CAPILLARY-DRIVEN ROOT MODULE DESIGN FOR MICROGRAVITY

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Abstract

A capillary-driven root module design for growing plants in microgravity is presented. Matrix-based root modules have been developed for conditions of microgravity which require active pumping or an elaborate control system to operate. The capillary-driven system is passive and relies on root uptake to develop the necessary gradient within the media to operate the liquid control valve. A collapsible reservoir supplies water to a porous membrane which maintains the system continuity. Porous membranes facilitate matric potential control and should be matched to the media and operating system limits. Membrane pore size is a key element of the capacity of the system suction. The media particle size should match the system operating limits to maintain adequate air-filled porosity and fluid conductivity.

Introduction

Researchers have proposed and/or tested systems to supply water and nutrients to plants in reduced gravity fields (Morrow et al., 1992, 1993, 1994; Ivanova et al., 1992b; Bugbee and Salisbury, 1989; Dreshel and Sager, 1989; Wright et al., 1988). Potential types of plant growth systems considered for microgravity include nutrient film, aeroponic, hydroponic and substrated hydroponic. Though hydroponic systems provide a more ideal rooting environment, matrix-based systems have the advantages of nutrient storage and liquid control via the matrix. Plants are proposed as part of a bioregenerative life support system for long duration space missions. In addition to being a source of food, plants remove carbon dioxide from cabin atmosphere, provide oxygen, and a source of potable water from transpiration. Soviet scientists have grown arabidopsis, radish, cabbage, and wheat plants on the space station "Mir". The plants developed somewhat abnormally and it is unknown if the effects of reduced gravity caused the abnormality or if the cause was due to observed environmental stresses (i.e. water, nutrient, oxygen).

Microgravity experiments of imbibition in porous media, conducted on the Mir space station, showed that 1 - 1.5 mm particles had higher hydraulic fluxes than 1.5 - 2.5, or 2.5 - 3.5 mm particles. Cosmonauts observed particle separation in the substrate and suggested this effect as a reason for differences in speed of propagation between ground and orbit. This phenomenon of particle separation may be one of the key problems for porous media research in microgravity. The loss of hydraulic continuity and resulting reduction in cross-sectional flow area are likely reasons for the differences of liquid imbibition into initially dry media noted in microgravity as compared to Earth. Podolsky and Mashinsky (1994) found substantial differences in the distribution of moisture on orbit, among four replicated experiments, compared to the ground controls. They suggested that magnified inertial and frictional forces in microgravity may counteract capillary forces.

US scientists, Morrow et al. (1992, 1993) showed that water transfer rates through a granular substrate (Arcellite) were higher in fine (0.35 - 0.65 mm) than in more coarse granules (0.65-1.00 mm) under various induced differential matric suctions. They also noted that water transfer rates were higher on the orbiting space shuttle than in ground tests.

Media having solid phase continuity have been proposed by Russian scientists as a plant growth media. Mashinsky et al. (1994) used a combination of different ion-exchange fabrics to support wheat growth in microgravity. Fibrous media could provide a more reliable (continuous) path for water transport, reducing the potential problem of particle separation and reduced hydraulic conductivity. Podolsky (1993) has suggested use of a sponge like media with air passage holes which are 2 to 13 times the

diameter of the water retaining pores. This media would also maintain a continuous path for water movement while providing large pores for gas exchange. These concepts have come about from the results of previous space flight experiments conducted by scientists from the former Soviet Block.

Here on Earth, researchers have attempted to provide optimum plant growth media for container grown plants by characterizing the physical properties of different media (Milks et al., 1989a and 1989b, Beardsell et al., 1979, Spomer 1974) and adjusting the proportions of various materials. Media which have been used include peat, tuff, sand, vermiculite, Perlite, bark, and rockwool. The main functions of the media are to anchor plant roots and to store and supply adequate amounts of water and nutrients while maintaining adequate gas exchange within the substrate. Most media should supply adequate anchorage of roots with the ideal media being light weight with low resistance to root penetration.

Even though differences have been observed between Earth bound and orbital liquid behavior in porous media, these differences appear to be within the realm of traditional porous media behavior. We therefore propose the use of proven soil physics models to design a capillary-driven root module for use in microgravity.

Theoretical

The pore-size distribution of a medium or substrate is characterized using the substrate-water characteristic (SWC). The van Genuchten equation for dimensionless water content, Θ, as a function of matric potential, h, is given as

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1+(\alpha_{VG}\, h)^n}\right]^{\frac{n-1}{n}} \tag{1}$$

where α_{VG} and n are empirical parameters and the assumption m = 1-1/n is used (van Genuchten, 1980). Water content is θ and the subscripts s and r refer to saturated and residual water contents, respectively.

