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Preliminary Investigation of Vortex Phase Separator-Based Spacecraft Cabin Air Dehumidification Subsystem for CO_2 Removal

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Cabin atmosphere revitalization, more specifically CO_2 removal, is a key technology to pursue long-duration, crewed space missions. The ISS currently uses the Carbon Dioxide Removal Assembly (CDRA) that employs desiccant (silica gel) and solid sorbent (zeolite) to remove humidity and CO_2 from cabin air, respectively. However, CDRA has challenges with high reliability and low maintenance requirements. Air dehumidification is an important process for state-of-the-art and emerging technologies since it helps provide higher CO_2 removal efficiency and purer CO_2 downstream product. The desiccant in CDRA degrades over time, causes substantial reduction in water removal capacity, and would require an additional energy cost for regeneration. A promising technology to perform successful dehumidification in support of new CO_2 removal systems is the Vortex Phase Separator (VPS). The VPS operation in microgravity relies on creating and maintaining a liquid vortex, which offers centrifugal acceleration in replacement of gravitational acceleration, within a right circular cylinder. Warm and humid air enters the VPS, breaks into very small bubbles, and passes through cold liquid desiccant. Rapid, direct heat and mass exchange between the liquid and gas phases facilitates high water absorption and/or condensation capability, and allows for high throughput per unit energy consumed. This preliminary study investigates the VPS for cabin air dehumidification as part of NASA's spacecraft CO_2 removal systems under consideration. A prototype microgravity VPS system was designed, built, and tested to separate water vapor from a warm, humid air stream to characterize its performance using water and ionic liquid (IL) in the separator. Experiments with 77 SCFH airflow rate and 200 ml IL charge demonstrated the VPS capability to reduce up to 45% of water content in a humid air stream.

Nomenclature

A_{AT} = axial and tangential flow area (m^2)
CCAA = Common Cabin Air Assembly
CDep = Carbon Dioxide Deposition System
CDRA = Carbon Dioxide Removal Assembly
CO_2 = Carbon Dioxide

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D = separator diameter (m)
D_z = height from inlet nozzle to baffle plate (m)
IL = Ionic Liquid
ILDS = Ionic Liquid Dehumidification System
ISS = International Space Station
NASA = National Aeronautics and Space Administration
Re_N = Reynolds number of fluid into liquid inlet
R = separator radius (m)
r = bubble radius (m)
t_a = axial transit time of a bubble (m/s)
t_r = radial transit time of a bubble (m/s)
VPS = Vortex Phase Separator
$\dot{V}$ = liquid flow rate into nozzle (m^3/s)
v_z = average axial velocity of a bubble (m/s)
ρ_l = density of liquid at inlet nozzle (kg/m^3)
ρ_g = density of gas at gas nozzle (kg/m^3)
μ_l = dynamic viscosity of fluid at liquid inlet (N-s/m)
v = kinematic viscosity of liquid (m^2/s)
ω = rotational speed of fluid inside separator (Hz)

I. Introduction

The Carbon Dioxide Removal Assembly (CDRA) (Figure 1) consists of dual adsorbent and desiccant beds to perform CO_2 and humidity removal on the ISS. Adsorbent beds utilize granules of a synthetic rock called zeolite (solid sorbent) to “scrub” CO_2 from cabin air, and desiccant beds utilize silica gel (desiccant) to remove humidity.[1,2] NASA seeks to replace these solid sorbents as they have large volume, high desorption temperatures causing them to require high power usage, and long-term reliability issues.[3,4] Liquid amine CO_2 removal technologies offer an alternative to solid sorbent based CDRA, however determination of reliability and effectiveness are still in work.[5-6] The Cryogenic CO_2 Deposition System is another unique alternative to perform CO_2 removal without use of solid sorbents, and requires an upstream humidity control. To accomplish this, an Ionic Liquid Dehumidification System (ILDS) was selected.[7] However, CDep utilizes cryogenic coolers and results in high power consumption.[8] Therefore, alternative methods are needed to achieve effective, reliable, energy efficient dehumidification systems.

