Liquid Behavior in Partially Saturated Porous Media under Variable Gravity

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Several key processes associated with advanced life support systems for long-duration space missions rely on dependable management of fluids in partially saturated porous media. For example, plants are proposed as bioregenerative components of life support systems serving as a renewable food source, removing CO₂ from the cabin atmosphere, providing O₂, and treating wastewater. The need for a better understanding of multiphase flow and liquid behavior in the absence of gravity in regimes dominated by capillarity is considered important for many other microgravity fluid management applications, as pointed out in a report on future directions in microgravity research of the National Aeronautics and Space Administration (NASA) (National Research Council, Committee on Microgravity Research, 2003). In-depth knowledge of microgravity fluid behavior is essential not only for growing plants, but also for improving the design and management of bioreactors for wastewater treatment, and for numerous other processes such as gas separation and recovery, fuel management, capillary pumps, etc., all of which involve multiphase fluid management in porous media in reduced gravity environments.

Plant-based bioregenerative life support components are likely to play an increasingly prominent role as space mission distances and durations increase and as missions become more autonomous (Bugbee and Salisbury, 1989). Various systems for supplying water, nutrients, and gases to plants under reduced gravity have been previously proposed (Bugbee and Salisbury, 1989; Dreschel and Sager, 1989; Hoehn et al., 2003; Ivanova and Dandolov, 1992a; Morrow et al., 1992, 1993, 1994; Wright et al., 1988). Some of these designs have been tested in space flight experiments during the past two decades (Bingham et al., 1996a; Dutcher et al., 1994; Nechitailo and Mashinsky, 1993), often revealing considerable difficulties in maintaining adequate supplies of water and air to plant roots (Steinberg et al., 2002). Anomalous plant development was generally attributed to suboptimal root module design and fluid management, reflecting limited understanding of liquid behavior in containerized particulate porous media under reduced gravity. There was an indication that enhanced sensitivity to the onset of hypoxic conditions within the plant root zone was due to nonuniform distribution of water or elevated water contents (Hoehn et al., 2000; Jones and Or, 1998, 1999; Scovazzo et al., 2001). The major finding of these studies was that the characterization of the water retention properties of growth media in microgravity should precede plant growth experiments and mission-critical crop production (Jones et al., 2002, 2003).

Experimental data concerning flow behavior and transport properties of plant growth media under reduced gravity remain scarce due to high costs, short duration, and other limitations associated with research during parabolic flights (e.g., NASA parabolic flight aircraft) or aboard spacecraft (e.g., NASA shuttle, the Mir space station, or the International Space Station). Ancedotal evidence suggests that porous media water contents under microgravity are generally higher than under Earth’s gravity (Podolsky and Mashinsky, 1994), and matric-head-controlled wetting and drying rates show dependency on both gravity and media particle size (Morrow et al., 1992, 1993). Water imbibition into an initially dry medium onboard the Mir space station revealed particle separation and cessation of...
flow in an experimental module (Ivanova and Dandolov, 1992b). Mohamed et al. (2002) used a numerical model to simulate imbibition experiments for sand–kaolinite mixtures with distilled water and surfactants. The experiments were conducted with water moving upward against gravity on Earth and during parabolic flight. The microgravity phase of parabolic flight resulted in enhanced wetting rates compared with Earth-based testing. Numerical modeling was able to reproduce some of the wetting behavior, while in many instances significant deviations from the one-dimensional Richards equation based model were attributed to changes in the microstructure of the soil samples under microgravity.

Jones and Or (1999) analyzed the ASC-1 experiment flown aboard the space shuttle Columbia (STS-50) from 25 June to 9 July 1992 testing nutrient delivery systems used to control water status and flow in particulate porous media (Morrow et al., 1994). Data from the Greenhouse-2 experiment (Bingham et al., 1996b) conducted aboard the Russian space station Mir from 9 July 1996 to 22 Jan. 1997 using the SVET plant growth unit were also analyzed (Ivanova et al., 1993; Podolsky et al., 1991). Their analysis suggests that despite some differences in liquid behavior observed between Earth-bound and orbital experiments, the use of conventional unsaturated porous media flow theory (e.g., the Richards equation) remains a viable framework for macroscopic fluid behavior and for certain modeling and design aspects. Nevertheless, mounting experimental and theoretical evidence suggests that a diminishing gravitational force may affect various pore- and cluster-scale hydrodynamic and hydrostatic processes, giving rise to enhanced phase entrapment, unstable wetting and fingering, particle rearrangement and segregation, and enhanced hysteresis (Levine et al., 1977).