The hydraulic conductivity, K(h), of the media is also expressed in terms of h and n using van Genuchten's (1980) equation given by

$$K(h) = K_s \frac{\left[1-(\alpha h)^{n-1}[1+(\alpha h)^n]^{\frac{1-n}{n}}\right]^2}{[1+(\alpha h)^n]^{\left(\frac{n-1}{2n}\right)}} \tag{2}$$

where K_s is the saturated hydraulic conductivity and may be inferred from the Kozeny-Carman (Bear, 1972; Koltermann and Gorelick, 1995) expression given as

$$K_s = \left(\frac{\rho g}{\mu}\right)\frac{D^2\, \Phi^3}{180\,(1-\Phi)^2} \tag{3}$$

where ρ, μ and g are the fluid density, viscosity, and gravitational force, combining to form the "fluidity term". The volume weighted particle diameter is D and Φ is the porosity of the media.

Having an estimate of unsaturated hydraulic conductivity allows the prediction of the one-dimensional liquid flux, q, using the Buckingham-Darcy equation

$$q = -K_s\, K(h)\left(\frac{\partial h}{\partial x}\right) \tag{4}$$

where h is the suction head and x is the distance.

These expressions allow the estimation of the water retention, hydraulic conductivity and liquid flux within porous media. These models will be used to provide criteria for the design of the root module.

Materials and Methods

Root modules made from Lexan (**Figure 1**) were designed and built with dimensions (15 x 30 x 12 cm) similar to modules used in the growth chamber, Svet, on board the Space Station Mir (Ivanova et al. 1993). Four different matric potential control membranes were tested (**Table 1**). Three of the membranes were flat sheets which separated the water supply chamber from the media compartment. Sheet materials consisted of 5 μm porous stainless steel, #400 Nylon monofilament screen, and 5 μm Polyester monofilament screen. The fourth
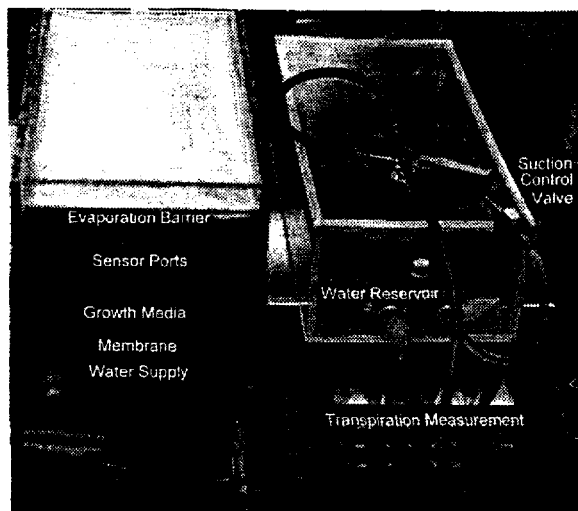
Figure 1. Capillary-driven root module (D) with membrane potential control via a spring-loaded check valve.

membrane was 1.27 cm (O.D.) x 0.95 cm (I.D.) tubing made of 0.5 μm porous stainless steel which served as both membrane and the liquid supply chamber. Nutrient solution was supplied to the module liquid supply reservoir from the liquid storage container, which for modules A, B, and C, was a 9 cm (I.D.) x 50 cm tall column (marriotte tower). A suction of 9 cm water column was maintained on the membranes by the marriotte tower. In module D (see **Figure 1**),

liquid was supplied by a 4 liter collapsible bag (No. 4432 I.V. container, Abbott Laboratories, North Chicago, IL) and the membrane potential was maintained at 8.4 ± 3.5 cm via a spring loaded check valve (Smart Products Inc. San Jose, CA).

Using a procedure to optimize the fluxes of liquids and gases to plant roots within the media (Jones, 1995), a quartz sand mixture was created for use as the growth media. The media was placed to a depth of 10 cm in each module and was initially saturated and allowed to drain in response to the matric potential of the membrane.

Water content of the sand was measured at 3, 7, and 9 cm depths using the CASMI time domain reflectometry system (TDR: Easy Test, Lublin, Poland). Pressure transducers (Micro Switch, Freeport, IL) hooked to 0.6 x 8.0 cm ceramic cups (Soil Moisture Equipment, Santa Barbara, CA) were used to measure matric potential of the media at 3, 7 and 9 cm depths. Oxygen concentration of the soil atmosphere was measured at a 7 cm depth using galvanic cell devices (Figaro USA, inc., Wilmette, IL; Jensen Instruments, Tocoma, WA). Instantaneous transpiration rates of module D were measured using a 12 kilogram capacity scale. Changes of water storage in the marriotte towers were recorded daily to determine transpiration in the other three modules (A, B, C).

