2003-01-2614

Design, Testing and Operation of Porous Media for Dehumidification and Nutrient Delivery in Microgravity Plant Growth Systems

Alex Hoehn, Paul Scovazzo
BioServe Space Technologies

James Clawson, Tobias Geissinger, William Kalinowski, Jon Pineau
University of Colorado, Aerospace Engineering Sciences

ABSTRACT

Porous plate dehumidifiers (PPD) and porous tube nutrient delivery systems (PTNDS) are designed to provide a means for accurate environmental control, and also allow for two-phase flow separation in microgravity through surface tension. The technological challenges associated with these systems arise from the requirement to accurately measure and control the very small pressures that typically occur within and across the porous media. On-orbit automated priming or filling of the system in the absence of gravity may be necessary. Several porous plate dehumidifiers and porous tube nutrient delivery systems have been tested and evaluated, and experimental results for engineering design are presented.

INTRODUCTION

The technological challenges associated with porous media systems arise from maintaining the delicate balance between the capillary forces within the plate and the pressure control device. These challenges are intensified during microgravity applications due to the reliability requirements, minimal availability of crew time, and difficulties associated with on-orbit refurbishments. In general, the challenges with porous media systems are as follows:

- The porous systems require very precise pressure control within and across the porous media in order to function properly. If the pressure is not properly maintained, the system could easily lose prime or flood. Control is complicated due to the variability of materials, pore size, length of intended operation, and performance.
- Operational requirements and limitations associated with ISS often require the systems to be disabled (unpowered) for extended durations as occurs during transfers to and from the Space Shuttle and during plant harvests. During these times, the system may not have the ability to maintain pressure control and thus may need to be dry. This in turn necessitates the ability for on-orbit priming or re-priming. These activities are successfully accomplished on Earth only with difficulty.
- The difficulties associated with two-phase flow and maintaining prime require the integration of flow separation technologies (e.g., bubble traps, de-aeration) into the spaceflight hardware.
- Temperature / humidity control and nutrient delivery systems are very ‘expensive’ in terms of mass, power and volume, and redundant systems often may not be possible within these constraints.

This paper describes some approaches as well as design and operational guidelines based on test data and analysis to deal with the technical challenges associated with porous systems in microgravity. Several porous plate dehumidifiers and porous tube nutrient delivery systems have been tested and evaluated, ranging from very small systems for insect habitats (very low flow rates) to larger systems for plant growth systems. Concepts covered include:

- Porous material selection and trade considerations.
- Fluid pressure control dynamics involved with micro-dispensing an incompressible fluid into porous media at very small pressures.
- Dynamics and control of porous media systems must be characterized in order to properly size the systems for the particular application, such as a) evaporation-induced flow rates, and b), surface area and suction pressure constrained maximum flow rates through the porous media.
- Material preparation and treatments.
- Acceptance testing.

BACKGROUND

HUMIDITY CONTROL

Several methods exist for controlling the humidity or moisture content of an air volume (dew point control, membrane concentrators, salt-based systems), but dew point control systems are the most common. The use of dew point control systems in a microgravity environment is complicated by the fact that the condensed water must be collected and removed from the chamber in the absence of gravity. Centrifugal condensing heat exchangers are used for large systems such as the Space Shuttle humidity control system, but are not feasible for small life sciences payloads. Porous, temperature-controlled water-filled membranes can be utilized as microgravity-compatible dew point controllers that not only condense moisture from the air, but also provide for two-phase fluid separation. If properly primed (water-filled), and operated within the required design parameters, only liquid water crosses the water-filled membrane, while surface tension prevents air entry into the membrane. The temperature of the (porous) humidity control device controls the net flow of water, and thus the chamber humidity (Scovazzo, 1997; 1998a,b; 2000b).

Dehumidification occurs when the surface temperature of the porous membrane is sufficiently below the dew point. Water vapor then condenses, and water is removed from the air stream. Relative humidity in the chamber is reduced, if the condensation rate is larger than the rate of evapo-transpiration within the chamber. The lower the temperature, the higher the rate of condensation. The suction pressure typically does not affect humidity, but may affect the flow rate.

Humidification occurs when the temperature of the porous membrane is increased, and water is allowed to evaporate from the membrane. The suction pressure can remain the same for de- and re-humidification. The chamber humidity can increase both due to evapo-transpiration from the plants / substrate, and due to evaporation of water from the porous membrane. As water evaporates from the membrane, the pressure control system must resupply appropriate amounts of water from a reservoir to maintain prime and constant trans-membrane suction pressure.

Most plant chambers use humidity condensate recovery to maintain constant water content in the root zone. Condensed water is returned to a reservoir or directly back to the root zone (Figure 1). The humidity of the chamber is a function of the temperature of the dew point controller, i.e., the phase-separating porous membrane surface temperature only. Since the dew point humidity controller affects the overall temperature control system as well, a second temperature control system is necessary to independently control temperature and humidity (Hoehn et al., 2003).

NUTRIENT DELIVERY / ROOT ZONE HYDRATION

Water and nutrient delivery systems developed for spaceflight applications employ similar porous systems to control and separate the liquid and gas phases (Hoehn et al., 2000; Levine et al, 1998 a, b; Scovazzo, 2001). The water may be contained in porous tubes, controlled to a slight negative cross-membrane pressure. The tubes may be embedded in a substrate, or plants can be grown directly on the porous membrane (Burtness, 2002). In the absence of small, reliable, easy to use substrate moisture sensors, the pressure within the porous tube can be used to control the water content of the substrate. Positive pressure will force water out of the tubes, while negative (suction) pressure within the tube only allows flow of water from the tube if the plants can actually transport water against this pressure gradient. The typical delivery pressures (suction) necessary for optimum growth of the plants on ‘naked’ porous tubes are often less than ≈ -125 Pa (≈-0.018 psi; 12 mm water column; see Goins et al., 1997, 1998; Levine et al., 1998a,b).