Predicting the impact of reduced gravity conditions on liquid behavior and distribution within partially saturated porous media remains a challenge. We review the theoretical analyses of reduced gravity on liquid distribution and flow in partially saturated porous media at the micro- and mesoscale and summarize key findings from observational studies.

**THEORETICAL AND PRACTICAL ASPECTS OF REDUCED GRAavity**

It is instructive to consider the effects of reduced gravity on fluid distribution and transport in unsaturated porous media at different spatial scales. At the pore scale, the equilibrium shape of liquid–vapor interfaces may vary in the absence of gravity relative to their configuration on earth. Under certain conditions, such differences at the pore scale could alter macroscopic water retention and flow behavior. Theoretical and experimental studies by Sasges and Ward (1998) indicated that the contact angle at the triple point (liquid, gas, and solid) is affected by gravity. Their thermodynamically based analysis was confirmed to a certain extent in their experiments (Sasges and Ward, 1998); however, the significance of this phenomenon on overall liquid behavior in porous media remains uncertain.

Experimental evidence suggests that the primary impact of reduced gravity on fluid control and management is manifested at scales involving clusters of pores (the mesoscale) and displacement fronts (Méheust et al., 2002; Or, 2008). These effects could be accentuated by minute changes in particle packing and size segregation (e.g., due to launch vibrations) that may result in preferential capillary flow lanes bypassing large volumes of the porous medium and enhancing phase entrapment during wetting and drainage. Consequently, the values of macroscopic transport properties required for fluid management of plant growth media could be modified and lead to suboptimal plant growth conditions (Chau and Or, 2006).

In the following, we provide a brief overview of the theoretical aspects associated with the impact of microgravity on fluid organization and dynamics in partially saturated porous media.

**Gravity Effects on Pore-Scale Interfacial Configuration**

An extension of the analyses presented in Tuller et al. (1999) enables quantification of the effect of gravity at the pore scale. Interfaces forming between liquid and gaseous phases within partially filled pores are considered to be surfaces of constant partial specific Gibbs free energy (or chemical potential $\mu$), which is comprised of adsorptive, capillary, and gravitational components:

$$\mu = \frac{A_{svl}}{6\pi \rho h} - \frac{2\sigma \kappa}{\rho} - g y$$  \[1\]

The first term on the right-hand side of Eq. [1] is the adsorptive component characterized by the Hamaker constant ($A_{svl}$) for solid–vapor interactions through the intervening liquid, the liquid density ($\rho$), and the thickness of the adsorbed liquid film ($h$). The capillary component (second term) is defined by the classical Young–Laplace equation where $\sigma$ is the liquid–gas interfacial tension and $\kappa$ is the radius of interface curvature that is positive for an interface concave outward from the liquid. The third term accounts for gravitational effects and is comprised of the acceleration due to gravity, $g$, and the spatial coordinate, $y$, along the direction of gravity.

The shape of the liquid–vapor interfaces between parallel plates with surfaces at $y = 0$ and $y = 2Y$ can be calculated based on Philip’s (1977) solution. Because of symmetry, it is sufficient to consider the region $0 \leq y \leq Y$:

$$x(y) = \int_y^Y \left[ \frac{\sigma}{\rho u(y)} - 1 \right]^{1/2} dy$$  \[2\]

where the function $u(y_0)$ is defined as

$$u(y_0) = \int_y^{y_0} \left[ \mu - \frac{A_{svl}}{6\pi \rho y} + \frac{gY}{3} d\bar{y} \right] d\bar{y}$$  \[3\]

The value of the equilibrium chemical potential that satisfies adsorptive, capillary, and gravitational components simultaneously within a given geometry is found by an iterative procedure:

$$\mu_{n+1} = \frac{-\sigma}{\rho} + \int_A \frac{A_{svl}}{6\pi \rho y} d\bar{y} + \int_A \frac{gY}{3} d\bar{y}$$  \[4\]

with the inverse function of the adsorption term given as

$$A^{-1}[\mu] = \frac{\sqrt{A_{svl}}}{6\pi \rho \mu}$$  \[5\]

Comparison of the interface shape calculated with and without consideration of the gravitational term reveals that interfacial de-
formation due to gravity is significant only when pore sizes exceed a few millimeters and the matric potential is close to saturation.

