the WVX during water transfer tests, and Figure 9 shows the once-through test setup. Separate air streams were used for the shell and tube sides. Both streams came from Creare's laboratory compressor, which provides essentially dry air (dew point < 35°C). The shell side (humid) stream is conditioned by passing part of the flow through a humidifier, then recombining the humid stream with the rest of the flow. The tube side (dry) stream comes directly from the compressor. We measure temperature and relative humidity of both the shell and tube side streams before they enter the WVX. All flow rates are measured using calibrated orifices. Pressure drops are measured from locations just upstream of the inlet plena and just downstream of the exit plena. Table 3 lists the instrumentation used in the once-through tests along with the expected accuracy.

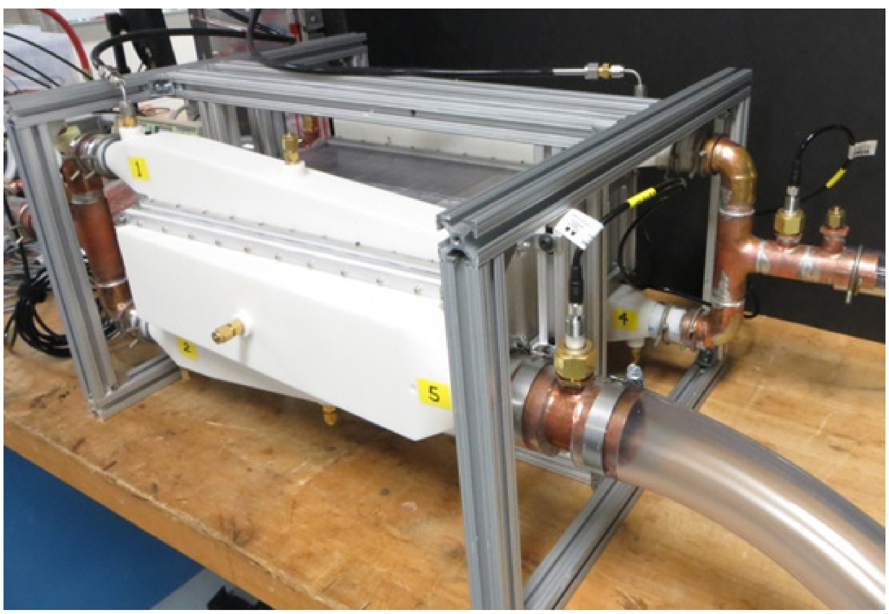


Figure 8. WVX during water transfer testing.

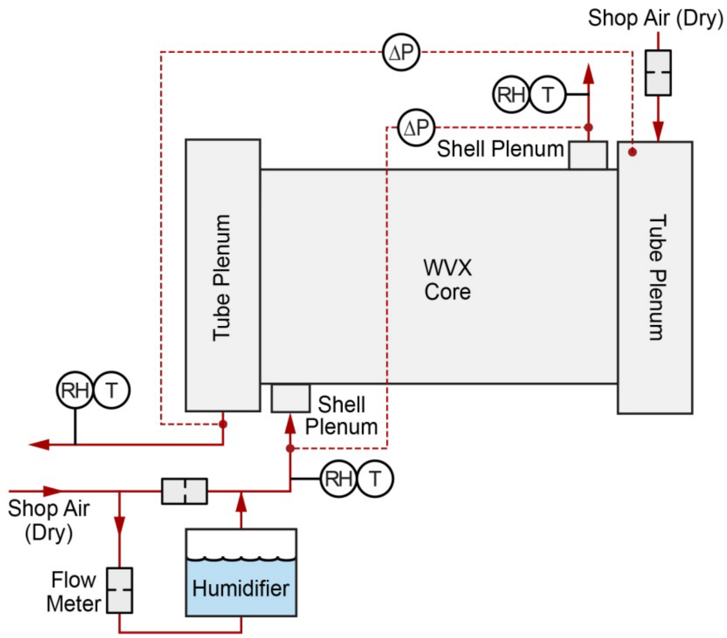


Figure 9. Once-through test rig to measure water transfer effectiveness.