Most often, the tubes have been embedded within a substrate, but plants have been grown successfully on ‘naked’ tubes on the ground. The slight suction pressure within the porous distribution system is intended to ensure that the root zone is not flooded. Although the plant root system is capable of withdrawing water against this negative pressure, the amount of available water is related to the magnitude of the suction pressure. Less than optimal growing conditions will result if enough water is not available. The best plant growth results have been obtained with the smallest suction pressure (Goins et al., 1998) that can be reliably controlled by the pressure control system. Using such small suction pressures on Earth is further complicated by the fact that the hydrostatic pressure across the porous tube system is often larger than the desired suction pressure setpoint, and water may ‘pool’ on the bottom during 1-g operation.

For smaller plants and low water re-supply flow rates, and to prevent any accidental flooding of the substrate, spaceflight nutrient delivery systems to date have been operated under slight suction pressures only. At very high transpiration rates, and based on the backpressure of the porous tube delivery system, positive tube pressure may be required at peak water demand rates (Scovazzo, 2001). For positive delivery pressures, pressure alone can no longer be used to control the water availability to plants without the risk of flooding, and additional sensors such as substrate moisture sensors may be necessary for proper control. With the increasing availability of adequate soil moisture sensors for small spaceflight plant growth systems (Meek, 1999; Wells, et al., 2000, Levine, 1998; Norikane, 2002), additional control schemes may emerge. The challenges to control the low suction pressure in the nutrient delivery systems are the same as outlined for humidity control systems.

SYSTEM INTEGRATION - CLOSED WATER CYCLE

Since safety requirements (containment) as well as the desire to maintain a plant-optimized environment (isolation) typically require a sealed plant chamber (Figure 2), evapo-transpiration water can be easily condensed in the humidity control system, and returned to the plants through the nutrient delivery and root zone hydration system. This reduces the need for large amounts of water resupply, and only nutrients may need to be added over time. In addition, some make-up water to compensate for unavoidable losses through atmospheric leakage and during harvest operations may need to be provided. Water on ISS may not be suitable for plant growth due to the addition of biocides and silver, and each plant chamber would need to supply its own suitable water source.

Recycling the humidity condensate may create the small risk that a harmful contaminant may be spread to the entire plant growth system through the water (dissolved gas contaminant, compounds leaching from the water distribution system, infection). Spreading of infections may be controlled through microbial check valves. Careful material selection and proper design may reduce the risks to plants through dissolved contaminants.

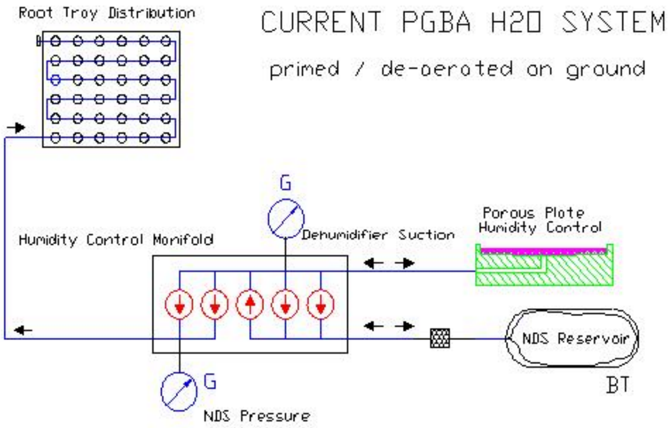

Figure 1. Humidity control – cooling the porous plate below the dew point results in condensation of water on the porous plate, from where it can be pumped back to the root zone and/or to a reservoir.

For short periods of time (weeks), the soil moisture may be kept fairly constant by just returning the evapo-transpiration water from the humidity control system to the root zone, even without actual knowledge of the soil moisture content. With unavoidable water vapor losses to the atmosphere environment outside the plant chamber, water may ultimately be lost from the system over longer periods of time (months). Porous tube root zone hydration systems can accommodate this loss of water and use pressure feedback and makeup water as a means to control the system water content. In substrate systems with porous tubes, the water content is in equilibrium with the porous tube pressure. Substrate systems without pressure control would require other sensor feedback, such as soil moisture sensors, to detect and compensate for water loss.

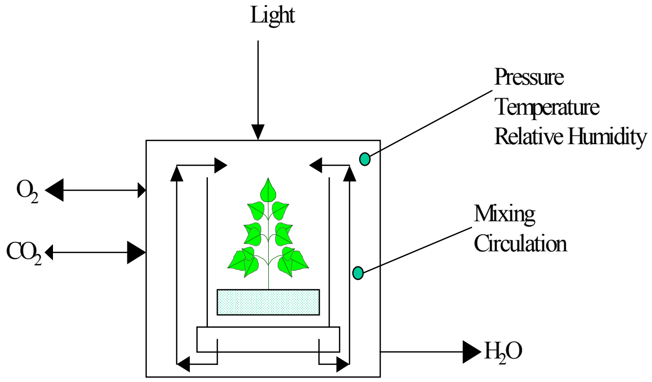

Figure 2. Environmentally sealed plant chamber with temperature-controlled walls for temperature control, and temperature-controlled dew point controller for humidity control.

OPERATIONAL ASPECTS

Crew time availability for payload operation aboard ISS is limited due to the limited crew size and the necessary housekeeping tasks. Most air-cooled payloads and all powered payloads received daily status checks and air inlet cleaning to ensure proper functionality (5 min/day). Plant harvest operations can take 2-4 hours for the currently available plant systems, depending on what type of data collection and sample processing is necessary. Multiple plant harvests or re-seeding may be necessary to establish a time course of microgravity exposure. Most plant systems will be powered down for crew access, leaving the systems without computer control. This may pose a risk to the suction pressure maintenance of the dehumidification system. Passive safety features must be included to ensure that the payload remains in proper operational configuration even if crew operations get interrupted, or the payload is unpowered over extended periods of time. Unpowered transfer operations to/from the Shuttle and ISS are typically accomplished within 15-30 minutes, and typically can be accommodated by the payload. Unpowered launch and landing of dry systems greatly enhances launch opportunities due to limited power resources during ascent and descent.

