

ORZS: Optimization of Root Zone Substrates for Microgravity

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ABSTRACT

The ORZS flight experiment is designed to measure gas diffusion through plant growth substrates at varying water content levels in microgravity. This information is critical for proper water management and the prevention of root zone hypoxia during plant growth and ALS biomass production experiments. Microgravity data that suggest enhanced hysteresis in water retention may alter the gas diffusion process, changing the optimum root zone moisture control setpoint in μg plant growth systems. Small gas diffusion cells are being evaluated as measurements systems for coarse-textured plant growth media at 1g and 0g. Design guidelines aim to minimize gravitational force while maintaining a representative porous medium. Substrate physical properties (e.g., water retention) pose additional complications for diffusion coefficient determination. Results of this study will directly support substrate selection and management for ISS plant growth experiments.

INTRODUCTION

Plants require adequate water and oxygen supply (inversely related processes) and metabolic gas removal from their root tissues. For terrestrial plants in porous substrates, pores are readily drained after watering providing adequate air-filled pore space for gas exchange with the root tissues. Under reduced gravity conditions, capillary forces are dominant, creating water distribution profiles and non-uniformities not observed on earth. A few space borne experiments have investigated water movement and control in μg , but none have investigated the region where oxygen diffusion becomes the limiting factor for plant growth. Our experiment will provide the first detailed measurements of substrate gas diffusion and water management. The measurements are designed to allow the development of

the theoretical models required for a wider range of reduced gravity plant experiments. ORZS is completing its Experiment Definition Phase, and is being designed as a locker style payload. The ORZS experiment module can be hosted by the FHAME controller being developed by ORBITEC, Inc. or by the LADA controller developed by SDL for ISS.

The objectives of this research project are to i) design and test a gas diffusion measurement device amenable to evaluating gas diffusion in 'coarse' textured (0.5 to 2 mm) growth media at 1g and in μg , ii) determine oxygen diffusion coefficients in plant growth media as a function of water content at 1g for eventual comparison to measurements at 0g.

THEORETICAL CONSIDERATIONS

SUBSTRATE WATER RETENTION

The water retention characteristic of a porous medium is directly related to gas diffusion within a substrate because they can both be tied to the air-filled porosity. The air-filled porosity (ϵ), is the difference between the total pore space (ϕ) and the volumetric water content (θ). The volumetric water content may be written in terms of the substrate matric potential (h) (van Genuchten, 1980)

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

where θ_r and θ_s are the residual and saturated water contents, respectively, and α , n , and m are parameters directly dependent on the shape of the $\theta(h)$ curve. The parameters required for estimation of the model are θ_r , θ_s , α , and n , where it is assumed that $m=1-1/n$. θ_s is

usually known and is easy to obtain experimentally with good accuracy by saturating the medium, leaving only three unknown parameters (θ_r , α and n) to be estimated from the experimental data. Note that θ_r describing the macropore retention is equal to θ_c and is not the residual value typically assumed for soils. Here it describes the water content where macropore drainage occurs, resulting in a drastic reduction in unsaturated hydraulic conductivity. Since water and nutrient supply to plant roots is most available via macropore water, we confine our focus on gas transport to the macropore realm.

DIFFUSIVE TRANSPORT

The major mechanism for gas exchange and transport within a porous medium, lacking a convective force, is by diffusion through the gaseous and the liquid phases. This spontaneous process results from the thermal motion of gas molecules in air or solution. Gas diffusion through air is roughly 10,000 time faster than through water, further confining our interest to the gas phase only. The driving force for diffusion is a gradient of partial pressure (or concentration) of any gas within the soil air causing motion or diffusion. The direction is from locations having higher concentrations to those of reduced concentration. Fick's law describes the flux of gas mass, J_{DM} , diffusing per unit area per unit time, given by

$$J_{DM} = -D_A \frac{dC_G}{dx} \quad (2)$$

where D_A [$L_2 T^{-1}$] is the diffusion coefficient in free air, and C_G is the gas concentration. The diffusion coefficient in air is about 1.5×10^3 to $2.5 \times 10^3 \text{ m}^2 \text{ s}^{-1}$ for gases of low molecular weight and decreases with the increase in molecular weight of the gas (Jury et al., 1991).