A useful measure for the importance of gravitational forces relative to capillary forces is provided by the dimensionless Bond number ($B_0$):

$$B_0 = \left(\frac{\rho \gamma}{\rho_g} r^2 g\right) \frac{\sigma}{\rho}$$

where $r$ is the capillary pore size (radius or length), and $\rho_1$ and $\rho_g$ are the liquid and gas densities, respectively.

Figure 1a illustrates the relationship between the pore radius and the Bond number for Earth (1g) and reduced gravity ($\mu$g) conditions. The working hypothesis for pore-scale effects was that in the presence of gravity, the liquid–gas interface becomes more deformed with increasing values of $B_0$ (Fig. 1b). These differences would lead to differences in the amount of liquid retained behind the interfaces and affect macroscopic transport properties such as hydraulic conductivity and the gaseous diffusion coefficient. Based on the foregoing analysis, however, we conclude that interface deformation due to gravity (at the pore scale) is insignificant for the plant growth media under consideration for NASA’s advanced life support system (with particle sizes in the range of 1–2 mm).

**Gravity Effects on Wetting Front Morphology and Phase Entrapment**

The morphology of an imbibition or drainage front within a porous medium is sensitive to the relative magnitudes of capillary, gravity, and viscous forces. It is informative to examine the impact of reduced gravity, especially in the range where capillarity and viscous forces are of similar magnitude, such as expected in media relevant to plant growth in reduced gravity environments (particle size $>$0.1 mm). For analysis of wetting front morphology, we introduce the dimensionless capillary number $C_a$, which characterizes the importance of viscous relative to capillary forces as

$$C_a = \frac{\eta v F^2}{\sigma k}$$

where $v$ is the average wetting front velocity (Darcy velocity), $F$ is the mean pore radius, $k$ is the intrinsic permeability of the medium, $\eta$ is the dynamic viscosity of the wetting liquid, and $\sigma$ is the liquid vapor interfacial tension.

Considering non-wetting-phase (air) invasion into a pore at the drying front, Auradou et al. (1999) have shown that the probability of invasion (air entry) into a pore throat is related to the ratio between the average pressure drop at the pore scale and the width of fluctuations in the capillary threshold pressure distribution (or pore throat distribution) in the medium, $1/W_t$ (Fig. 2). This ratio is expressed by the generalized fluctuation number $F$ (Méheust et al., 2002):

$$F = \frac{\rho g F - \eta v F}{k}$$

The pressure drop across a distance $\xi$ along the wetting front may be expressed as

$$P - P^* = \left(\frac{\rho g - \eta v}{k}\right)\xi$$

where $P^*$ is a reference pressure, chosen conveniently as the minimum air-entry value for the medium (the largest pore throat). The invasion probability $p$ into an arbitrary pore throat along the front is approximated by (Méheust et al., 2002)

$$P - P^* \sim N(P^*)(P - P^*) = \frac{\xi}{F}$$

Fig. 1. Illustration of (a) Bond number $B_0$ as a function of pore radius where the gravity force dominates for $B_0 > 1$ (assuming properties of water); (b) the increase in effective capillary radius, $R_c$, resulting in meniscus deformation with increasing $B_0$.

Fig. 2. Linearization of the water characteristic curve for Turface ceramic aggregates (1–2 mm) to estimate the uniform pore size distribution parameter $W_t$ ($r_{min} = 330 \mu$m, $r_{max} = 1500 \mu$m). The parameter $c = 2\sigma/\rho g$, where $\sigma$ is the liquid surface tension, $\rho$ is the liquid density, and $g$ is the acceleration force due to gravity.
where \(N(P^*)\) is the linearized pore size or throat distribution (linearized around air-entry pressure \(P^*\)), represented in this study by a uniform distribution \((1/W)\). Invoking the definitions of \(B_0^*\) and \(C_a\) and using the derivations above enable mapping of capillary pressure values into invasion probabilities, thereby defining the conditions for invasion with explicit consideration of the pore size distribution (in \(F\)), the flow regime, and fluid properties (in \(B_0^*\) and \(C_a\)) as summarized in a revised form of Eq. [10]:

\[
B_0^* = B_0 - C_a = \frac{\sigma}{\mu} W_1 F
\]

where \(B_0^*\) is defined as the generalized Bond number, whose value plays an important role in the resulting front morphology for drainage and imbibition.