DESIGN OF POROUS MEDIA SYSTEMS

POROUS MATERIAL SELECTION

There are several readily available membrane materials, including sintered metals, ceramics and various polymers. Available pore sizes range from 0.2µm to 100µm effective pore size, or media grade. Key aspects in the selection of porous media include:

- Uniform pore size for reliable pressure control, small enough for selected minimum pump flow rate.
- Acceptable thermal conductivity to cool water vapor below due point.
- Acceptable materials compatibility with plants, if condensate is returned for watering plants (metal contamination).
- Corrosion-resistant over expected usage time.
- Sufficient strength to sustain flight and user abuse loads.
- Small pore size may aid in biological contamination control ('microbial check valve') to prevent spreading of water-born diseases.
- Acceptable lifetime – several polymer / polyester membranes have superior performance data, but very short life times, rendering them currently useless for spaceflight systems.

Sintered stainless steel membrane materials have been used for several plant chamber payload designs, due to their ease of use, availability, acceptable thermal conductivity and strength against applied mechanical loads. Other materials may show improved performance in certain aspects, but to date, only stainless steel materials have been used for flight. The Astropore™ series of temperature-humidity control systems (WCSAR, Zhou et al., 1996, 1997) employs porous tube (knobs) systems, while other payload designs used porous plate system (Hoehn et al., 1998; Morrow et al., 1999, 2002; Scovazzo, 1996, 1998, 2001), mainly due to different systems integration and performance requirements.

Hydrophilic porous ceramic material may be easier to wet, but doesn't perform well in dew-point humidity control systems due to its low thermal conductivity, but may be advantageous for nutrient delivery applications. Uniformity and reproducibility of the quality of porous materials varies for different materials. To date, best results were obtained with stainless steel materials, but new materials are now available.

Thermal Optimization

The composition of the membrane material also affects the temperature gradient across the membrane based on the heat transport, both from condensing water and convective heat transfer to the membrane. It is important for highest system performance to minimize the temperature gradient across the porous membrane. This is best accomplished with a material of high thermal conductivity and minimal thickness between the air-exposed surface and the heat pump. Other factors that affect the surface temperature of the plate and the temperature gradient are:

- Temperature and water content of the air flowing over the membrane.
- Convective heat transfer coefficient between airflow and porous membrane / turbulence.
- Required airflow to transport adequate amounts of water in form of moisture to the membrane to control humidity.
- Heat pump capacity and minimal allowable temperatures.

Pore Size Selection

The largest pore size or leak / hole in the assembly defines the maximum allowable suction pressure before air may enter the fully water-filled porous matrix (air entry pressure). Exceeding this pressure will break the prime and renders the system inoperable. Simplified, the air entry pressure can be assessed by (Table 1):

$$P = \frac{2*\sigma}{r},$$

with r = largest pore size, σ = surface tension (assume: contact angle = 90°).

Table 1. Bubble pressure for sintered stainless steel membranes of different pore sizes (Mott). A fully primed (water-filled) membrane under suction pressure will let air pass once the bubble pressure is exceeded. Bubble point is affected by contact angle, which in turn is affected by material, surface treatment, contamination and plate preparation. Porous stainless steel plate pore size is not defined by the actual pore diameter, but by the capability to retain particles of the given size.

Pore	Bubble Pressure - Sintered SS (Mott)				
[um]	in HG	in H2O	psi	Pa	atm
0.2	5.60	76.16	2.751	18971	0.1872
0.5	2.60	35.36	1.277	8808	0.0869
1.0	2.35	32.00	1.156	7971	0.0787
2.0	1.60	21.70	0.784	5405	0.0533
5.0	1.21	16.50	0.596	4110	0.0406
10.0	0.68	9.20	0.332	2292	0.0226
20.0	0.40	5.50	0.199	1370	0.0135
40.0	0.26	3.50	0.126	872	0.0086
100.0	0.07	0.90	0.033	224	0.0022

In general, larger pore sizes are easier to prime, but pressure control becomes more demanding, and the risk to exceed the maximum allowable cross-membrane differential pressure increases. Therefore, the smallest pore size, with the highest bubble point, provides the highest operational safety margin for spaceflight, but may be difficult to prime on orbit to be useful. The design thus requires a careful balance between ease of priming and the risk of loss of prime.

Operational aspects / life time

Over time, flow capacity of the membrane may decay due to deposits, damage to the porous surface, bacterial growth / biofilm. Plates have been successfully cleaned in ultrasonic cleaners with cleaning agents, and could be rejuvenated for continued use. The PGBA plates have been used for up to 1 year without impacting the PGBA performance, but are always changed out with new plates prior to a flight. End-of-life tests or in-flight health assessment tests have not yet been developed. Passivation of the stainless steel plates should reduce, if not eliminate, the leaching of metal alloys into the water, which could ultimately poison the plants or cause deposits / blockage of the pores. Passivation with citric acid also improved wetting characteristics (Geissinger, 2003) and overall plate performance.

PRESSURE CONTROL

Both the porous tube nutrient delivery system and the porous membrane humidity control system require accurate control of trans-membrane pressure. Depending on pore size, pressure may need to be controlled to levels in the range of ≈-25 → -250 Pa. The sensor needs to be able to measure in a saline (nutrient delivery) water environment, with electric conductivity in the range of 2 mS/cm.

Ambient pressure changes on Shuttle and ISS potentially affect the pressure controller. The Space Shuttle undergoes a leak test to 116 kPa (16.2 psi) on the pad from 101 kPa (14.7 psi_a) ambient, and EVA de-/ re-pressurization rates as high as 2 psi/min (explosive decompression at 9 psi/min shall not create a hazard). This can provide a dynamic pressure environment to which the controller must be able to adjust quickly in order to maintain the proper cross-membrane pressure. Designs for ISS must also be able to withstand exposure to space vacuum in case of cabin depressurization (leak, fire suppression) without leakage (non-operational).

System Stability of Unpowered Systems

During crew-assisted operations such as harvesting, sowing, plant health inspections, NASA payload safety regulations and the unique payload design features often require that the plant chamber be unpowered. Power is also not always available on launch and landing, requiring payloads to sustain several days without power. Without power, the computer can no longer control the chamber environment, and especially the pressure of the porous plate. At the same time, water may evaporate from the primed, porous humidity control membrane when the chamber is open and exposed to the crew cabin (typically 40-60% rH). The evaporation of water may potentially lead to loss of prime. The humidity control system should either be able to passively maintain a minimum cross-membrane pressure (such as through a pressure-limiting check valve to the reservoir), or the control system must be capable for re- establishing prime on orbit.