GAS DIFFUSIVITY

The soil gas diffusion coefficient (D_g), which is air-filled porosity (ε) dependent, may be modeled using a variety of different models, such as the modified form of the Marshall (1959) model, termed the water-induced linear reduction (WLR) model by Moldrup et al. (2000) written as

$$D_g = D_a \frac{(\varepsilon)^{2.5}}{\phi} = D_a \frac{(\phi - \theta)^{2.5}}{\phi} \quad (3)$$

where D_a is the gas diffusion coefficient in air and ϕ is the total porosity. For aggregated porous media such as those evaluated here, we anticipate needing a modification of eq. (3) for modeling diffusion due to the substrate's dual pore nature. Our reasoning is based on the unchanged macroporosity for volumetric water contents below θ_c , providing a relatively constant macropore diffusion path.

EXPERIMENTAL

GAS DIFFUSION COEFFICIENT

The basis for many laboratory methods for measurement of soil gas-diffusivity is the application of Fick's second law (combination of continuity with Fick's first law)

$$\phi \frac{\partial C_G}{\partial t} = D_G^s \frac{\partial^2 C_G}{\partial x^2} + R \quad (4)$$

A simplified form of an analytical solution for eq. (4), with $R=0$ and with the boundary conditions established by Currie (1960) described in (Rolston 1986) is given as

$$\frac{C - C_S}{C_0 - C_S} = \sum_{n=1}^{\infty} \frac{2 h e^{-\frac{D_G^s \alpha_n^2 t}{\phi}}}{l (\alpha_n^2 + h^2) + h} \quad (5)$$

where C is the gas concentration in the chamber, C_S is the concentration at the surface, l is the soil length, $h = \varepsilon/(a \varepsilon_c)$, ε_c is the air content of the chamber, a is the length of the chamber or the volume (V) per soil area (A), and α_n are the positive roots of: $\alpha l \tan(\alpha l) = h l$. For most applications, only the first term in the series is used, and thus for large times (t) a plot of $\ln[(C - C_S)/(C_0 - C_S)]$ vs. time becomes linear with a slope of $-D_G^s \alpha_1^2 / \varepsilon$ where α_1 is the first positive root. The diffusion coefficient, D_G^s , is determined using least squares fitting of the time- O_2 concentration data. A second method for computing diffusion coefficient from the same data was presented by Taylor (1949).

DIFFUSION CELL DESIGN

The need for a shallow substrate sample using the coarse textured media selected for microgravity studies was apparent in order to reduce gravity's influence on the sample profile water distribution. Preliminary testing was done using a horizontal flux direction with the substrate being wetted from the bottom by a porous stainless steel plate. Measurements were compared to conventional diffusion cell diffusion determinations and were poorly correlated in similar media at low water contents. Guidelines set forth by Glauz and Rolston (1989) suggest gas chamber and soil chamber dimensions for minimizing gas diffusion measurement errors. These are described as the ratio of the gas to substrate chamber volumes and are presented as a function of air-filled porosity (ε) in Figure 1. After evaluating the volume ratio of our prototype diffusion cell's chamber and substrate volumes, it was determined that a larger gas chamber was needed to minimize measurement error. Since optimal dimensions are a function of air-filled porosity we had to optimize chamber dimensions based on an average ε , which is approximately 20 % for the macropore regime of typical microgravity plant growth media. An optimal length of 12 cm (Figure 1) was used to compute the required

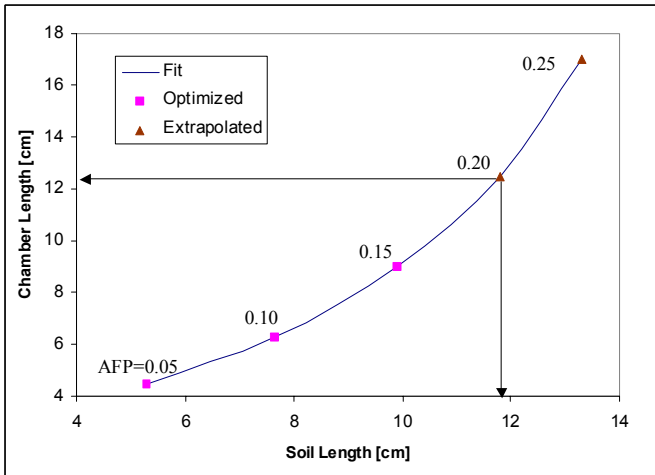


Figure 1. Optimal chamber dimensions as a function of air-filled porosity ($\epsilon = \phi - \theta$) (Glauz and Rolston, 1989)

prototype chamber volumes shown in Table 1. Using a source chamber two times larger than the sink provides additional diffusion capacity, which is reduced by the use of a dual closed-chamber system required for the Space Shuttle or ISS environment.

Table 1. Gas diffusion chamber characteristics.