Méheust et al. (2002) have shown experimentally that for \(B_0^* > 0\) (when \(B_0 > C_a\)) during drainage, the predominance of gravitational forces resulted in stable (flattened) displacement fronts. For \(B_0^* < 0\) or \(C_a > B_0\), the diminishing gravitational stabilizing force resulted in displacement fronts that became progressively unstable as \(B_0^*\) became more negative. At the slightly negative \(B_0^*\) values expected under reduced gravity conditions with slow liquid withdrawal or injection (e.g., \(-0.05 < B_0^* < 0\)), capillary forces became significant, resulting in behavior characteristic of capillary fingering. As \(B_0^*\) decreased further, viscous forces became significant and viscous fingering was observed for values of \(B_0^* < -0.08\) (approximate range). Figure 3 shows the results from the Méheust et al. (2002) experiments of air invasion (white) into saturated cells, illustrating the relationships between the generalized Bond number \((B_0^*)\) and front morphology. Based on Méheust et al. (2002) experimental and theoretical results, and considering negligible body forces under reduced gravity \((B_0 \sim 0\)), we should expect \(B_0^*\) to always be negative during drainage, hence front morphology becomes critically sensitive to the rates of liquid introduction or removal from the root module (much more than under Earth’s gravity).

We note that for comparison of flow regimes within a given porous system, \(B_0^*\) provides an informative and useful diagnostic tool as shown above; however, for comparison of flow regimes taking place in different porous media, we advocate the use of the generalized fluctuation number \(F\), which contains information on the pore size distribution for each porous medium not retained in \(B_0^*\) (c.f., Eq. [11]). Experimental methods for estimating \(F\) from the displacement front behavior are shown in Auradou et al. (1999), where the distance \(x\) is the correlation length for percolation clusters that define the displacement front roughness or width.

**Flow Morphology, Phase Distribution, and Gaseous Diffusion**

A consequence of enhanced flow instability and phase entrapment under reduced gravity is the potential for changes in macroscopic transport properties typically expressed as functions of average phase content only. In a recent study by Chau and Or (2006), a systematic evaluation of the effects of changes in \(B_0\) on flow morphology and consequently on gaseous diffusion was investigated numerically using the lattice Boltzmann method.

Chau and Or (2006) determined effective diffusion coefficients using the lattice Boltzmann method for displacement scenarios similar to those depicted in Fig. 3. Gaseous diffusion was simulated in flow domains with liquid contents ranging from zero to complete saturation. The degree of continuity of the air phase (or the amount of trapping of the liquid phase) determined the resistance to diffusive gas flux and therefore the effective diffusion coefficient. Relative diffusion coefficients as a function of water content for three representative series of simulations are shown in Fig. 4 (the relative diffusion coefficient \(D_{rel}\) is the effective diffusion coefficient scaled by diffusion in air). For the stable drainage case, \(D_{rel}\) decreases linearly with increasing volumetric liquid content. This is expected due to the regular geometry of the advancing front; each successive time step produces an almost rectangular air-filled region. Since the solid particles are uniformly distributed in the domain, the porosity of each region is the same, and therefore as liquid content decreases, the diffusive flux increases linearly.

In contrast, for the viscous fingering case, even a small amount of residual liquid content has a large effect on \(D_{rel}\). As the water content drops below full saturation, the continuity of the air phase increases slightly, since air invades in fingers and leaves large “antifingers” of liquid still in place. The antifingers persist throughout the drainage process and remain in place even at low water contents. This is the mechanism responsible for the large reduction in \(D_{rel}\) relative to the stable...
displacement case. The capillary fingering case gives results intermediate between viscous fingering and stable displacement. The lower drainage velocity gives rise to less instability than is observed in the viscous fingering simulation, and therefore the fingering effects on diffusion are not as pronounced. The maximum reduction in $D_{rel}$ compared with the stable value occurs at 0.31 volumetric water content with a reduction of 25%.

**FLUID BEHAVIOR DURING PARABOLIC FLIGHT EXPERIMENTS**

The measurement and observation of fluid behavior in reduced gravity environments are limited and experimentally challenging due to the associated high costs for overcoming Earth’s gravity. Only free-fall experiments such as in a drop tower or parabolic flight tests facilitate escape from Earth’s gravity but are limited to extremely short durations. Aircraft are able to establish short-duration microgravity ($\mu g$) phases when flying a parabolic trajectory (Fig. 5), providing approximately 25 s of weightlessness during each parabolic cycle. Onboard accelerometers measure the gravitational force in three directions, providing a quality measure for the microgravity condition experienced (Fig. 5). An undesirable effect of these flights is the preceding hypergravity phase associated with the pullout at the bottom of the parabola where the gravity force relative to earth reaches 1.8g.