Based on the external humidity of the spacecraft atmosphere and the leakage rate of the sealed chamber, the fully primed system may be able to remain unpowered for several days and not loose prime. During crew-assisted operations with open plant chamber, however, water losses to the crew cabin may be high enough to loose prime, unless passive design features can feed water to the membrane even without power and computer control. Control algorithms and procedures to re-gain prime on orbit are currently under development for several of the existing plant chamber designs.

Pumps

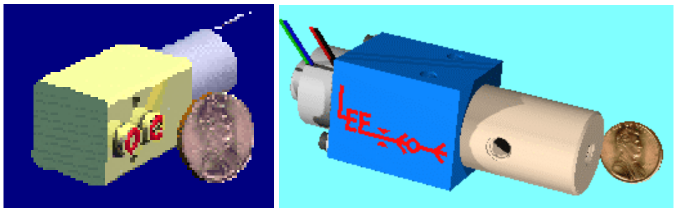

Figure 3. Fixed volume pump (left, as low as 10 µL/stroke; internal valves) and variable volume pump (as low as 50 µL/500 steps stepper motor; i.e., 0.1 µL/step; requires external valves) used in PGBA pressure control (from: The Lee Company).

Since water is an incompressible fluid, small volumetric changes result in large pressure changes. A pump that is able move very small amounts of water to minimize pressure changes is necessary. Miniature piston-pumps (fixed 50µl/stroke, Figure 3 left), or miniature stepper motor-driven, positive displacement pumps (≈0.1µl/step; 500 steps per stroke, Figure 3 right) have often been used to meet this requirement. Metering capabilities should be provided, as scientist typically want to know the volume of condensed water, as it is a rough indicator of the integrated evapo-transpiration rate, and a potential means of plant-physiological performance assessment.

An ideal pump would allow infinitely small volumetric changes to accurately maintain the desired setpoint suction pressure. The use of fixed volume pumps (0.1 to 50 µL), together with the flexibility of the system (bowing of the porous membrane under pressure, flexible tubing) results in dynamic pressure responses that may pose control problems (Figure 4). Flow rates are very small - example PGBA: 300 mL/day = 500 µL/min = 5 piston pump strokes per minute. Figure 4 shows one stroke every ≈60 seconds.

Pressure Sensor

Depending on the chosen pore size, relatively small pressures must be measured accurately in both gravity and micro-gravity environments. Sensor placement should consider hydrostatic pressure effects in the normal 1-g environment, as it may affect sensor calibration. On-orbit performance may be altered if the sensor is not appropriately placed and calibrated to consider gravity effects. The use of fixed volume piston pumps may send a pressure wave through the system, and the control software must be adjusted to the dynamic behavior after pump actuation through insertion of a time delay.

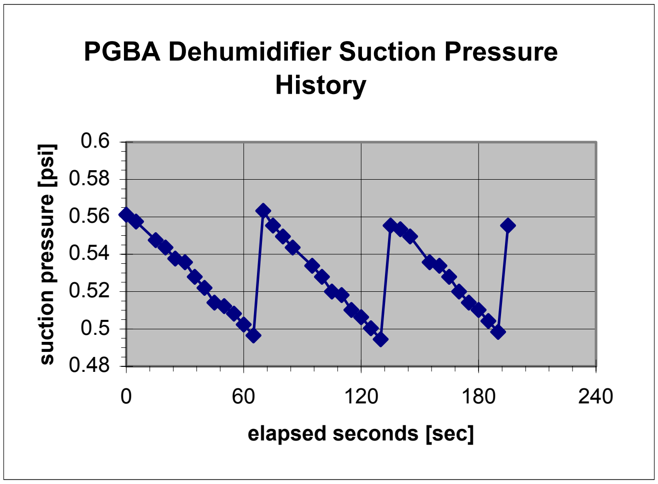

Figure 4. Dynamic pressure response of the PGBA dehumidifier with a 100μL pump discharge volume from the porous plate. The plate is very flexible and minimizes the pressure swings. Suction pressure setpoint is -0.5psi$_d$. The pressure increases slowly due to condensation of water. Once the setpoint of -0.5 psi$_d$ is reached, the pumps remove 100μL water, and the suction pressure decreases rapidly. Each pump activation (100μL) changes the pressure by ≈0.05psi$_d$ in this configuration.

Calibration of the sensor to maintain a suction pressure of –250 Pa on the tube can be challenging with a tube diameter of ∅2.5 cm. A hydrostatic pressure of 250 Pa already exists across the tube in a gravity field. Depending on sensor location and where the pressure is actually measured, the top of the tube experiences a suction pressure of 250 Pa higher than the bottom. Small calibration errors can yield positive pressures on the bottom of the tube (and subsequent dripping), while the top of the tube is under suction as desired. Once on orbit, the problems associated with hydrostatic pressure will disappear, but parallel ground or centrifuge experiments may be impossible at low suction pressures.

Air inclusion in the pressure sensor lines can lead to offsets in pressure readings due to their effects on hydrostatic pressure, surface tension effects and wetting angles in the same order of magnitude as the desired suction pressure control (250 Pa). Ideally, the system should be air-bubble free to avoid sensor offsets between 1-g and μg environments. Very few sensors for the required small size, small pressure range and with proper materials compatibility are readily available.

HUMIDITY CONTROL SYSTEM SIZING

SYSTEM SCALING

Several factors affect the size and performance of the humidity control system and are discussed below, such as a) expected evapo-transpiration rate, b) mass flow of moist air to the porous plate, c) mass flow of condensed water through the plate, and d) heat transfer and heat pump capacity.

Expected evapo-transpiration rates

Humidity control in the sealed plant chamber typically involves water vapor removal from the system. This process is ‘expensive’, as it typically requires power-intensive heat pump systems to condense the water vapor. As spaceflight systems are always power-limited, the amount of water condensation should be minimized. An ideal spaceflight system would therefore eliminate evaporation losses from the root zone, and reduce the required condensation to the plant transpiration.