NASA currently uses the Common Cabin Air Assembly (CCAA) (Figure 1) to aid in removing excess humidity from cabin air. Part of this less humid stream is then directed to the CDRA where humidity removal is further performed through use of desiccant (silica gel), and CO_2 is scrubbed.[9] Based on historical mission data, extended use of desiccant on the ISS shows degradation and effectiveness issues which reduce CO_2 removal capability by 50%.[10] The CCAA employs a condensing heat exchanger to perform initial heat and moisture removal.[9] When the air stream comes into contact with the lower temperature heat exchanger fins, it will condense onto the fin surfaces. As the condensate liquid layer on the fin surfaces increases, air flow directs the liquid condensate to a rotary separator (Figure 1) where it is spun at 5,000-6,000 RPM via fan to separate the condensate and air phases through centrifugal action.[11] This procedure is energy intensive and requires 500 to 2000W.

A recent CO_2 removal technology introduced by NASA replaces the solid sorbents used by the CDRA with liquid sorbents.[5-6] The Liquid Amine Carbon Dioxide Removal System uses a capillary-based gas/liquid contactor and degasser system to remove CO_2 from cabin air. A primary amine is used as the liquid sorbent, which acts to absorb CO_2. In this system, a condensing heat exchanger is used to reclaim water vapor lost from the liquid sorbent at high temperatures used during regeneration.[6] This condensing heat exchanger also provides dehumidification of to the CO_2 effluent allow for a purer downstream product, which aids downstream CO_2 conversion. It was found that substantial water vaporization occurred during regeneration of liquid amine, which was corrected by adding the previously mentioned condensing heat exchanger.[6]

NASA recently introduced a unique alternative to remove excess humidity from cabin air as a part of another alternative CO_2 removal system.[7] The CO_2 deposition system (CDep) generates a cold surface which is maintained to selectively deposit CO_2 from cabin air.[7] An ionic liquid dehumidification system was selected to reduce power generated and provide a purer CO_2 downstream product by removing humidity of cabin air. The Ionic Liquid Dehumidification System uses hollow fiber membranes to direct ionic liquid through the lumen side, and air through the shell side.[7] This system is estimated to remove 96% of absolute humidity from cabin air.

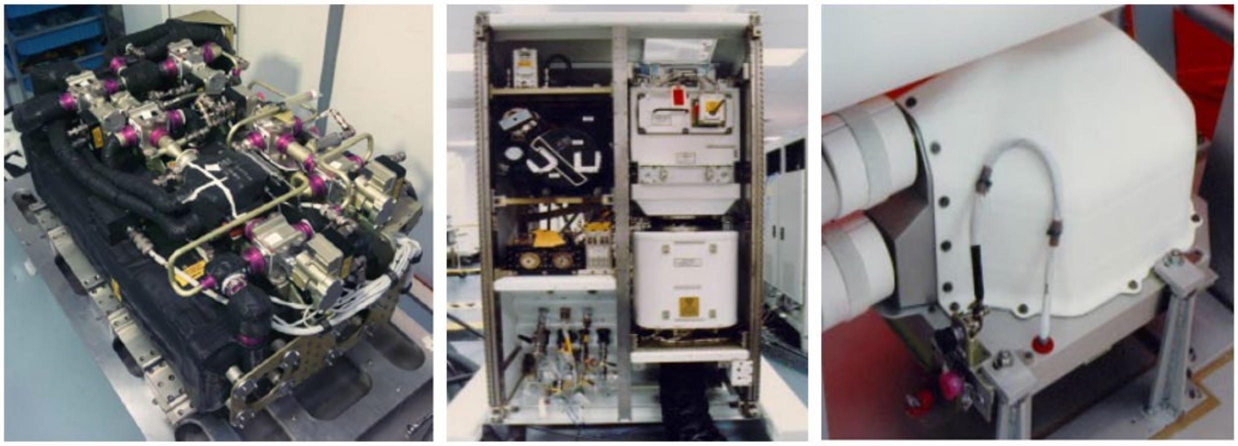

Figure 1: Carbon Dioxide Removal Assembly (CDRA)[1], Common Cabin Air Assembly (CCAA)[11], Rotary Separator[11]

A promising, alternative technology to perform successful dehumidification in support of the new CO_2 removal systems is the Vortex Phase Separator (VPS). This preliminary study investigated the VPS for cabin air dehumidification as part of NASA's spacecraft CO_2 removal systems under consideration. A prototype microgravity VPS system was designed, built, and tested to separate water vapor from a warm, humid air stream to characterize its performance using water and ionic liquid (IL) in the separator. Experiments at the considered operating conditions demonstrated the VPS capability to reduce up to 45% of water content in a humid air stream.