Recent experimental observations conducted onboard NASA’s KC-135 aircraft allowed us to significantly improve experimental procedures and subsequent modeling efforts (Heinse et al., 2005, 2006; Jones et al., 2005; Norikane et al., 2003; Steinberg et al., 2005). In the following, we highlight relevant aspects of reduced gravity on liquid behavior in porous media deduced from parabolic flight experiments.

The primary porous media considered in our parabolic flight experiments included porous ceramic aggregates (AIMCOR, Deerfield, IL) and glass beads (MO-SCI, Rolla, MO) sieved to specified particle size distributions. The ceramic aggregate size fractions were 0.25 to 1 mm (Profile) and 1 to 2 mm (Turface). The size fractions for glass beads included 0.35- to 0.5-, and 1- to 2-mm beads. The bulk (packing) densities were around 0.6 g cm$^{-3}$ for Turface and Profile, and 1.7 g cm$^{-3}$ for the glass beads. Dyed water (Brilliant Blue) was supplied at zero pressure to inlets of vertically oriented micromodels, providing contrast for visual observations.

**Visualization of Liquid Behavior in Hele–Shaw Cells**

To qualitatively examine fluid behavior under reduced gravity, we designed a number of transparent Hele–Shaw micromodels containing monolayers of variable sized glass beads arranged in different spatial patterns to test hypotheses concerning phase entrapment and differential imbibition rates and pathways.

In the micromodel depicted in Fig. 6a, water flows exclusively in the region made of small glass beads (0.9-mm diam.) during microgravity phases. The imbibition process is then interrupted by a 1.8g period that forces water into the coarse region and leads to equalization of the wetting front. Repeated cycles under $\mu g$ conditions confirm the role of “capillary lanes” forming and sustaining preferential pathways.

The potential for enhanced phase entrapment due to non-uniform particle segregation was simulated using micromodels with nonuniform particle and pore size distributions such as the design depicted in Fig. 6b with coarse regions (2.4-mm glass beads) surrounded by fine-textured glass beads (0.9 mm). This series of images illustrates imbibition during zero gravity that progresses exclusively in the fine-textured domain, bypassing and causing air entrapment in the coarse inclusions. The experiment is interrupted by unavoidable periods of 1.8g conditions that force water into bypassed and air-filled coarse inclusions.
A semiquantitative confirmation of enhanced water entrapment under parabolic flight-induced microgravity conditions is illustrated in the results from constant-rate drainage experiments. A 30-mL column containing saturated porous particulate media of different particle sizes provided an example of transitioning capillary behavior. The sample was drained at the bottom (air inlet at the top) at a fixed rate using a syringe pump under both μg and 1g conditions. The results shown in Fig. 7 indicate that more liquid was entrapped in the column under μg than under conditions of 1g. More liquid was entrapped within smaller particle sizes (less liquid withdrawn) irrespective of gravitational conditions reflecting the dominance of capillary forces. With the increase in particle size in the column, the difference in water entrapment between μg and 1g became more accentuated, as depicted in Fig. 7. The porosity increased slightly from smaller to larger particles, hinting at a size effect where porosities ranged between 0.32 and 0.38, with a mean and standard deviation of 0.36 ± 0.02. We surmise that the enhanced entrapment for smaller particle sizes under reduced gravity is due to unstable drainage pathways illustrated in Fig. 3 and in studies by Méheust et al. (2002) and Chau and Or (2006).

**Particle Rearrangement in Reduced Gravity**

In response to large vibrations during launch, or in the absence of body forces, pore spaces in particulate porous media may be altered relative to packing on Earth (Jones and Or, 1999). Even minute particle rearrangement or segregation could affect macroscopic transport properties, for example, by accentuating the potential instabilities discussed above or by forming capillary preferential pathways that bypass large volumes and alter water distribution patterns. These changes may lead to significant changes in gaseous diffusion for similar mean water contents, as illustrated by Chau et al. (2005) using simulations based on the lattice Boltzmann method. Additionally, Jones and Or (1999) discussed the potential for particle separation and rearrangement during imbibition under reduced gravity due to the overwhelming capillary force. For example, capillary forces during imbibition of a wetting front into initially dry media may pull particles and form gaps ahead of the advancing front (Fig. 8), thereby retarding or even halting subsequent advancement and redistribution (Ivanova and Dandolov, 1999b). Such effects are likely to be minimal for confined and densely packed porous materials and under conditions of partial Earth gravity (Mars and Moon conditions).