Table 3. Instrumentation for once-through tests.

Test Parameter	Instrument	Accuracy
Flow Rate	Calibrated Orifice	± 1.2%
Relative Humidity	Vaisala HMT130 with HMP 110 Probes	± 1.1%
Pressure Drop	Dwyer Oil Manometer	± 0.25%
Temperature	PT1000 RTD Class F0.1 Sensor Integrated in Vaisala HMP 110 Probe	± 0.2°C (from 15–25°C)

The water recovery fraction is the ratio of water flow rate out of the dry side of the WVX to the water flow rate into the humid side of the WVX. Since water can only enter the dry stream by transfer across the membranes, 90% water recovery (for example) means that 90% of the water that enters the exchanger in the humid stream transfers to the dry stream before leaving the exchanger, leaving only 10% to get trapped in the amine bed. The recovery fraction η can be calculated from test data in two ways, since the rate of water flow from the dry side can be measured in two ways. One method is based on the absolute humidity of the air leaving the dry (tube) side:

$$\eta_{tube} = \frac{\dot{m}_{dry,out}\, W_{dry,out}}{\dot{m}_{humid,in}\, W_{humid,in}} \tag{1}$$

where: $\dot{m}_{dry,out}$ is the mass flow rate of air leaving the dry/tube side of the WVX (kg/s), and
$\dot{m}_{humid,in}$ is the mass flow rate of air entering the humid/shell side of the WVX (kg/s).

Note that in a loop test, the air flow rates are always equal and the water recovery is just the ratio of absolute humidities ($W_{dry,out}/W_{humid,in}$). The other method of calculating the recovery ratio uses the water loss from the humid (shell side) stream:

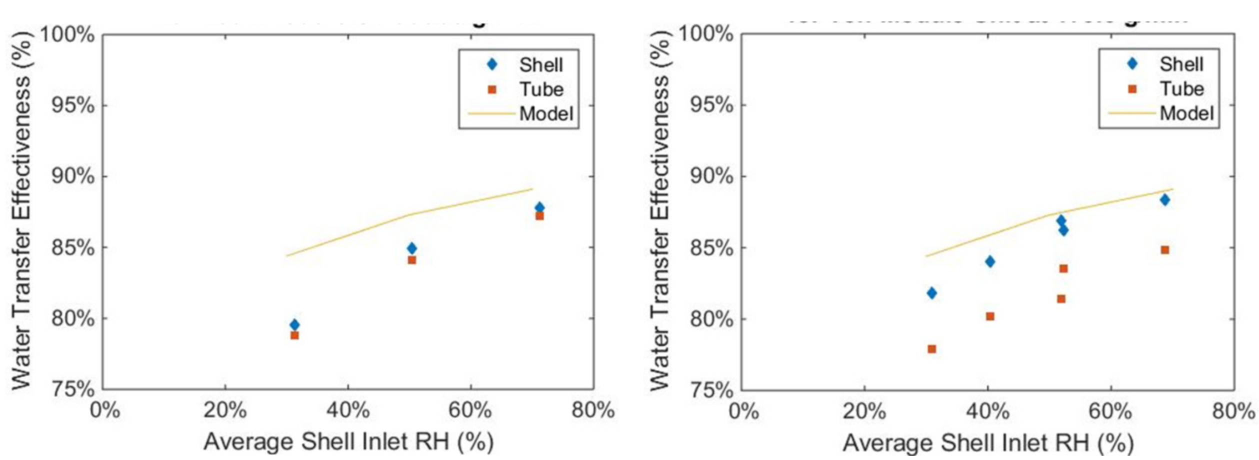
$$\eta_{shell} = \frac{\dot{m}_{humid,in}\left(W_{humid,in} - W_{humid,out}\right)}{\dot{m}_{humid,in}\, W_{humid,in}} = \frac{W_{humid,in} - W_{humid,out}}{W_{humid,in}} \tag{2}$$

The absolute humidity, W_i, in each stream i is computed from the measured temperature and relative humidity:

$$W_i = \frac{M_W\, p_{W,i}}{M_a\, p_a} = \frac{M_W\, RH_i\, p_{sat,W}(T_i)}{M_a\left(p_{tot} - RH_i\, p_{sat,W}(T_i)\right)} \tag{3}$$

Saturation pressures for water are computed using REFPROP (NIST standard reference database 23, version 9.1).