In PGBA, the soil root substrate is enclosed in gas-permeable polyethylene membranes, while the entire root-shoot zone is covered with a white or gray retaining plate. In this configuration, with light levels of 200-300μmol PAR•m^{-2}•s^{-1} and a 0.075m^2 growth area, the following evapo-transpiration rates were measured at steady-state humidity of ≈80% rH:

Pine seedlings, 1-2 years, 15 trees	≈600 ml/day.
Wheat, <21 days old, ≈140 seedlings,	≈300 ml/day.

Mass flow of moist air to the porous membrane

Spaceflight plant chambers are typically operated with a desired setpoint between 70 and 85% rH, with potentially higher humidity levels during germination. Air circulation within the chamber is necessary to provide:

- Forced convective heat transfer (heat removal from plants and hardware to the temperature control surfaces).
- Transport of water vapor from within the chamber to the humidity control surface.
- Reduction of gradients throughout the chamber, i.e., mixing of air for proper gas composition control.

The airflow rate and the moisture content of the air limit the amount of water that can be condensed and removed from the air stream. Figure 5 shows the obtained condensation rates in a 20°C plant chamber, at 3 different humidity conditions, as a function of membrane surface temperature. The area of the humidity control surface and the flow rate of moist air to the surface determine the maximum condensation rate for that humidity control system. Data in Figure 5 may be used to scale the required dehumidifier surface area for a given system based on the expected evapo-transpiration rate. The rate of condensation per area could be increased with higher transport rates to the plate, or lower temperatures, but temperatures below 0°C are not possible due to freezing.

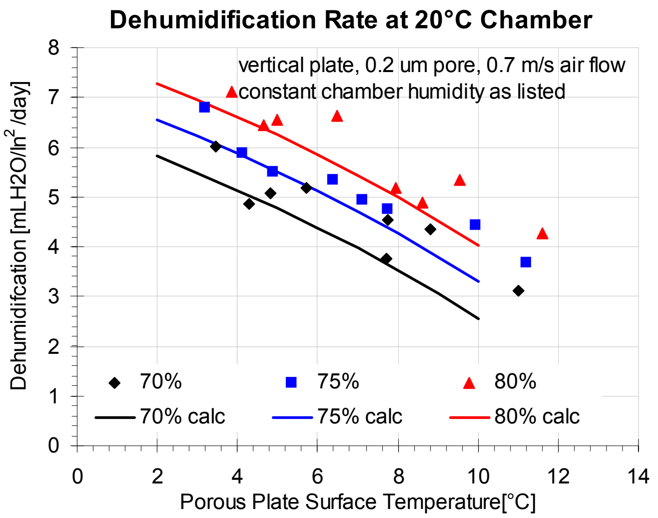

Figure 5. Rate of condensation per day on a 14.5cm² porous plate at various plate surface temperatures and ambient humidity (70, 75, 80%). The rate in these tests is believed to be limited by the transport of moisture to the plate. The plate was operated vertically, in an environmentally controlled plant chamber at 20°C and the noted chamber humidity.

Mass flow through the plate

The water condensing on the plate increases the trans-membrane pressure as water follows the pressure gradient and enters the porous material and water-filled cavity behind. The water must be removed from the system in order to maintain the desired cross-membrane suction pressure. The flow is limited by the pump capacity and the pressure-dependent flow rate based on the backpressure (resistance) within the porous material. The small piston pumps employed in PGBA provide a flow rate of 50 µL/stroke, with up to two strokes per second, for a maximum flow rate of 6 mL/min or 8,640 mL/day (typical evapo-transpiration in PGBA: <600 mL/day).

Therefore, neither pump flow rate nor pressure-dependent trans-membrane flow arte are typically limiting. In most cases, the heat pump capacity will be limiting the dehumidifier capacity and performance.

Heat Pump Scaling

The heat pump must be capable of cooling the moist air stream in the boundary layer to below the dew point so that water vapor can condense and be removed from the plant chamber. Therefore, both convective heat transfer between the air stream and the cold surface, and the latent heat of condensation must be considered. The heat pump capacity at a given plate temperature will limit the maximum possible rate of condensation. The heat pump must also account for heat losses and parasitic heat conducted / convected to the cold dehumidification system. Without proper insulation and careful design layout, these losses can be dominant. All components that are cooled below the dew point, but are not part of the porous membrane dehumidification system, must be carefully insulated with airtight, closed cell foam and waterproofed to prevent uncontrolled and undesirable condensation.

$$Q_{required} = Q_{convection} + Q_{condensation} + Q_{losses}$$

$$Q_{convection} = h * A * (T_{air} - T_{plate}) \quad \text{Ex: } Q_{convection} = 11.2 \text{ Watt}$$

$$Q_{condensation} = \dot{m} * L \quad \text{Ex: } Q_{condensation} = 8.7 \text{ Watt}$$

PGBA example with:
$h \approx 50$ Watt/m², $A = 0.3x0.05=0.015m^2$, T_{air}=25°C, T_{plate}=10°C. m_{dot}=0.3kg/day, L=2500 $J*kg^{-1}$.

Additional heat pump capacity may be necessary due to parasitic heat conducted from the chamber structure. It should be noted that the humidity control system might contribute substantially to the heat transfer from the plant chamber (i.e., temperature control). Humidity control operation during a night cycle, when heat dissipation from the lights into the chamber is at a minimum, typically requires reheating of the air stream after humidity control to maintain the desired chamber temperature.

Heat pumping is very 'expensive' in spaceflight applications (power, mass, volume); therefore it is mandatory to minimize the load. This can be done through careful design of the plant chamber and the root zone. The chamber should be insulated from the typical hotter ambient environment. Heat sources within the chamber should be limited to reduce the required heat pump capacity for temperature control. Especially the light sources must be located outside the chamber, and radiative heating can be further minimized through optical coatings, while maximizing the light transmissivity into the chamber. The water losses from the root zone, which contains most of the water other than that stored within the plants, must be minimized while maintaining good gas exchange to the root zone. The ideal plant growth system would then only deal with transpiration water losses from the plants, while evaporative water losses from the soil are minimal. This is typically accomplished by containing the root zone in a gas-permeable and light-tight / light-reflecting membrane. This membrane should allow adequate carbon-dioxide and oxygen transfer for root respiration, have minimal water vapor permeability, be light-tight to prevent algae growth within the root zone, and reflect light back to the plants to reduce root zone heating and maximize light availability to the plants. Too high reflectivity may disorient plants in the absence of gravity as a directional stimulus.