Spring wheat (Yecoro Rojo) was planted

Table 1. Root module membrane characteristics.
†Mott Metallurgical Corp. Farmington, CT ‡Gilson Company, Inc. Worthington, OH

Module	Material	Pore size	Bubble Pressure	Membrane Thickness	Surface Area	Saturated conductivity
		μm	m	μm	cm^2	$cm\ d^{-1}$
A	Sstl. tubing†	0.5	+ 2	1570	430	1.3
B	Sstl. sheet†	5	0.7	1570	320	140
C	Nylon‡	38(#400)	0.9	100	320	41
D	Polyester‡	5	+ 2	65	150	0.17

in two rows at a density of 25 seeds per row. Media surface was covered with a polyethylene membrane to minimize evaporation. Lighting from fluorescent tubes was supplied at 200 umol m^{-2} s^{-1} PPF for the first 40 days, and from a 1000 W sodium vapor lamp during the last 40 days. Light intensity reached 1300 umol m^{-2} s^{-1} PPF under the sodium vapor lamp as measured with a Licor Quantum Meter (Licor, Lincoln, NE).

Results and Discussion

The performance of the matric potential control membrane is a key part of the root module. All four membranes maintained hydraulic continuity through 80 days of plant growth. Total water use for modules A, B, C, and D were 33, 34, 20, and 35 cm, respectively, with evaporation being less than three percent of transpiration. Extensive flooding in module C caused a drastic reduction in transpiration. After 48 days of plant growth, the light intensity above the canopy was increased to 1300 μmol m^{-2} s^{-1} in order to maximize root uptake within the module. During this peak period, transpiration reached daily rates of 1 cm day^{-1} and instantaneous rates from 2.5 to 3 cm day^{-1}. In modules A, B, and C, steady-state conditions were maintained even with these high fluxes, indicating the membrane

did not create a significant barrier to flow. In Module D however, matric potential measurements indicated increased gradients within the media during these high flux rates. Differences in measured matric potentials at 1, 3, and 7 cm above membrane D were less than the resolution of the pressure transducers. This is an indication that the majority of the pressure drop occurred across the membrane rather than through the media. **Figure 2** shows the calculated fluxes based on the saturated conductivity of membrane D and measured flux passing the membrane for a 24 hour period. More than half of the root mass developed directly on the membrane where most of the uptake likely occurred. The unsaturated conductivity of the media at the operating suction is 4 orders of magnitude greater than the conductivity of membrane D (see **Figure 3**). The gradient calculated from eq. **(2)** to maintain the peak transpiration of 3 cm day^{-1} is 2.2, 0.021, 0.073, and 18 for membranes A, B, C, and D, respectively. From this analysis it appears that a membrane conductivity less than the peak transpiration rate will require significant hydraulic gradient development across the membrane. Increasing membrane saturated conductivity, however, also leads to a reduction in the bubbling pressure of the membrane as illustrated in **Figure 3**. Selection of the membrane must
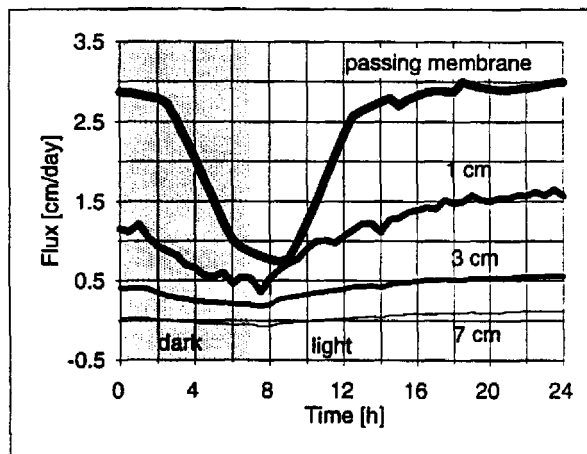

Figure 2. Measured flux passing the membrane and calculated flux rates passing tensiometers at 1, 3, and 7 cm above the membrane in root module D, 49 days after planting.
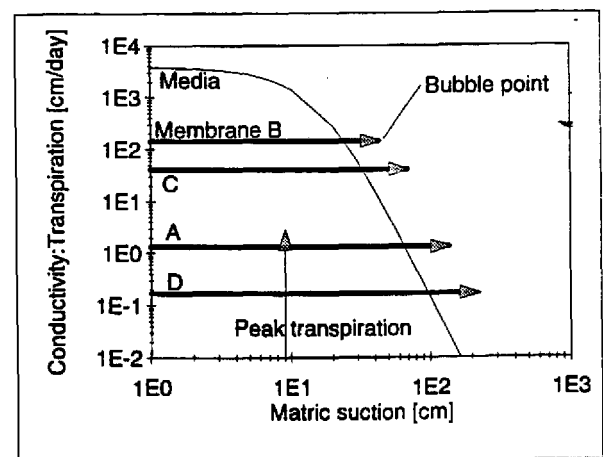