II. Background: Vortex Phase Separator Technology for Dehumidification

The VPS operates by producing and managing fluid vortices within a cylindrical separation volume and creates a replacement for gravitational acceleration in the form of centrifugal acceleration. When VPS technology is applied to dehumidification, it offers rapid, direct heat and mass exchange by allowing humid air to pass through a circulating, chilled liquid desiccant on the inner VPS cylindrical walls.

Schematic of a VPS system for air dehumidification is included in Figure 2. Warm, humid air in this system is supplied through the humidifying/heating tank. Slightly compressed, room temperature air is first directed to the spargers inside of the tank, which bubble the air through water pool (heated by an immersion heater, if needed) where heat exchange occurs, creating humid air to simulate cabin conditions. This warm, humid air is then directed into the gas inlet nozzle on the VPS where it passes through cold, swirling liquid desiccant directed into the separator by the liquid inlet nozzle. When these two fluids come into contact, thermal energy is rapidly exchanged between the two phases, decreasing the air temperature to that of liquid and removing water vapor present in the air through condensation and/or absorption. This results in a less humid volume of air in the VPS cylindrical core that is directed to the VPS gas outlet. The water removed from the air stream mixes into the swirling liquid layer and exits from the VPS liquid outlet. It can then be chilled and redirected into the liquid inlet nozzle to continue the dehumidification process.

This particular VPS configuration operates in a batch processing; thus, the system dehumidifies air until the water content of the liquid inside the VPS reaches to a certain point, and then it needs to be isolated to regenerate the liquid by reducing the water content back to initial level. In this study, water and IL were used as liquid desiccants in the VPS.

III. Design of Vortex Phase Separator

The design of VPS for dehumidification was guided by analytical calculations to ensure successful dehumidification of the humid gas stream for flow rates of liquid at the liquid inlet nozzle to be tested. The VPS liquid inlet nozzle is very sensitive to design parameters, as this is what drives the liquid film volume on the inner cylindrical walls of the separator. This liquid film volume is what interacts directly with the humid air stream and causes removal of water vapor by direct absorption and/or condensation from this stream. If the inlet area of the liquid inlet nozzle is not sized correctly, the VPS will not maintain stability. This is due to either liquid flooding into the gas outlet (carry-over), or gas flooding into the liquid outlet (carry-under).[12] Both phenomena cause dehumidification failure. To design