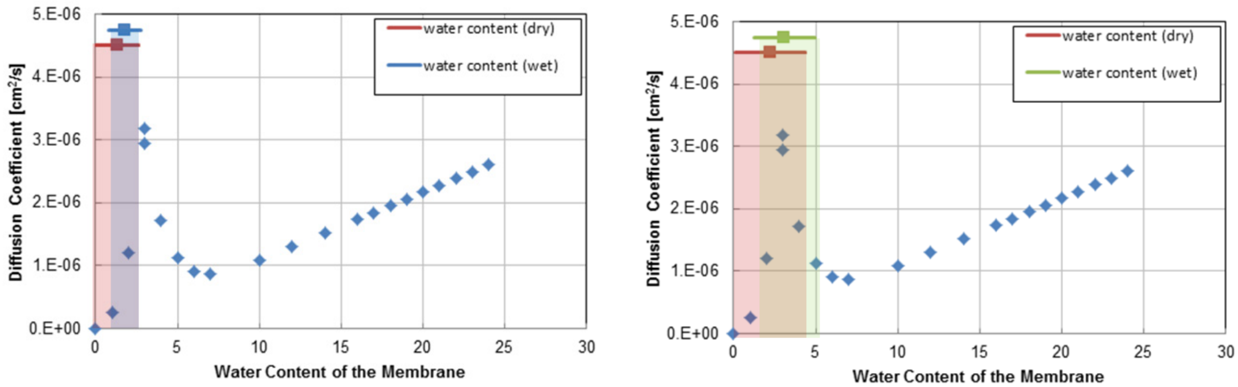
Figure 10 plots the water recovery measured in the four- and ten-module WVXs as a function of inlet RH with constant flow rates of air. Values are shown using both the shell- and tube-side calculation methods, and their difference is an indication of the experimental error. As expected, the water recovery increases with the average inlet RH because the permeability of the Nafion membrane increases with increasing water content over this operating range. Also shown in Figure 10 are water recovery predictions made using our design model. The design model prediction agrees generally well with the test data; however, the model overpredicts water recovery by 2 to 5% depending on operating conditions. The model and the data both show increasing water recovery at higher levels of ambient RH.



(a) Four Module (2 ft^3/min) (b) Ten Module (5 ft^3/min)

Figure 10. Water vapor transfer efficiency measurements and model predictions as functions of inlet RH.

We believe that one reason why the predicted water recovery is greater than the measured water recovery is uncertainty in the diffusion coefficient for water in Nafion. The mass transfer resistance of the membrane is the major factor that determines the overall rate of water transfer, so uncertainties in the diffusion coefficient will have a direct effect on the calculated recovery fraction. Figure 11 shows the diffusion coefficient computed using Motupally's correlation along with the humid and dry side values for Nafion water content for 30% RH (left-hand plot) and 70% RH (right-hand plot). In all cases, the computed water content of the membranes in the WVX span a range of water content where the diffusion coefficient varies very rapidly and non-linearly. As a result, small uncertainties in water content and/or the original diffusion coefficient data can have significant effects on the calculated water recovery.