**Water Retention and Hydraulic Conductivity Measurements in Variable Gravity**

**Water Retention**

Heinse et al. (2007) presented Earth-based water retention curves for three different dual-pore-sized media using shallow 1-cm-tall cells (nine replicates). Both primary wetting and draining retention curves were described using the van Genuchten (1980) parametric water retention model along with 95% confidence intervals around each curve (Fig. 9). The shallow samples, although not ideal in terms of being a representative size, were used to minimize the effects of gravity and approach equilibrium conditions for the broadest water content range possible. They found that wetting water retention data from microgravity for two finer pore-sized media (the Profile ceramic aggregates and the 50:50 mix of Profile and Turface) fell within the Earth-based 95% confidence intervals of the primary wetting curve. For the draining data, μg values fell below the 1g primary draining curve, probably as a result of the 1.8g force experienced before each microgravity period. The coarsest pore-sized medium, Turface, exhibited reductions in both wetting and draining data below 1g values, shown in Fig. 9c.

**Saturated Hydraulic Conductivity**

Darcy’s law has been validated for conditions of hypergravity using centrifugal testing for saturated and unsaturated conditions (Nimmo et al., 1987, 1994). It is also of interest to consider Darcy’s law for conditions of reduced or zero gravity. The saturated hydraulic conductivity, \( K \), in Darcy’s law is an empirical coefficient of proportionality between gradient and flux that may be expressed more explicitly in terms of porous medium hydraulic permeability, \( k \), and fluidity, \( \rho g/\eta \). The one-dimensional vertical water flux, \( J_w \), may thus be written as
\[ J_w = k \frac{\rho g}{\eta \rho g} \left( \frac{\Delta P + \rho g \Delta z}{\Delta z} \right) = k \left( \frac{\Delta P}{\eta \Delta z} + \rho g \right) \]  \[ 12 \]

where \( \Delta P \) is the pressure gradient, confirming a lack of dependence of permeability (a geometrical factor) on gravitational forces.

Saturated hydraulic conductivity measurements for coarse-textured glass beads and porous aggregates (Heinse et al., 2007) showed no significant differences relative to values on Earth. Loosely packed particulate media may suffer rearrangement under the variable gravity of parabolic flight, causing unpredictable dynamic pressure gradients. Unsaturated hydraulic conductivities have not been measured in microgravity; however, phenomena such as air entrapment and altered water distributions expected in microgravity will probably alter the unsaturated dynamic behavior in porous media (perhaps more pronounced than the effects on gaseous diffusion).

Root Module Design and Fluid Management Considerations

Our primary conclusion from the series of reduced-gravity experiments presented in this and previous studies (Heinse et al., 2007; Steinberg et al., 2002) is that reducing the impact of phase entrapment, preferential wetting, and particle segregation in plant growth media requires alternatives to particulate media, for example engineered media with a multifunctional rigid pore structure. While it is clear that particulate media, such as the calcined clays commonly used in the past, are convenient for the removal and study of roots on Earth, lightweight disposable or recyclable media are more likely to be used in long-duration extraterrestrial missions. The pore space should serve as a storage and transport conduit for water and nutrients while also providing adequate gaseous diffusion to maintain root and microbial respiration. This typically requires sufficient contrast in pore-size or surface properties (i.e., hydrophobic vs. hydrophilic) so that subtle changes in water content or matric potential do not significantly alter the balance of gas and liquid supply. Various gravitational environments envisioned for space exploration (zero gravity aboard spacecraft, partial gravity on Mars or Moon colonies) present different challenges with respect to fluid management and design considerations related to volume and porous medium optimization. The interplay between capillarity and gravity force impacts water retention and liquid removal (drainage), which are essential for the formation and maintenance of gaseous diffusion pathways. Reliable knowledge of the macroscopic water characteristic is critical for optimizing the delivery of water and \( \text{O}_2 \) to roots, as demonstrated by Jones and Or (1998). If the water characteristic and phase spatial distributions change under microgravity conditions (e.g., due to particle rearrangement, degradation, or root growth), the ramifications of these changes on transport properties such as the air-phase percolation threshold (i.e., the onset of gas diffusion) and impacts on plant growth system management must be accounted for. This concept is illustrated in Fig. 10, where gas diffusion and hydraulic conductivity are inversely related as a function of saturation and a summation of these transport processes in addition to the critical gas concentration (e.g., \( \text{O}_2 \)) suggests optimal water content (saturation) near the gas percolation threshold. Using porous membranes requires optimization of the porous medium pore size distribution for proper management of water content. In Fig. 10, \( b \) is scaled based on the matric potential associated with the residual water content, which may be set to the maximum safe suction imposed by the management system.