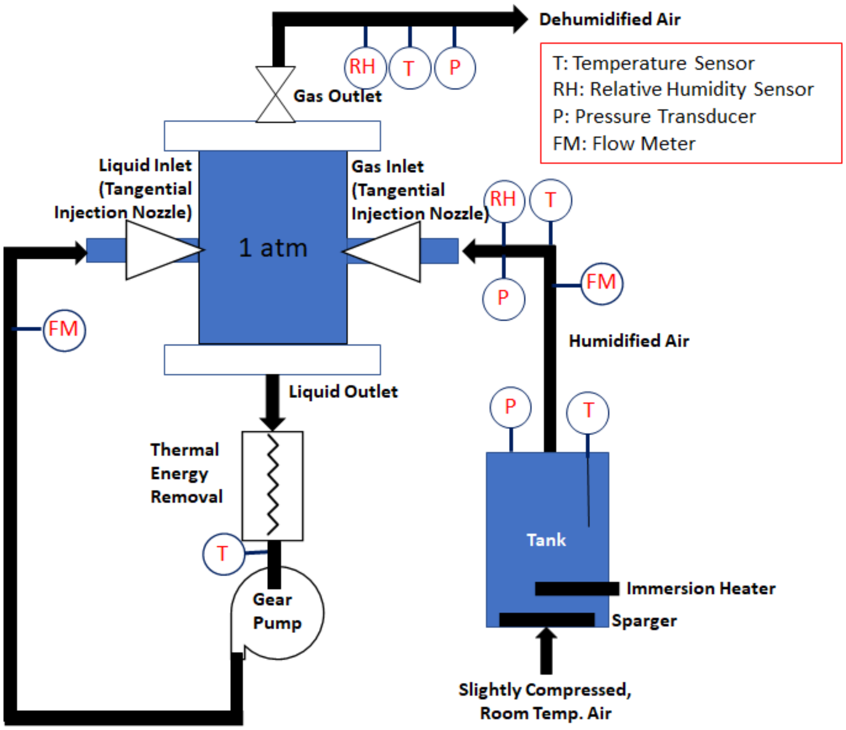

Figure 2: Schematic of Vortex Phase Separator (VPS) System for Air Dehumidification

the VPS, the radial and axial bubble transit times are calculated and compared with design parameters for the radius of the cylindrical VPS body, and the inlet area of the liquid inlet nozzle. Design procedures follow previously obtained data for VPS technology.[12] The predicted rotational speed for fluid inside of the VPS was given by ground data and CFD results.[12]

The radial bubble transit time is defined as the time required for a bubble to travel from the VPS wall to the centerline of the cylindrical separation volume, and the axial bubble transit time is defined as the time required for a bubble to travel from the VPS wall to the baffle plate (Figure 3). Baffle plate prevents the exit of air from the liquid outlet. These bubbles occur during the coalescing and mixing of the liquid and gas phases. The liquid from the liquid inlet nozzle (liquid phase) and gas from the gas inlet nozzle (gas phase) combine and become two-phase flow within the VPS cylindrical body. Small gas bubbles containing humidity exist in this two-phase flow where their humidity is removed through condensation and/or absorption by the swirling liquid phase. The less-humid gas bubbles then move to the centerline of the VPS cylindrical body due to density difference and exit from the gas outlet. Removed water from the air stream and the swirling liquid film is directed to the liquid outlet, and then chilled and redirected to the liquid inlet to drive the continuous dehumidification process. Flow rates for the liquid to be directed into the liquid inlet nozzle during testing are found simultaneously to the selected design parameters of the VPS. Flow rates and VPS design parameters are carefully chosen to ensure vortex stability by preventing both carry-over and carry-under.

The rotational speed of fluid inside of the VPS (ω) was found from previous data obtained for VPS technology, given by Equation 1[12]

$$\boldsymbol{\omega} = \frac{\boldsymbol{v}[\mathbf{0.394}(\boldsymbol{Re_N}) - \mathbf{2020}]}{\boldsymbol{R^2}} \qquad \textbf{[1]}$$

where v is the kinematic viscosity of the liquid, Re_N is the Reynolds number of fluid at liquid inlet, and R is the separator radius.