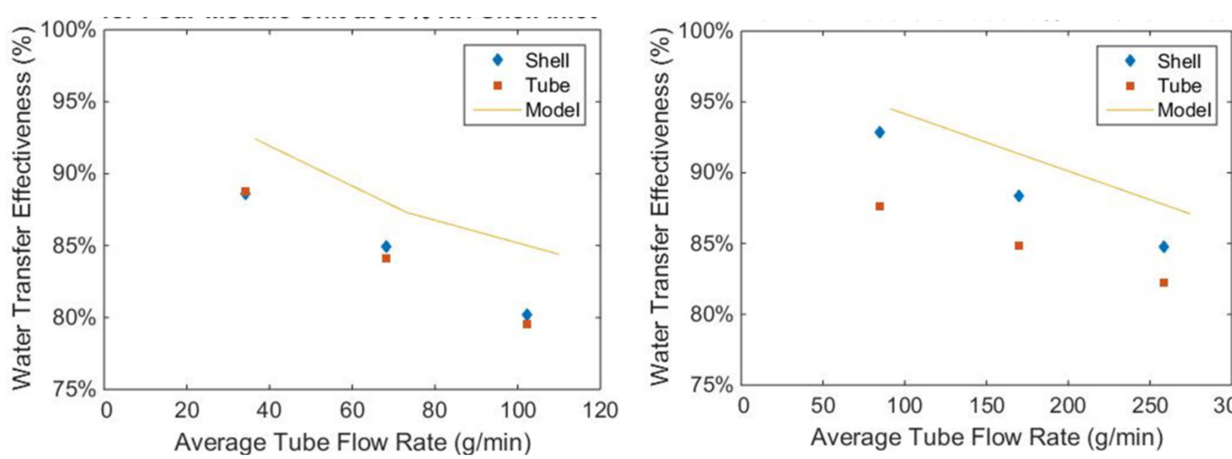


(a) 30% RH (b) 70% RH

Figure 11. Calculated values of diffusion coefficient for water in Nafion.

A second reason predicted water recovery is greater than the measured water recovery is the flow distribution. The model assumes perfectly even flow distribution on both the shell and tube side. Our structured WVX is designed for good shell and tube flow uniformity over a wide range of operating conditions. However, in reality there will be imperfections leading to a small performance penalty. In the future, the performance model could be updated to account for predicted flow non-uniformities in the shell and tube side flows. In Section IV, we use the model to predict WVX performance with a fraction of the flow bypassing the core on the tube side. This is a simplification of the non-uniform flow expected in an un-structured WVX.

Figure 12 shows the measured shell- and tube-side water recovery as a function of air flow for fixed inlet relative humidity values of 50% and 70%. As expected, the water recovery increases as the flow rate decreases, since lower flow rates correspond to longer residence times inside the exchanger. At the nominal flow rate (170 g/min), the water recovery measured in the ten-module WVX was 85 to 87%.

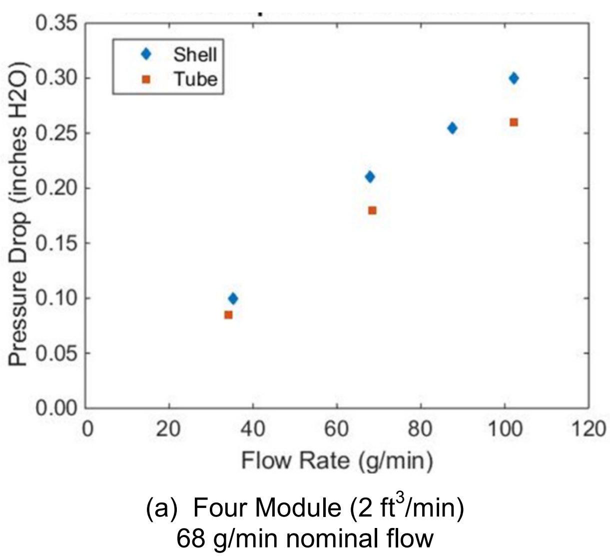


(a) Four Module (2 ft^3/min) at 50% inlet RH (b) Ten Module (5 ft^3/min) at 70% inlet RH

Figure 12. Water vapor transfer efficiency measurements and model predictions as functions of flow rate.

B. Pressure Drop

Figure 13 plots the pressure drops as a function of flow rate for the four-module and ten-module WVXs. In both cases the shell side pressure drop is slightly higher than the tube side, but they are very close in magnitude. Under nominal flow conditions the total pressure drop for the exchanger is less than 0.5 in. H_2O (125 Pa) for both units.