Figure 3. Saturated conductivity of membranes A, B, C, and D compared to the unsaturated conductivity of the media and peak transpiration rate. Bubble point indicates suction value at which membrane becomes unsaturated.
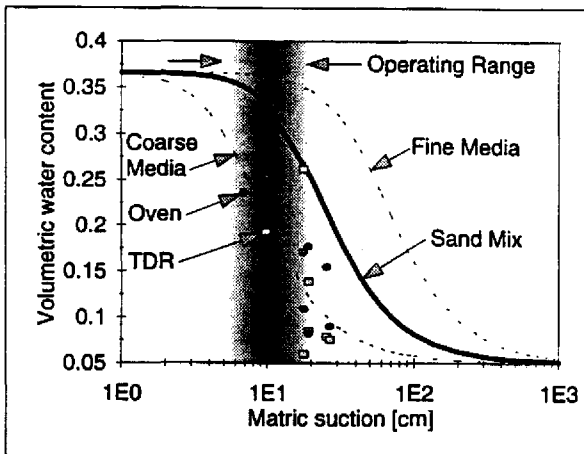
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Figure 4. Media water content as a function of matric suction with water content measurement using oven drying and TDR. Hypothetical fine and coarse media illustrate effects on water content at operating matric suction.
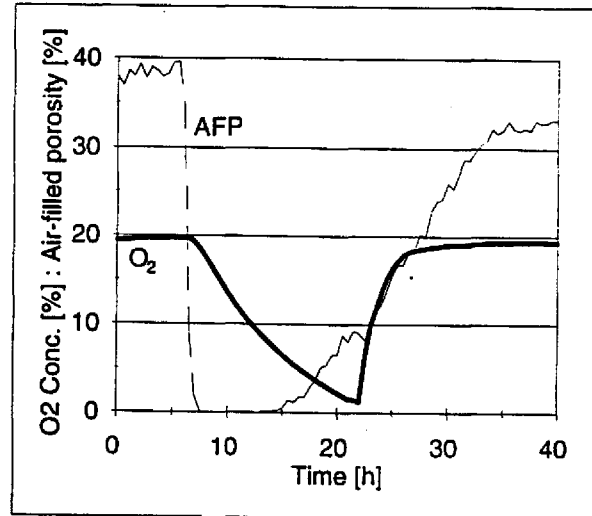

Figure 5. Effect of air-filled porosity (A.P.) on oxygen concentration at 3 cm above membrane A (7 cm below surface). Rapid depletion and resupply occur at about 10% A.P..

also consider the operating range of the suction control system.

The system operating suction is the key to controlling the water/aeration status of the media. The SWC of the media is described by eq. **(1)** where the water content is a function of the media potential. **Figure 4** illustrates the effect of the media particle size on the SWC. The central curve is the characteristic for media (quartz sand) used in this study. The media was optimized to operate at a matric suction of 20 cm, providing a minimum of 20 percent air-filled porosity assuming no gravity effects. In order to offset the effects of gravity on the distribution of water in the media profile, the suction control point was reduced to 9 cm. Even with this adjustment the media did not sustain the high water contents expected from the model. If the overall distribution of particle sizes is decreased, a hypothetical finer media results. The resulting water content for the finer media increases at the system operating potential. Conversely, a more coarse media would reduce the water held at the same matric potential. This reduction in water content would lead to a decrease in the unsaturated conductivity of the media. Ideally this decrease would not be less than the saturated conductivity of the supply membrane. While a reduction in water content

reduces liquid conductivity, it also increases the diffusion of gases by increasing air-filled porosity (A.P.). **Figure 5** shows the decrease in oxygen content with an increase in water content at 3 cm above the membrane in module A. The minimum aeration level in normal soils is approximately 10 to 20 percent air-filled porosity (Bunt, 1988; Royston, 1986). Note that the rapid depletion and resupply of oxygen to the sensor occurs at around 10 percent A.P.. In terrestrial potting soils, gravity removes excess water within hours of irrigation, in microgravity however, the removal of excess water is more challenging. The capillary forces of porous media will tend to absorb liquid until saturated without any counteracting for (i.e. gravity). By maintaining the matric potential of the media, via the membrane, water content, and thus air-filled porosity can potentially be well managed. In each of the four root modules, near atmospheric levels of oxygen were maintained at a depth of 7 cm in the media, with the exception of flooding events in A, B, and C illustrated by **Figure 5**.

Conclusions

A capillary-driven root module incorporates a suction control membrane to control the matric potential within the porous

media. The range of matric potential control should not exceed the membrane bubbling pressure. The membrane saturated conductivity should be at least as great as the peak transpiration rate of the plants. The matric potential control should consider the SWC of the media in order to maintain adequate aeration within the media.

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