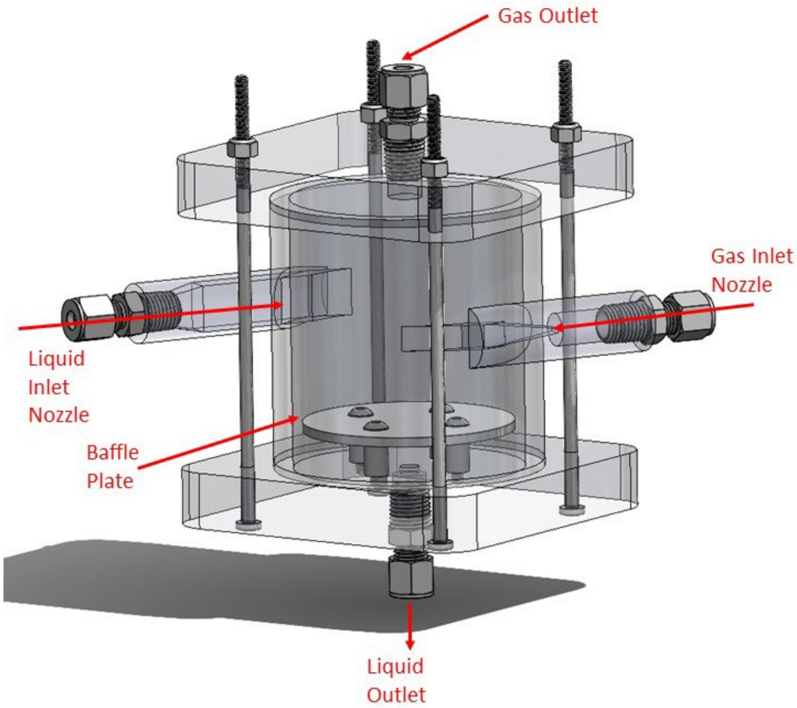

Figure 3: CAD Model of VPS for Air Dehumidification

The radial transit time of a bubble (t_r) was found using Equation 2, where μ_l is the dynamic viscosity of fluid at liquid inlet, ρ_l is the liquid density, ρ_g is the gas density, and r is the bubble radius (assumed to be 0.001 m). If this time is less than the axial transit time of a bubble (t_a), liquid will flood into the gas outlet (i.e., carry-over will occur).[12]

$$\boldsymbol{t_r = \frac{9\mu_l}{r^2\omega^2(\rho_l - \rho_g)}} \qquad \textbf{[2]}$$

Axial and tangential flow area (A_{AT}) is defined as the area in which a bubble can travel perpendicularly along the centerline of the VPS. This area may be calculated by using the separator radius and diameter (D), and the area of a circle. It can then be used to find the average axial velocity of a bubble, and the axial transit time of a bubble.

$$\boldsymbol{A_{AT} = \pi\left(\frac{D^2}{4} - \frac{R^2}{4}\right)} \qquad \textbf{[3]}$$

The average axial velocity of a bubble (v_z) can then be found using the axial and tangential flow area, and the flow rate of liquid at the liquid inlet nozzle ($\dot{V}$).

$$\boldsymbol{v_z = \frac{\dot{V}}{A_{AT}}} \qquad \textbf{[4]}$$

Finally, the axial transit time (t_a) is calculated by using the height from the liquid inlet nozzle to the baffle plate (D_z) and the average axial velocity of a bubble.

$$\boldsymbol{t_a = \frac{D_z}{v_z}} \qquad \textbf{[5]}$$

Radial transit time is dependent on liquid inlet nozzle geometry as is it affected by rotational speed, which is dependent on Reynolds number, which is dependent on the inlet area of the liquid inlet nozzle. Axial transit time is affected by the axial and tangential flow area, which can be seen in Equation 3 to be directly dependent on the diameter of the VPS. Design parameters were determined for both the VPS diameter and liquid inlet nozzle by utilizing the discussed equations to ensure carry-over does not occur.

IV. Experimental Setup and Procedure

An experimental setup was built to investigate the VPS-based air dehumidification subsystem as shown in Figure 4. The major components of the setup include a prototype, subscale VPS, an air humidifying/heating tank, a pump, a heat exchanger, and a chiller, as well as instrumentation to measure key operating conditions. The VPS was fabricated using Al 6061 material for a cylindrical body, baffle plate, top and bottom lids, and liquid and gas nozzles. A large humidifying/heating tank, also made from Al 6061 material, featured multiple spargers to bubble air stream into the water pool and an immersion heater that can control temperature. A gear pump was employed to circulate liquid between the VPS liquid outlet and the VPS liquid inlet nozzle in a closed loop. A heat exchanger and chiller were used to cool down the liquid circulated in the system.

A comprehensive LabVIEW program was used to monitor and collect data from all thermocouples and pressure transducers in the system. Relative humidity sensors were used at both the gas inlet and gas outlet to effectively provide data on total absolute humidity removed during tests. Flowmeters were used to measure flow rates of gas and liquid streams. The VPS outer surface was insulated with closed cell foam to help maintain the cold liquid temperature inside the separator.

