Oxygen Diffusion Measurements in Partially Saturated Porous Media aboard the International Space Station

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Introduction

- Uncertainties in water, nutrient, and air supply to plant roots resulted in limited success in many plant growth experiments in space. These were often attributed to design flaws due to limited understanding of liquid behavior and configuration in particulate porous media under reduced gravity (Steinberg et al., 2002, 2005).
- Pore scale phenomena observed under short-term microgravity conditions on board NASA's KC-135 aircraft, reveal similarities in liquid imbibition behavior at 1g and μg, but microgravity appears to significantly affect water retention properties and thus could alter the gas percolation threshold in plant growth media (Heinse et al., 2005).
- Our objectives were to observe and quantify microgravity effects on porous media water retention and gas diffusion during long-term microgravity experiments aboard the International Space Station.
- The ORZS-MIS (Optimization of Root Zone Substrates – Module for the Investigation of Substrates) experiment was launched on a Russian Rocket to the ISS in May of 2007.

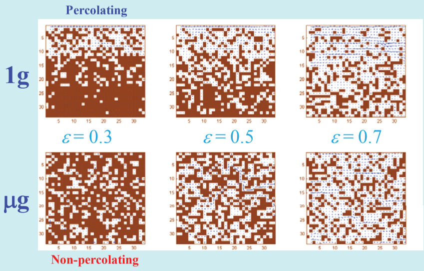


Fig.1: Hypothetical 2-D pore networks with air-filled porosities of 0.3, 0.5 and 0.7 illustrating earth (1g) and space (μg) gravitational influence on development of horizontally oriented percolating pathways.

Closed-Chamber Diffusion Cell

- A closed-chamber oxygen diffusion cell was designed and constructed for use in microgravity. A cylindrical cell geometry was used to facilitate fluid handling and sample symmetry.
- The cell is described in Fig. 2 showing the variably saturated porous medium (Fig. 3a) housed between two gas chambers.
- Solenoid valves control gas purging after each water content step and to prepare the chambers while O_2 sensors monitor chamber concentrations during each diffusion event.

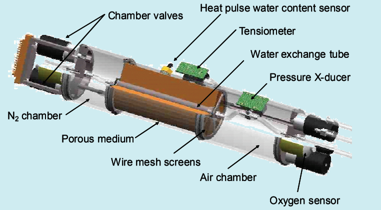


Fig.2: Cross-section of the water retention and gas diffusion cell designed for μg experiments aboard ISS.

Ground-Based Modeling

- The fundamental physical relationship for soils and plant growth media describing volumetric water content, θ, and matric potential, h, is also useful for describing other physical processes such as gas diffusion (Fig. 3b).
- A commonly used parametric model for relating measured θ to h was proposed by van Genuchten (1980), given as

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1+(\alpha\,|h|)^n}\right]^{(1-\frac{1}{n})} \qquad (1)$$

- This relationship describes θ in terms of the residual (θ_r) and saturated (θ_s) water contents and in terms of the empirical parameters α and n, which are physically related to bubbling pressure and pore size distribution, respectively.
- Gas diffusion is air-filled porosity (ε) dependent and described as ε = ϕ - θ, which exhibits a vertical profile gravity dependence (Fig. 3c).
- A soil gas diffusivity, D_s, model is written in terms of an exponential fitting parameter, δ, described in terms of either ε or θ, given as (Moldrup et al., 2000)

$$\frac{D_s}{D_a} = \frac{(\varepsilon)^\delta}{(\phi)} = \frac{(\phi-\theta)^\delta}{(\phi)} \qquad (2)$$

Fig. 3. Cosmonaut Oleg Kotov priming the Optimization of Root Zone Substrates (ORZS) experiment on board the International Space Station in June 2007. Note the non-uniform wetting of substrate.

Ground-Based Results

- Three different particle-sized aggregated (triplicate) samples were used to observe the influence of gravity on water retention and gas diffusion data. Samples included 1-2 mm Turface, T, 0.25 – 0.85 mm Profile, P, and a Mixture of these, M.
- The experiment induced both wetting , W, and draining, D, processes to generate a functional relationship for oxygen diffusion as a function of water content.
- Figure 5 shows corresponding gas diffusion coefficient determinations at 1g and μg using the analysis approach of Glaus and Rolston (1989).

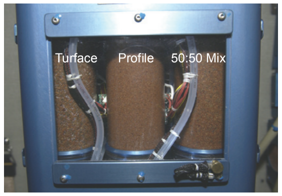
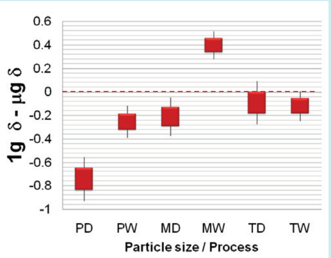


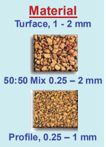
Fig.4: The 9-cell array tested on the ISS.

Statistical Approach to Compare Significance of 1g and μg Data

- Non-linear optimization was used to determine parameters (i.e., α, n, δ in Eqs. (1) and (2)) and to establish a 95% confidence interval (CI) for the difference in parameters describing triplicate water retention and gas diffusion measurements in ground and flight cells measured at 1g.
- Microgravity results were compared to earth-based (reference) values in Fig. 6, exhibiting significant differences in the exponent δ for the finer textured materials, P and M, which is counter intuitive considering the lower bond numbers (reduced gravitational influence) associated with smaller particles.

Fig.6: Model parameter δ comparison showing the difference between ground- and ISS-flight cell fitted exponents. The mean difference ± standard error of triplicate samples forms the symbol and the 95% CI is represented by vertical bars. Intervals crossing 0 represent a non-significant parameter difference between ground and flight cells. TD and TW are not significantly different at the 95% CI. Differences in exponents are attributed in part to hydrostatic forces acting on ground-based flight cell configuration, which is shown in Fig. 3.





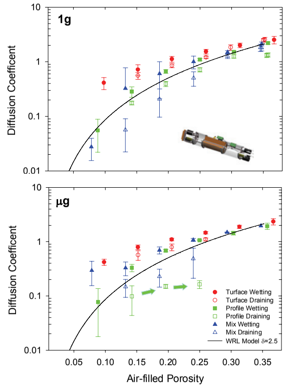


Fig.5: Gas diffusion coefficient measurements in three different particle-sized aggregate media on earth (1g) and on the ISS (μg). Mean and Stdev. shown along with eq. (2) with δ = 2.5. Note departure in Profile draining data which may be tied to a shifting percolation threshold in finer particle-sized media.

Summary and Future Testing

- We assumed reduced gravity and especially microgravity would alter gas diffusion processes due to altered water content distributions that differ from the vertical distributions generated in earth's gravity.
- A 'shift' in the gas percolation threshold or in the assumed optimal water content for plant growth could have disastrous consequences for plant-based life support systems planned for future μg, lunar and Martian missions.
- Results from the ORZS-MIS experiment suggest the microgravity influence on gas diffusion through 1-2 mm particles is minimal, but diffusion coefficients and diffusion model exponents were significantly altered by μg in finer textured media.
- A second ORZS-MIS experiment will repeat measurements of water retention and gaseous diffusion in microgravity aboard the ISS with a launch date scheduled for the summer of 2008.

Acknowledgements

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