POROUS MATERIAL PREPARATION

Priming

For proper function and highest mass-flow capacity, the porous material must be primed properly, i.e., all pores must be filled with water. Air inclusions reduce the flow capacity, and remaining air passages across the membrane disable the system (lost prime). Larger pore sizes are easier to prime (fill with water), but require more accurate pressure control and have lower air entry pressures; air entry results in the failure of the system due to loss of prime.

Best priming results were routinely obtained with citric acid passivated porous materials (Geissinger, 2003), then pre-treating the system with water-soluble carbon dioxide prior to water injection, but other options exist for on-orbit priming, such as priming by water immersion/soaking of the membrane, or pretreatment with a wetting agent (Scovazzo et al., 1997, 1998, 2000a,b).

Repriming a still wet porous system is not trivial once prime has been lost and air entered the membrane. It may be necessary to fully dry the system before repriming is possible. Alternatively, the air inclusion may be 'flushed' from the system, if the design allows for this operation (additional pumps, plumbing, gas-liquid separation – bubble trap, automated algorithms). Typically, these technologies are not yet implemented.

Surface Treatment - Corrosion

To reduce the risk of materials 'leaching' from the stainless steel porous membrane material, or any components of the plumbing system, it is highly recommended to passivate all components in contact with the condensing and pumped water. Different passivation protocols can be used for metal and plastic components. Many of the materials that could leach from the fluid system can reach toxic levels for the plants.

Furthermore, the use of de-ionized water may cause corrosion even for stainless steel components. SS316 is recommended for its higher compatibility with de-ionized water, but it should still be passivated. Citric acid passivation also improved wetting and priming of the porous steel system (Geissinger, 2003).

ACCEPTANCE TESTING

When preparing the system for use, several tests are advisable to ensure proper operations, especially prior to flight. The porous membrane system could have assembly flaws / leaks, the porous media could have become clogged through deposits (water impurities, metal ions and salt deposits), or the system may not have been primed properly, leaving air inclusions within the membrane. Flow tests and air entry pressure tests are described below.

Flow Tests

On occasions, porous surfaces have become clogged with deposits during use, and may not be able to provide the necessary water transport characteristics. During spaceflight operations, water may still condense on the surface, but the applied suction pressure may be insufficient to remove the water from the chamber at fast enough rates, resulting in pooling of water. A 'quick' test to assess the capacity of the plate is to measure the flow rate of water, at a given suction pressure. The water is made available freely on the membrane surface for test purposes (Figure 6). If the available flow rate is within acceptable tolerance levels based on historic test data, the membrane can be accepted for use.

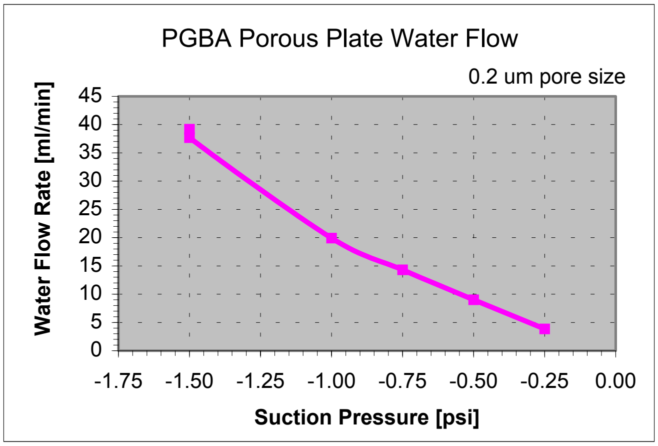

Figure 6. Mass flow rate through PGBA stainless steel porous plate as function of cross-membrane suction pressure. A 'typical' rate of condensation for a mature crop in PGBA is ≈300-600 ml/day, or <0.42 mL/min. For the nominal PGBA suction pressure of -0.5 to -0.75 psi, pressure is not the limiting factor. Plate size is 300 cm^2.

Air Entry (Leak) Pressure Test

To verify that the system is properly sealed and has no leaks or flaws in the porous plate, the system can be fully primed, sealed and left to 'dry'. As water evaporates from the plate, the cross-membrane pressure decreases. The suction pressure at which air enters the system is a function of both the smallest pore size and the quality of priming. Once it can be established that the plate or the seals have no defects with diameters larger than the desired pore size of the plate, the membrane assembly can be accepted for use (Figure 7). Best quality prime can be accomplished with the following steps performed prior to operation of the dehumidifier:

- Cleaned / pristine porous membrane material.
- Citric acid passivated stainless steel material.
- Flushing of the dry system with water-soluble CO_2 gas prior to water fill.
- Water-fill and multiple flush with distilled and filtered water (system components are not compatible with de-ionized water).

Once prepared for use and filled with water, a similar test can be performed to verify that an acceptable prime has been accomplished. A test suction pressure can be applied (typically 50% of theoretical air entry pressure) – if air doesn't enter the system, the porous membrane system can be accepted for use. If air does enter under the test pressure, the membrane must be dried and reprimed (Figure 7).

