Challenges to understanding fluid behavior in plant growth media under microgravity

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ABSTRACT

Fluid management in plant growth media in reduced gravity remains a challenge hindering integration of this critical component of advanced life support. A recent NASA-funded project diagnosed causes for limited progress in control of water and air in the root zone. Small finite volumes of porous medium are used for plant growth in microgravity. Difficulties controlling water and air in the root zone likely result from an incomplete understanding of the system in 1g that is compounded by changes in water and air distribution due to microgravity. Interpretation of existing hydraulic data from microgravity is currently limited by inadequate characterization of the root module in earth gravity. Most noteworthy has been lack of consideration of the impact of root volume within a finite volume of porous medium and understanding output from flight compatible water content or matric potential sensors. The effect of microgravity on fluid flow through porous medium is most significant at the cluster scale (cluster of several particles “glued” together by water). Clusters rather than individual particles are most likely to separate in microgravity. Cluster scale instabilities may become apparent in microgravity but not 1g. Capillary forces will control the configuration of air and water at the cluster scale. In the absence of gravity the capillary length scale increases supporting capillary flow in larger pores as compared to 1g. Variation in pore size distribution and increased length scales lead to phase entrapment and increased hysteresis during infiltration or drainage in microgravity. Use of porous medium with a broader pore size distribution may reduce cluster scale affects caused by microgravity. Investigation of how microgravity induced changes in air and water distribution at the cluster scale translate into averaged hydraulic parameters at the root module scale is ongoing. At the root module scale the most significant effect of microgravity is the lack of hydrostatic gradient of water and air. As a result gaseous diffusion may be slightly reduced below levels measured in 1g. The Richards equation continues to provide a good description of average flow characteristics on the root module scale. Key areas for future progress include engineered plant growth media for reduced gravity, improvements in sensing technology and better understanding of rhizosphere processes.
INTRODUCTION

A recent NASA Workshop concluded, “Plants are essential for closed, regenerative life support systems. As mission durations increase and colonial scenarios develop, resupply becomes impractical and the cost untenable.”(3). Even though plants/crops would be grown in a protected habitat in transit vehicles or on the surface of Moon and Mars, the environment is hostile to growth unless conditions are carefully controlled. The added complication that methods and procedures for water and nutrient management are necessarily modified under micro- or reduced gravity conditions presents a unique challenge that has yet to be met. The ability to predict and tailor water, air and nutrient transport in porous media under micro- or reduced gravity conditions remains a critical constraint to development of reliable experimental and production plant growth facilities. Successful plant growth during space missions is dependent on adequate control of the rooting and canopy environments and understanding impact of micro- reduced gravity on plant physiological functions. An especially critical area has been control of water and air in plant growth media. An important conclusion from another NASA Workshop was that despite 20 years of plant research in space, we lack an understanding of basic fluid distribution and flow through porous media in microgravity (11). Hardware had been built to deliver water to root modules without sufficient understanding of key physical processes governing flow.

IMPACT OF REDUCED GRAVITY ON FLUID BEHAVIOR IN PLANT GROWTH MEDIA – CHALLENGES

In 2002 our NASA funded multidisciplinary team began to address flow and distribution of fluid phases in porous plant growth media in microgravity. This research effort has identified several problems ranging from inadequate characterization of media properties under variable gravity, to phase entrapment and onset of flow behavior not representable by standard flow theories. Some of the key issues involve:

CHARACTERIZATION OF POROUS PLANT GROWTH MEDIA. Optimal set points for water delivery in any g environment strongly depend on growth-media physical and hydraulic properties. Although baked ceramic aggregates have been used in space flight for over 10 years, our team conducted the first rigorous characterization of their physical and hydraulic properties(10). This work has enhanced the understanding of aggregate maximum density, dual porosity, pore size distribution, water conducting porosity, air entrapment, and air entry that allow critical examination of water delivery set points that have been used in space flight. Figure 1 shows the detailed water retention characteristic of 1-2 mm baked ceramic aggregate, used for many recent space flights. While the top figure shows retention in both micro- and macro-pores, it is the macro-pores primarily that control the plant-available water and therefore hysteresis in this pore domain (Figure 1B) is of great interest since the water content control will lie within this envelope of operation. One of the challenges with particulate porous media is the pore-size variability that occurs from one sample to the other and this pore restructuring leads to subtle changes in water retention making precise water content control difficult. Water retention of baked ceramic aggregates under microgravity remains a key physical property of interest that awaits experiments conducted in microgravity. The short 20 sec. 0g period provided during recent KC-135 flights is a limitation to getting a complete water retention curve.

ISSUES RELATED TO FINITE VOLUME AND SMALL SPATIAL SCALE. Space flight limitations on mass and volume result in root modules characterized by small volume of growth media and high root density. The small spatial scale accentuates the impact of inherently
irregular wetting patterns due to gravity(4) or a combination of viscous, gravity and capillary forces (7). Wetting front irregularities may span the entire root module depth promoting entrapment and discontinuous phase formation.

Root proliferation modifies media properties, especially with high root density where an entirely new porous medium is created with different physical and hydraulic properties (Fig. 2). High root densities decrease saturated water content and increase hysteresis between draining and wetting curves. Consequently, water management based on macroscopic criteria (set points) may be constantly changing. For example, the volumetric water content corresponding to a matric potential control point of −3 cm H₂O is 0.04 cm³ cm⁻³ below saturation in unrooted medium, but only 0.01 cm³ cm⁻³ below saturation in rooted medium (Figure 2). A volumetric water content set point of 0.57 cm³ cm⁻³ could become either too dry or too wet in rooted medium depending on the measurement volume of the sensor and what the sensor “sees” in that volume (water plus roots or unrooted medium, respectively).