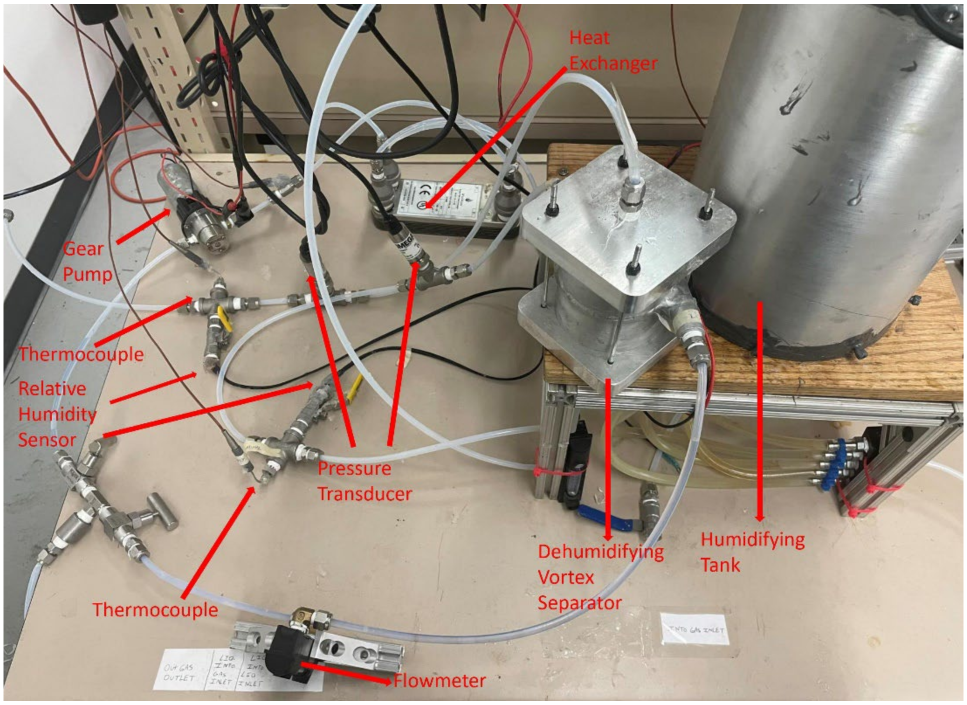

Figure 4: VPS Experimental Setup for Air Dehumidification

The protype VPS system was tested in a systematic way to investigate its air dehumidification performance using two working fluids, first using water and then using ionic liquid (IL) 1-Ethyl-3-methylimidazolium ethyl sulfate, [EMIM][EtSO$_4$]. The experiments were conducted at the same inlet conditions of humid air at 25°C, 95% relative humidity, and 77.5 SCFH flow rate. The liquid entering the liquid inlet nozzle was held at a constant 16°C for both water and IL for initial runs, although another test at the end was performed with colder water stream at 12°C. Volumes of 100, 150, and 200 ml of liquid charge in the VPS were tested for both water and IL.

V. Results

Figure 5 shows the VPS air dehumidification performance using water, in terms of % change in absolute humidity of air between the inlet and outlet of the system, as a function of flow rate at the liquid inlet nozzle. In these tests, the water flow rate was varied between 0.5 to 2.5 l/min, and three levels of liquid charge at 100, 150, and 200 ml of water was added to the separator (in addition to the required liquid charge to fill other components of the loop, such as tubing, pump, heat exchanger). For every level of liquid charge, the data show an increase in % change in absolute humidity as liquid flow rate increases. This result can be attributed to the higher liquid rotational speed within the VPS and increased interaction of the liquid desiccant (water, in this case) with warm, humid air bubbles, facilitating more effective dehumidification due to condensation. The data indicates that the highest amount of absolute humidity removal was 24% with 200 ml of charge, at 2.5 l/min flow rate.