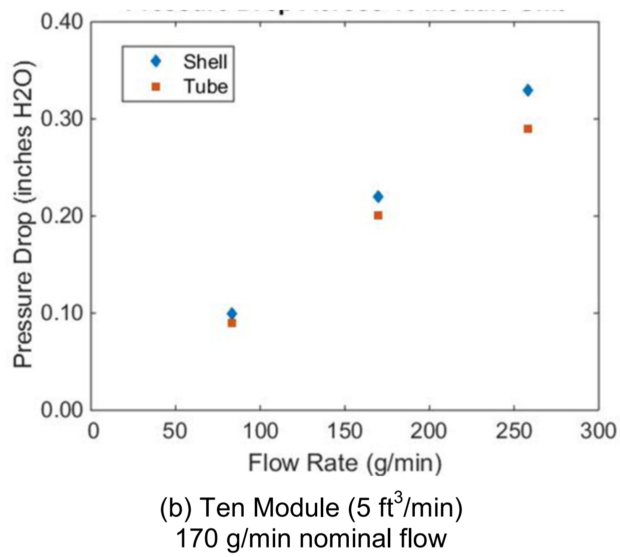


Figure 13. Pressure drop measurements and as functions of flow rate.

VI. Comparison with Unstructured Tube Bundles

Alternative WVX Approaches. The Nafion membrane WVX is superior to alternative methods for conserving water:

- Humidity condensers would actually need to be humidity freezers to capture 90% of the water, so they would require very low temperature refrigeration, as well as a complex exchanger design that can deal with frozen water.
- Desiccant wheels require power to heat and regenerate the sorbent. Heating consumes power, and the heat ultimately enters the cabin and imposes an additional cooling load on the thermal control system.
- Unstructured tube bundles would have a very difficult time matching water recovery performance due to their inability to effectively utilize all the Nafion tubes. It would be nearly impossible to match the WVX's pressure drop performance with an unstructured bundle without much higher water loss.

A conventional Nafion tube dryer was pictured in Figure 3a. Unlike the uniform tube configuration in the Creare WVX, the conventional WVX uses an unstructured tube bundle. In the core of the unstructured bundle, many of the individual tubes contact each other and wrap around adjacent tubes. Near the center of the tube bundle, this dense unstructured packing reduces the fraction of tubes fully exposed to shell side flow. This effective "blockage" reduces the maximum possible water recovery in two ways: (1) by decreasing the total fraction of Nafion that participates in water vapor transfer, and (2) by forcing more of the shell side flow to pass over tubes near the outer diameter of the tube array. Figure 14 illustrates the conceptual model of this situation, showing the active WVX core is an unbalanced mass exchanger with less participating surface area than an ideal unit with well-distributed flow.

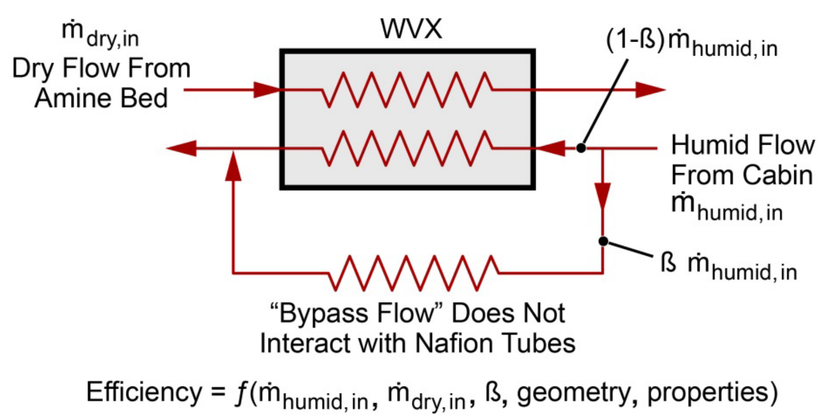


Figure 14. Model of a conventional Water Vapor Exchanger with a non-uniform tube array. *The effective bypass fraction can be estimated from measured water transfer efficiency.*