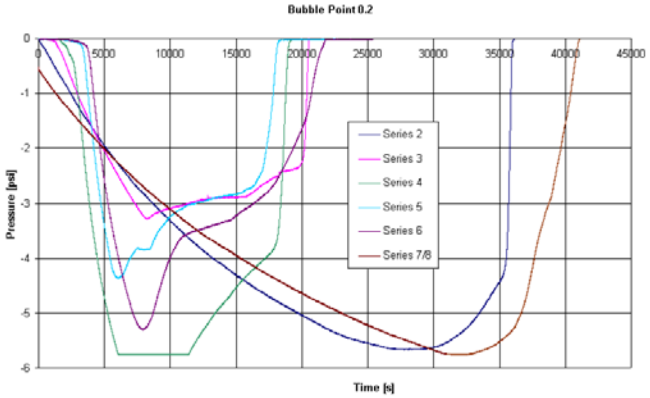

Figure 7. Air entry pressure tests with 0.2μ media grade plates. Plates were left to 'dry'. As water evaporated, the suction pressure in the membrane increased until air entered the system, and the pressure in the membrane rapidly increased to ambient pressure. The 'best' primed and sealed system achieved the lowest suction pressure prior to air entry. Different plate treatments and priming methods were used for the different test series to develop methods to detect 'good' and 'bad' prime (see Geissinger, 2003).

EXAMPLE: PGBA HUMIDITY CONTORL SYSTEM

The PGBA Plant Growth System uses a single 0.2μm media grade stainless steel porous plate, which provides the highest air entry pressure and therefore highest operational stability (Figure 8-9). The large size of the plate (30cm x 10 cm) and a 1.5 mm water gap behind the plate allow the plate to flex and reduce pressure swings in response to the 2x50μL = 100μL pump strokes. In this configuration, each stroke of the two parallel piston pumps results in a 0.05 psi incremental pressure change (Figure 4), allowing fine pressure control with ≈350 Pa (0.05 psi) step resolution. Two pumps are used in parallel for redundancy. Without this flexible design, smaller pump strokes would be necessary to prevent the controller from exceeding the maximum allowable suction pressure. Stepper-motor driven pumps of similar design allow volumetric resolutions of as small as 0.1μL per step.

The dehumidifier pressure control and nutrient delivery pump system is shown in Figure 1. One set of redundant pumps decrease the pressure behind the porous plate by pumping the condensed water from the dehumidifier to the plants. A second set of pumps can pump water from the dehumidifier to a reservoir to effectively remove water from the system. A single pump is used to move water to the plate, in case re-humidification is necessary. The plate is cooled by temperature-controlled water flow behind the membrane. This coolant flow is separate from the water condensate flow. Alternatively, the plate temperature can be controlled directly by heat pumps mounted to the dehumidifier, if the payload geometry allows this.

Figure 8. PGBA humidity control porous plate (0.2μm media grade) inside the sealed plant chamber (plant insert removed).

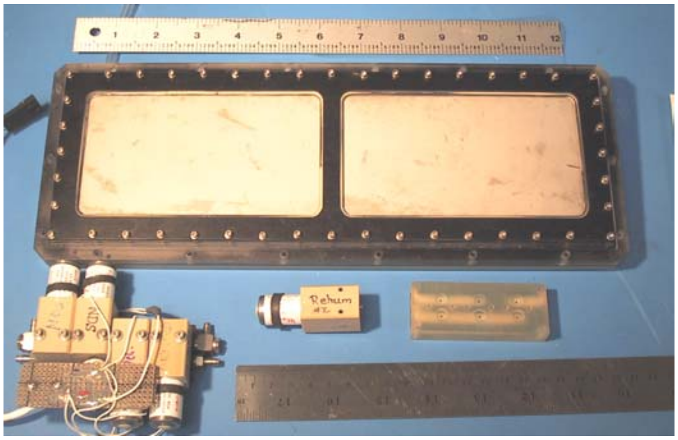

Figure 9 PGBA Humidity control porous plate (0.2μm media grade), with 50μL/stroke fixed volume piston pumps, pump manifold and individual pump and manifold.

CONCLUSION

Porous membrane systems for humidity and root zone water availability control play an important role in the design and operation of space life sciences payloads. These systems have matured to a point where routine operation in the spaceflight environment are now possible for operational times of weeks and months. However, the systems are vulnerable, and pose single point failure risks for the entire experiment. Redundant systems are difficult to include in the designs due to limited mass and volume, and therefore, robust, high-reliability components are necessary. The payloads are typically difficult to repair (inaccessible), maintain or re-initiate on orbit, and replacement parts are not readily available. Current payload designs and increased payload operations on the international space station will help to increase the necessary knowledge base, and will help to further increase the reliability and performance of these systems. Further improvements are necessary for on-orbit initiation or error correction, both autonomously and through crew assist. Redundant systems, or subsystem replacement units are recommended.

CONTACT

Dr. Alex Hoehn is the associate director of engineering of BioServe Space Technologies, a NASA Research Partnership (formerly: Commercial Space) Center, located at the University of Colorado, Aerospace Engineering Sciences, in Boulder. He can be reached at: BioServe Space Technologies - University of Colorado, 429 UCB, Boulder, CO 80309-0429, USA. Tel: +1-303-492-5875. Fax: +1-303-492-8883. email: alexander.hoehn@colorado.edu.

ACKNOWLEDGMENTS

This research and space flight program is supported by NASA grants: NASA-MAR: NCC8-131 (NASA MSFC cooperative agreement) and NASA-NCC2-5290 (NASA Ames cooperative agreement).