**MICRO- AND REDUCED GRAVITY EFFECTS ON WATER TRANSPORT** - Water moves within porous media under the influence of pressure, gravity and surface/capillary forces. Surface/capillary forces dominate in micro- or low gravity environments when both water and air phases are present. Wetting front irregularities or surface forces that cause water and air to segregate into wet and dry clusters are difficult to control or predict. As mentioned previously wetting front instability (also referred to as “fingers”) during initial infiltration of water into porous medium is common. Glass et al. (4) document evidence “wet” fingers persist during steady infiltration and wetting and drying cycles in 1 g due to hysteresis in the water retention characteristic. This process may be exacerbated in microgravity. Pictures of water infiltration of water into dry and pre-wetted glass beads taken during the variable gravity (~20 sec 0g~ 60 sec 1.8 g) of KC135 flight (8) document the occurrence of preferential flow and phase entrapment that occurs during 0g. Variation in pore size distribution and expansion of capillary length scales enhance phase entrapment in 0g. Once these clusters
become established during initial infiltration they may be hard to remove in 0g due to the combination of water-primed pathways and dominance of capillary forces (Fig. 3). During 0g water preferentially flows into finer beads leading to air entrapment (Fig 4) or increased infiltration rates into pre-wetted as compared to dry beads (Fig 5).

Particle movement has been speculated to occur in microgravity(6). Preliminary investigations during KC135 flight indicate that microgravity had little effect on pore fluid blobs corresponding to residual saturation of Hexadecane. However groups of particles containing Hexadecane blobs appeared to rearrange themselves(9) (Fig. 6). Movement of individual particles or clusters in microgravity may affect pore size distribution or the continuity of hydraulic pathways in microgravity. Future research must address the effect of gravity on fluid distributions above residual saturation.

Fig. 5. Preferential infiltration of water (blue) into finer (0.9 mm) glass beads bypassing coarse regions (2.4 mm) during consecutive KC135 parabolas. Infiltration proceeds at a faster rate in prewetted beads (4 and 6) than dry beads (2) during the 20 s of 0g. Preferential infiltration results in gas entrapment and faster overall advance.

Investigation of how microgravity induced changes in air and water distribution at the cluster scale translate into averaged hydraulic parameters at the root module scale is on going. At the root module scale the most significant effect of microgravity is the lack of hydrostatic gradient of water and air. As a result gaseous diffusion may be slightly reduced below levels measured in 1g. The Richards equation continues to provide a good description of average flow characteristics on the root module scale.

Fig. 6. Illustration of particle separation during microgravity while glass beads are bonded by Hexadecane (from (9)).

WATER CONTENT SENSING AND CONTROL.

Matric potential or water content sensors have been used to control and schedule water delivery to plant growth media. Limited sensing volume of most sensors used in root modules (<1 cm³) may result in “accurate” readings on the mesoscale (several pores or particles), but an inaccurate assessment of water content in the bulk volume of growth media. The presence of discontinuous phases and roots, mentioned above, may confound interpretation of water content sensor output. Numerous questions remain about what the sensor “sees”, placement and numbers required to obtain good control of water in the root zone.

MANAGEMENT OF FLUIDS IN PLANT GROWTH MEDIA UNDER REDUCED GRAVITY – OPPORTUNITIES

The greatest promise for improved monitoring and control of fluids in plant growth media is related to advances in the following areas:

ENGINEERED PLANT GROWTH MEDIA

Horticulturists spent the better part of the 20th century developing plant growth media for containerized production (2). The baked ceramic aggregates, used in recent space flight experiments, were selected because they were more controllable, consistent, and uniform than any other currently available plant growth media (Personal communication. T. Tibbitts. Professor Emeritus. University of Wisconsin, Madison). These media were selected within the implied 1g framework of hydrostatic gradients of water and air and “drainage” that removes excess water, salts and nutrients. Figure 7 clearly shows a hypothetical porous medium that could be used to study the effect of a well defined pore size and distribution of sizes on the air-filled pore space and its impact on gas exchange with plant roots. The adjustment of matric potential allows draining or filling of pores, thereby modifying the path length for gas diffusion. Advantages of an engineered or manufactured porous medium lie in the repeatability and consistency of the pore structure affecting the water retention character as well as the ability to produce lightweight and
Predictions of the influence of roots both on water content measurements and on changes in physical properties of the growth media itself is needed.

MODELING

Modeling can be used to address many questions that would be difficult and/or expensive to obtain experimentally in microgravity. For example, if the range of pore size distributions under microgravity/vibration is known, the range of water retention curves can be derived using a 3D pore network model. In another example, mechanistic modeling of multiphase flow in plant growth medium can be used to predict how the system will behave in microgravity, optimal design or control strategies for water air and nutrient, and interpret spatial or temporal point measurements.

CONCLUSION

Issues related to control of water and air in small volumes of rooted porous media in micro- or low g will remain for the foreseeable future. Existing plant growth systems for microgravity all rely on solid porous substrates for water containment and phase separation. “Salad machine”(1) type growing systems conceptualized for the International Space Station or Mars transit will likely be the initial systems deployed on the Lunar or Martian surface as the large-scale crop production facilities envisioned for long term surface bases will take significant time and resources to deploy.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

\( \theta \): Volumetric water content; saturated water content, all pores are filled with water; satiated water content, porous media does not attain complete saturation but is as wet as it ever gets to be under natural conditions (5).