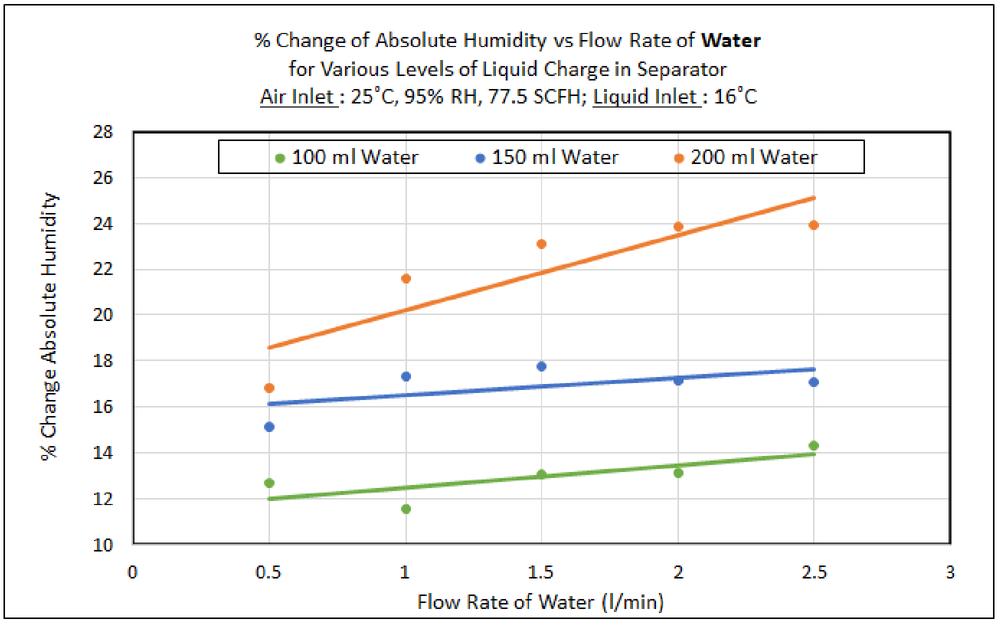

Figure 5: VPS Air Dehumidification Performance using Water

Figure 6 shows the VPS air dehumidification performance using IL, in terms of % change in absolute humidity of air between the inlet and outlet of the system, as a function of flow rate at the liquid inlet nozzle and levels of liquid charge in the separator. In these tests, all operating conditions were kept the same as the previous tests. The data showed similar trends; however, the amount of absolute humidity removal was much higher at 43-45% with 200 ml of charge, at 2.0-2.5 l/min flow rates. This significantly improved performance was achieved by using IL as the liquid desiccant that provides air dehumidification by both condensation and chemical absorption.

An additional test was conducted to evaluate the effect of liquid temperature on the air dehumidification performance. Figure 7 compares two cases both using water, with 150 ml of charge, at 0.5-2.5 l/min flow rates. In one of the tests, temperature of the liquid entering the liquid inlet nozzle was maintained at a lower, 12°C, vs. 16°C as in the previous tests. As can be expected, lower temperature of the swirling water layer within the VPS considerably increased the amount of absolute humidity removal up to 27% at 2.5 l/min flow rate. Such improvement can be explained with increased condensation due to larger temperature difference between the liquid layer and the warm, humid air stream.

Effect of IL temperature on the air dehumidification performance would be similar, but it needs to be further evaluated. Decreasing temperature of IL would help with both water condensation and absorption rates; however, lower temperatures would also increase IL’s viscosity and its associated pumping power.