REFERENCES

1. Burtness, K.A., Norwood, K.L.L., and Levine, H.G. (2002)" "Development of a Porous Tube Based Plant Growth Apparatus". *Proceedings, 32nd ICES, SAE paper 2002-01-2389*.
2. Geissinger, T. (2003): "Design, Testing, Operation and Systems Engineering Optimization of Porous Media for Dehumidification in Microgravity Plant Growth Systems". *Diplomarbeit (Master's Thesis)*, Lehrstuhl für Raumfahrttechnik, Technische Univeristät München (in English).
3. Goins, G.D., Yoria, N.C., Vivenzio, H.R. (1998): "Performance of Salad-Type Plants Using Lighting and Nutrient Delivery Concepts Intended for Spaceflight", *Proceedings, 28th ICES, SAE paper 98-1554*.
4. Goins, G.D., Levine, H.G., Mackowiak, C.L., Wheeler, R.M., Carr, J.D., Ming, D.W. (1997): "Comparison Studies of Candidate Nutrient Delivery Systems for Plant Cultivation in Space". *Proceedings 27th ICES, SAE paper 97-2304*.
5. Hoehn, A., Scovazzo, P., Stodieck, L., Clawson, J., Kalinowski, W., Rakow, A. Simmons, D., Heyenga, A.G. and Kliss, M. (2000) "Microgravity Root Zone Hydration Systems". *Proceedings, 30th ICES SAE* paper 2000-01-2510. Toulouse, France; July 9-13, 2000.
6. Hoehn, A., Clawson, J.M., Heyenga, A.G., Scovazzo, P., Sterrett, K.S., Stodieck, L.S., Todd, P., and Kliss, M.H. (1998): "Mass transport in a spaceflight plant growth chamber." *Proceedings, 28th ICES, SAE paper 98-1553.*
7. The Lee Company, ElectroFluidic Systems Division, 2 Pettipaug Rd., PO Box 424, Westbrook, CT 06498-0424, USA. http://www.theleeco.com/.
8. Levine, H. Piastuch, W.C. and Dreschel, T.W. (1998a): "Development of a Microgravity-Rated Hydroponic Plant Culture Apparatus". Dynamic Corporation, Kennedy Space Center, FL.
9. Levine, H., Wells, B., Anderson, K., Piastuch, W., Moyer, J., Knott, W., Etheridge, G. (1998b): "Microgravity Plant Nutrient Experiment MPNE-01 Flight Report". Kennedy Space Center, FL.
10. Meek, D. (1999): personal communication, Applications Engineer, Campbell Scientific, Inc., 815 West 1800 North, Logan, UT 84321-1784. Phone: 435-750-9555. Model 229-L matric potential sensor (miniature heat dissipation sensor, embedded inside a hypodermic needle). For explanation, see also: (http://parker.ou.edu/~jbasara/229l.html
11. Morrow, R. C., Frank, J. G. Stolp, K. M., and Lee, M. C. (2002): "Biomass Production System (BPS) Ground Based Performance Testing", *Proceedings, 32nd ICES, SAE paper 2002-01-2482,* San Antonio, Texas.
12. Morrow, R.C. and T. M. Crabb (1999): "Biomass Production System (BPS) Environmental Control Subsystem Performance". *Proceedings, 29th ICES, SAE paper 1999-01-2180*.
13. Mott Corporation Resource Center, "*Porous Metal Overview"*, Mott Corporation, 84 Spring Lane, Farmington, CT 06032 – 3159, www.mottcorp.com.
14. Norikane, J.H., Tyners, G.K., Frazier, C.M, and Levine, H.G. (2002): "Evaluation of Two Soil Moisture Sensor Designs for Spaceflight Applications". *Proceedings, 32nd ICES, SAE paper 2002-01-2385*.
15. Scovazzo, P., Illangasekare, T.H., Hoehn, A., and Todd, P. (2001): "Modeling of two-phase flow in membranes and porous media in microgravity as applied to plant irrigation in space". *Water Resources Res*. 37(5): 1231-1243.
16. Scovazzo, P., Hoehn, A., and Todd, P. (2000a): "Methods for Saturating Rigid Porous Membranes with Water". *American Laboratory*. In print.
17. Scovazzo, P., Todd, P., Hoehn, A. (2000b): "Membrane Porosity and Hydrophilic Membrane-based Dehumidification Performance", *Journal of Membrane Science*, vol. 167, pp. 217-225.
18. Scovazzo, P., Burgos, J., Hoehn, A., and Todd, P. (1998a): "Hydrophilic membrane-based humidity control." *J. Membrane Sci.,* Oct 14, 1998, 149(1): 69-81.

19. Scovazzo, P. (1998b): “Multiple-phase mass transport in membranes and porous media in low gravity experiments.” *Thesis (Ph.D.)*, University of Colorado.
20. Scovazzo, P., Todd, P., Burgos, J., Lattarulo, N., Hoehn, A. (1997): “Membrane-Based Humidity Control in Microgravity: A Comparison of Membrane Materials and Design Equations”*, Proceedings, 27th ICES, SAE paper 972275*, July 1997.
21. Scovazzo, P. (1996): “Membrane-based dehumidification for microgravity plant growth chambers.” *Thesis (M.S.)*, University of Colorado.
22. Wells, B., Hoehn, A. and Levine, H. (2000) “Collaborative development of a spaceflight experiment comparing two plant nutrient delivery systems”. *Proceedings, 30th ICES, SAE paper 2000-01-2509*, Toulouse, France; July 9-13, 2000.
23. Zhou, W.J., Bula, R.J. (1997): “Thermal Analysis and Control in the Astroculture™ Space-based Plant Chamber”. *27th ICES, SAE paper 972295*, July 14-17, 1997, Lake Tahoe.
24. Zhou, W.J., Bula, R.J., Duffie, N.A., Jetka, R.A. (1996): “State of the Art Commercial Plant Biotechnology Facility, CPBF”. In: *Proceedings, 2nd Space Technology & Applications International Forum (STAIF-96)*, Albuquerque, NM., pp. 1011-1017, January, 1998.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

A	Area.
cm, cm^2	centimeter, centimeter squared.
CO2	Carbon Dioxide.
COTS	Commercial of the Shelf.
g	Earth gravity, 9.81 ms^{-2}.
Hg	Mercury, hydrargyrum (lat. liquid silver).
H_2O	Water.
In	inch, 1 inch = 25.4 mm
ISS	International Space Station.
k	thermal conductivity in $W\ m^{-1}\ K^{-1}$.
Lbm.	Pound mass (1 kg = 2.2 lbm.).
MPNE	Microgravity Plant Nutrient Experiment.
mL	milli-liter.
mS	milli-Siemens; conductivity in Ampere/Volt.
N/A	not available, not applicable.
NASA	National Aeronautics and Space Administration.
NDS	Nutrient Delivery System.
Pa	Pascal; 101,325 Pa = 14.7 psi
PGBA	Plant Generic BioProcessing Apparatus.
psi	Pounds per Square Inch pressure, 14.7 psi = 101,325 Pa.
PTPNDS	Porous Tube Plant Nutrient Delivery System.
rH	Relative humidity [%].
STS	Space Transportation System.
T	Temperature.
W	Watt.
WCSAR	Wisconsin Center for Space Automation and Robotics.