The traditional reliance on Earth-based particulate media to supply plant needs in the extremely limited space and mass constraints aboard a spacecraft introduces unnecessary complications. We envision innovative design of recyclable, engineered, porous media (Akay et al., 2005) with well-defined
diffusion, summation of the four functions, induced control system. The objective function, OF, is obtained by minimizing the energy required to maintain the integrity of a suction-driven environment where mass and volume need to be minimized. The relative matric potential, \( \Theta_r \), in addition to a critical \( O_2 \) concentration, \( C_r \), prescribed by the gas percolation threshold. The relative matric potential, \( h_r \), seeks to minimize the energy required to maintain the integrity of a suction-induced control system. The objective function, OF, is obtained by summation of the four functions, \( K_r, D_r, C_r \), and \( h_r \).

matrix pore architecture and mechanical properties optimized for plant rooting environments. Additionally, the competition between liquid and gaseous pathways, both essential for plant root function, could be reduced by prescribed domain segregation, as proposed in Fig. 11. The spatial decoupling based on critical path lengths for nutrient or gas diffusion (i.e., to roots and microbes) would enhance robustness and manageability for this vital component of life support systems. Future efforts to engineer optimal porous medium properties should strike a balance between the biological needs of the plants’ rhizospheric conditions, practical limitations regarding material properties (e.g., cost, weight, etc.), and providing the desired transport properties.

As mentioned, previous plant root-support modules have been designed and tested using porous water delivery tubes embedded in a particulate medium (Ivanova et al., 1993; Morrow et al., 1994; Bingham et al., 2002; Hoehn et al., 2003). For systems tested with plants, the root-zone–canopy interface (the diffusion barrier in Fig. 11) typically involved a woven chloride cloth that prevented particulates from escaping and wick- ing water to the seed bed. Additionally, a compressible foam sublayer was introduced to maintain a firmly packed substrate. The wicking of water to the surface promoted germination and root growth to water sources below (i.e., lacking gravitropism). The wick enhances evaporation and buildup of surface salts, which can be problematic for multiple cropping. Furthermore, water retention in the wick’s fine pores was higher than that of the particulate medium, often leading to a disparity in water management between the two domains. Manipulation of material surface wettability could alleviate some of the issues of excess evaporation while containing particulates, roots, etc. An air-distribution system may also be important in maintaining gas exchange and removing toxic gases produced by roots, such as ethylene.

For planetary life support systems (i.e., Martian or lunar), the presence of gravity and less limiting mass and size constraints may relax these requirements but could introduce new challenges including robust scaling of Earth-based methods and models. The suitability of the local regolith alone or in combination with other materials for use in low-gravity environments must be examined. Engineered plant growth media have the potential of improving the reliability and reducing the risk associated with control of water delivery. In addition to optimizing the rooting environment, reliable methods for real-time monitoring of the hydration status of the root zone are needed with due attention to sensor sensitivity and its measurement volume.

**RECOMMENDATIONS AND SUMMARY**

Theoretical calculations of pore-scale liquid configurations based on the augmented Young–Laplace equation reveal that for all practical purposes, the effect of gravity on interfacial configuration at the scale of a single pore is relatively small and may be negligible for porous media with pore sizes less than \(~1\) mm. The impact of gravity is more significant at the intermediate scale of several pores or liquid clusters. It has been shown theoretically and experimentally that the morphology of imbibition or drainage fronts within porous media is sensitive to the relative magnitudes of capillary, gravity, and viscous forces. The impact of reduced gravity in the range where capillarity and viscous forces are of similar magnitude, such as those expected in media relevant to plant growth in reduced gravity environments, was examined on the basis of Bond \( B_0 \) and capillary \( C_a \) numbers. Experimental results reveal that if \( B_0 > C_a \), during drainage, the predominance of gravitational forces resulted in stable displacement (flattened fronts). For \( C_a > B_0 \), the diminishing stabilizing gravitational force produced fronts that became progressively unstable (different relations hold for infiltration, where gravity is a destabilizing force). Considering negligible body forces in reduced gravity, front morphology becomes critically sensitive to the rates of liquid introduction or removal from the root module.