We used our WVX design model to assess the performance penalty associated with an unstructured tube array and compare the performance of a conventional Nafion air dryer with Creare's WVX. For this comparison, we considered a commercial style air dryer built to fit the specifications of the low-power CO_2 removal system (LPCOR). We used published[8] test data for the LPCOR WVX to determine the geometry of the commercial WVX and the actual water transfer effectiveness of the LPCOR. Next, we used a textbook formula that relates the efficiency of a heat or mass exchanger to the number of transfer units for unbalanced flow. Using this relation, we calculated the actual number of transfer units for the LPCOR. We can compare this value with the ideal number of transfer units predicted by our design model (which assumes perfect, uniform flow) to calculate the fraction of "blocked" tubes in the LPCOR tube bundle. For this analysis, the WVX geometry in our design model was modified to match the geometry of the LPCOR. The equivalent fraction of blocked tubes (β) is also the ratio of bypass, humid flow to the flow of humid air through the active WVX core.

The blocked fraction calculated above can be used to scale the WVX effectiveness predicted by the model and simulate the performance of the commercial WVX. We account for this in the model by assigning a fixed percentage of flow bypass on the tube side. We assumed perfect flow distribution in all other areas of the WVX. To facilitate an apples-to-apples comparison between the two designs, we adjusted the core volume for the commercial style bulk drying in our LPCOR model to match the Creare WVX while keeping the ratio of core length to diameter fixed. We then compared the performance of the two designs using model predictions. The results of this analysis are shown in Table 4 below along with the predicted pressure drop for both designs.

Table 4. Predicted performance summary for 30 CFM Creare WVX and scaled unstructured WVX. *Core volume fixed at 74 L and Nafion tube wall thickness fixed at 9% of the tube ID.*

<table>
<tr><th>Model Description</th><th>"Blocked" Fraction of Tubes (β)</th><th>Number of Tubes</th><th>Tube ID</th><th>Active Tube Length</th><th>% H_2O Recovered</th><th>ΔP</th></tr>
<tr><td>Creare WVX</td><td>-</td><td>13,500</td><td>0.066 in. (1.68 mm)</td><td>8 in. (203 mm)</td><td>0.88 (measured)</td><td>0.20 in. H_2O (250 Pa)</td></tr>
<tr><td>Commercial LPCOR WVX Modified to Match the Core Volume of the Creare WVX</td><td rowspan="2">0.164</td><td>17,679</td><td>0.038 in. (0.97 mm)</td><td rowspan="2">43.6 in. (1107 mm)</td><td>0.825</td><td>2.57 in. H_2O (643 Pa)</td></tr>
<tr><td>Commercial LPCOR WVX Modified to Match the Predicted Tube Side ΔP for the Creare WVX</td><td>857</td><td>0.110 in. (2.79 mm)</td><td>0.693</td><td>0.20 in. H_2O (250 Pa)</td></tr>
</table>

These calculations show that the predicted water vapor recovery ratio for the commercial bulk dryer is significantly less than the Creare design. The predicted pressure drop is also much higher than the Creare design as a result of the smaller tube diameter and longer length used in the structured bundle. We can match the pressure drop between these two designs by reducing the number of tubes in the commercial WVX and increasing the inner diameter of each tube to maintain a constant cross-sectional area on the tube side. The result is a significant reduction in the number of tubes and the net water vapor recovery ratio. Overall conclusions from this comparison are:

- For the same core volume, the unstructured tube bundle will lose 46% more water than the Creare WVX with pressure losses that are 13 times higher.
- For the same core volume and pressure loss, the unstructured tube bundle will lose 2.6 times more water than the Creare WVX.

VII. Application to Exploration Spacecraft

The WVX technology is expected to be most useful for vehicles that are designed for an intermediate point between the short-duration missions of Orion and the very long-duration missions of the ISS. The WVX described here clearly has benefits over the unstructured tube bundle using Nafion membranes. The primary competition to the Nafion membrane technologies in general are desiccant materials, which typically require active heating and cooling to enable thermal swing adsorption processes. The passive, low power, 90% water saving capability of the WVX could enable use of a compact Orion-like technology and enable a partially-closed loop system with condensate recovery, with lower energy consumption. Shorter duration missions would also have less of a penalty from ammonia exposure over time.