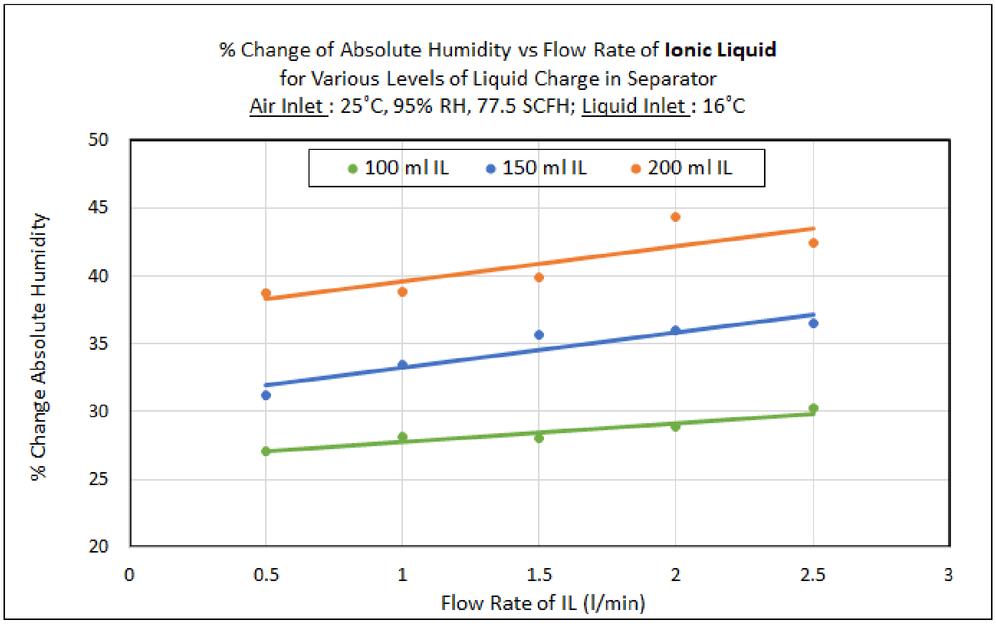

Figure 6: VPS Air Dehumidification Performance using IL

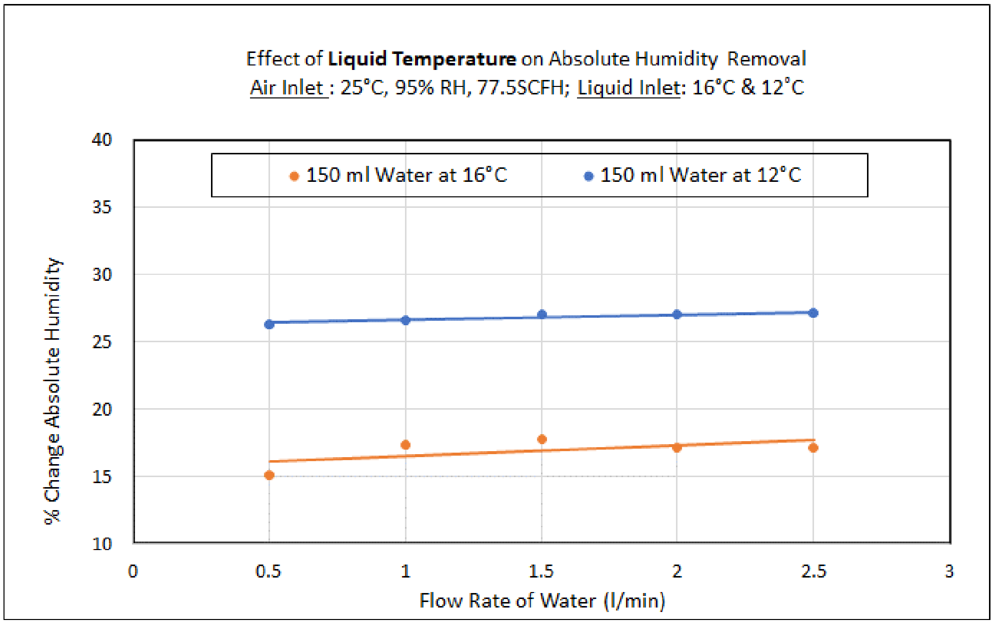

Figure 7: VPS Air Dehumidification Performance using Water: Effect of Water Temperature

VI. Conclusion & Future Work

This preliminary study investigated the VPS for air dehumidification as part of spacecraft CO_2 removal systems under consideration. A prototype microgravity VPS subsystem was designed, built, and tested to separate water vapor from a room temperature, humid air stream to characterize its performance using water and IL in the separator. Experiments showed that increase in liquid flow rate and level of liquid charge (within the range of 0.5-2.5 l/min and 100-200 ml, respectively) increase air dehumidification. In general, using IL as the liquid desiccant, compared to water, provided better air dehumidification through condensation and absorption. Results indicated that the system can remove up to 45% of absolute humidity from inlet air stream at 77.5 SCFH flow rate, 25°C temperature, and 95% relative humidity.

Future work will consider further investigation of several parameters, such as the effects of inlet air relative humidity, inlet air flow rate, IL temperature, and level of liquid charge on the VPS air dehumidification performance. Additional experimental data and insights gained would then facilitate optimization, scaling, and continued development of VPS-based air dehumidification subsystem for CO_2 removal as an alternative technology.

Acknowledgments

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