Fluid management in partially saturated porous media under re-
duced gravity is critical for many aspects of bioregenerative life support systems ranging from plant growth to wastewater treatment. In addition to the technical aspects of fluid introduction to porous media, the absence of gravitational forces results in particle rearrangement in particulate media and may accentuate wetting and drying front instabilities due to a dominance of capillary and viscous forces. The resulting preferential flow pathways and instabilities enhance fluid-phase entrapment within the plant growth media and may significantly alter the behavior of the macroscopic transport properties used for fluid management. For example, similar average water contents may result in vastly different gaseous diffusion pathways and macroscopic diffusion coefficients, which, if unaccounted for, could cause irreversible damage to plants.

Lattice Boltzmann simulations were used to demonstrate the potential differences in gas diffusion between 1g and μg resulting from altered liquid configuration. In the absence of gravity, liquid is held in the smallest pore spaces due to the dominance of capillary forces; with gravity, liquid tends to accumulate at the bottom of the domain. The effect of gravity on gaseous diffusion in porous media is highly dependent on the pore size distribution and pore arrangement in the medium relative to the gravitational field, and also on water content. At extreme water contents (i.e., near saturation or in a dry state), gas diffusion coefficients are similar under μg and 1g; the greatest potential difference in diffusion rates occurs near the gas percolation threshold (80–90% saturation) where the distribution of air-filled pores becomes critical (see Fig. 10). The occurrence of viscous fingering coupled with a lack of gravity-induced water distribution could shift the percolation threshold under microgravity to lower saturation levels and, consequently, water management set points.

Particle rearrangement and separation due to wetting front advance and recession are other potential mechanisms for air entrapment and formation of extended ganglia in reduced gravity environments. For example, the overwhelming dominance of capillary forces during imbibition of a wetting front into initially dry particulate media may pull particles and form gaps ahead of the advancing front, thereby retarding or even halting subsequent liquid advancement and redistribution. Such effects are likely to be minimal if confined and densely packed porous materials are used and under the conditions of partial Earth gravity (Martian and lunar conditions). Visual observations of fluid behavior under reduced gravity in Hele–Shaw cells were used to demonstrate the formation of preferential “capillary lanes” where the wetting phase circumscribes coarser particle regions, thereby enhancing the probability of nonwetting-phase entrapment relative to conditions on Earth. We also demonstrated that when coarse inclusions are surrounded by fine material, air is easily entrapped within the coarser region. Initial wetting is another important determinant for flow behavior and phase entrainment, where pre-wet media are less likely to exhibit wetting anomalies.

Dynamic measurements of water retention during parabolic flight have shown a nonlinear transition of matric potentials toward static equilibrium during μg. The speed of this transition is determined by the water content and sample height and decreases with decreasing water content and increasing height. The porous-media water retention characteristics were approximated for microgravity conditions from quasi-steady-state conditions at the end of the μg phase. Despite the apparent influence of the hypergravity phase on dynamic water retention during μg, measurements suggested similar water retention characteristics in microgravity compared with 1g for wetting conditions. Long-term microgravity testing is needed for more reliable and rigorous measurements of porous media water retention due to the prolonged steady-state period and absence of the dynamic constraints of the parabolic flight environment. Our experiments and simulations further indicate that to a first order, the Richards equation describes macroscopic flow behavior under microgravity conditions.

In summary, the experiments presented highlight key processes and conditions affecting fluid behavior in partially saturated porous media. Our primary conclusion for future plant growth considerations for extremely limited space and mass constraints aboard a spacecraft is not to rely on Earth-based particulate porous media for the plant rooting environment. Much of the ambiguity and difficulties encountered in past experiments could be overcome by designing a rigid porous environment with fixed and optimal pore spaces (similar to horticultural foams), possessing the desired mechanical properties, and most importantly, designed with spatially segregated domains for water retention and gaseous flow and exchange. Such engineered porous media would be tailored to meet space and weight limitations, may be equipped with built-in water supply and monitoring systems, and would provide an environment for the predictable and optimal fluid management essential for space exploration. For plant growth on planetary surfaces, the presence of gravity and reduced mass and size constraints make consideration of the local regolith in combination with other materials an attractive solution for plant-based cropping and life support systems.

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