Several types of mission architectures benefit from this implementation. One possible application is an incremental evolution of habitation capabilities in deep space, where the Orion vehicle visits other habitable elements to prepare for longer missions.[9] Most closed-loop life support functions make non-potable water, so a water polishing step is required in all combinations. If the Orion spacecraft visited a habitable volume that did not yet have a complete life support system installed, but started with a water processor, the WVX could enable simultaneous use of a condensing heat exchanger and water processor in the new element, while still relying on Orion's CO_2 removal system. Since long-duration missions are also expected to have greater exercise requirements than Orion, a supplemental condensing heat exchanger for humidity control is expected to be needed anyway. A second architecture that benefits from this system is a short-duration exploration vehicle,[10] like a rover or Mars-moon hopper. These vehicles would return periodically to a larger habitat or base that could recycle collected wastewater stored during the mission. During the mission, stored wastewater would provide additional benefit as a useful radiation shield. Additionally, the WVX should be included in the trade space for upstream options for any CO_2 control system with a residual drying step to save the final 10% of water. In all of these architectures, the clean air that has had CO_2 removed still has standard cabin levels of humidity present. This may be more comfortable for the crew than the very dry air that may be returned to the suited crewmembers in a system like Orion when an amine swing bed is used without this technology.

VIII. Conclusions

WVX Design and Assembly. We have successfully designed and built a Nafion-membrane water vapor exchanger that maintains uniform flow channels across all operating conditions. Uniform channels are critical for achieving high water recovery efficiency. The prototype is sized for a ventilation flow rate corresponding to a single crew member. The modular design will be straightforward to scale up to meet the flow requirements of a full-size crew. Separate effects tests show that the fabrication and assembly methods produce core components that are highly durable.

WVX Performance. The prototype recovered 85 to 90% of the water vapor in simulated cabin flow before it left the exchanger. The water recovery under nominal (5 ft^3/min (8.5 m^3/hr) per crew at 65% RH) conditions is 88%. In an ECLSS that uses amine bed CO_2 absorbers, this high water recovery would reduce water loss by nearly an order of magnitude. Pressure drops are less than 0.5 in. H_2O (125 Pa) under nominal conditions, so that the WVX requires very little additional motive fan power (about 0.3 W aero power per crew) from the spacecraft ventilation system.

WVX Performance Modeling. Data from WVX performance tests have validated the accuracy of our performance models and will enable confident design of future units. Performance models based on absorption/diffusion mechanisms with diffusion coefficients that vary with water loading can predict water recovery efficiency to within ± 3%. Pressure drop models based on analysis of flow through the core and manifolds are accurate to within ± 15% estimated uncertainty. While the pressure drop through the tubes is predicted well, the shell side pressure drop has significantly higher uncertainty due to the multiple pressure drops and the uncertainty in the detailed geometry.

WVX Technical Feasibility. Prototype performance data show that it is feasible to achieve very high water recovery with low pressure losses. Analysis of alternative water recovery approaches shows that the WVX promises the best water recovery performance with very low pressure drop and without imposing additional requirements (power, thermal) on the spacecraft ECLSS.

Future Work. Next steps in developing the WVX technology should include: (1) detailed analysis of WVX performance in spacecraft ECLSS; (2) assessment of the performance benefits of thin-walled Nafion tubes; (3) trade-offs associated with various approaches for ammonia mitigation based on specific exploration mission requirements; (4) development of a mechanical assembly for improved sealing and reduced mass in future units; (5) exploration of improved fabrication and assembly methods; and (6) mechanical testing to demonstrate flight-worthiness. As mentioned in Section V, additional work is also needed to improve the accuracy of the WVX design models, including: (1) additional measurements and analysis of water diffusion through Nafion, and (2) improved methods for modeling flow through non-uniform tube bundles.

Acknowledgments

This work was sponsored by the Crew and Thermal Systems Division, NASA Lyndon B. Johnson Space Center, and the NASA Small Business Innovation Program.

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