	Ground-based chamber		
	Source	Substrate	Sink
Volume (cm ³)	244.4	122.2	122.2
Area* (cm ²)	26.83	9.68	22.79

* $L = V / A$, where A = substrate cross-sectional area.

Ground-based diffusion cell

The ground-based diffusion cell depicted in Figure 2 illustrates the basic components that resulted from improvements to the prototype design. The prototype unit operated with only a single 'sink' chamber, relying on stable atmospheric O₂ concentrations and minimal pressure fluctuations in the laboratory for the O₂ source. The new two-chamber design (Figure 2) is expected to be an important modification for measurements made in the environment of the space shuttle or international space station where both pressure and oxygen concentration vary considerably. Oxygen is measured with a galvanic O₂ sensor installed in the upper plates of the two chambers providing continuous O₂ concentration measurements.

In preliminary testing, the prototype sink chamber was purged with nitrogen using two methods prior to diffusion. In one case the chamber gate was closed and

in the other the chamber gate was left open during purging. Diffusion coefficients determined were 2.07 ± 0.18 (closed) and 1.90 ± 0.20 (open), which are not significantly different. Because of this and the additional complexity of having a gate to open and close, the gate was eliminated from the new design shown in Figure 2. Once the O₂ concentration in the sink chamber reaches the desired level, the initiation of a diffusion test begins with the oxygen sensor monitoring the increase in O₂ concentration with time as atmospheric gas diffuses through the substrate sample. The measurement completion time varies from several hours for dry material to several days for very wet substrate. Wire screens support the substrate, which sits on a porous stainless steel plate covering a water reservoir. Water pressure within the reservoir is maintained under constant suction to control the substrate water content using the matric forces of the porous plate and substrate. A Marriott tower connected to the water reservoir serves to supply water to the substrate while simultaneously maintaining the suction on the water beneath the plate. This maintains a stable water content throughout the diffusion cycle and can re-supply water losses in the substrate if needed. The plate at the bottom of the substrate was the optimal design for 1-g gas diffusion measurements, while for 0-g measurements, we have chosen a radially symmetric design patterned after porous tube water supply systems which have been previously tested in microgravity (Morrow et al., 1992, 1993).

Flight diffusion cell

The prototype flight diffusion cell is illustrated in Figure 3 demonstrating the radial symmetry and streamlining,

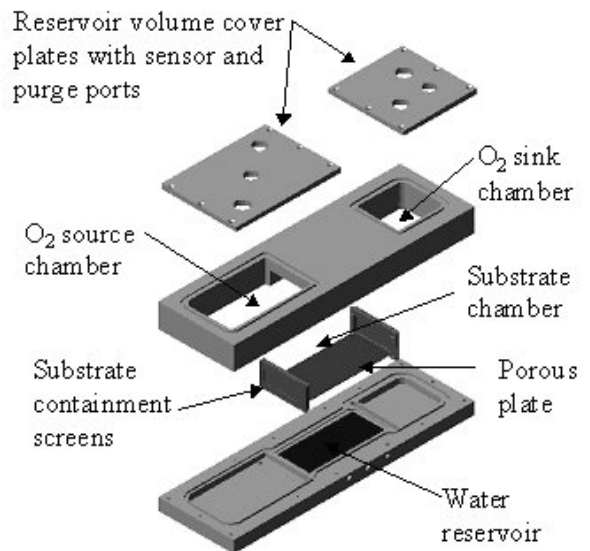


Figure 2. Oxygen diffusion cell for gas diffusion coefficient determination in porous plant growth substrates.

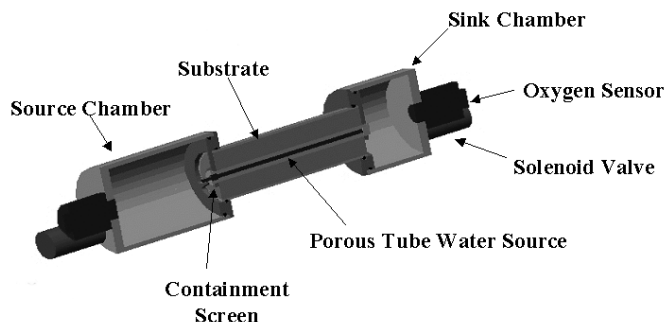


Figure 3. Flight prototype gas diffusion cell design using dual sealed gas chambers and a radially symmetric geometry with the water supply tube in the center.

designed to provide efficient packaging for multiple cells in a microgravity experiment. The flight prototype maintains the same design criteria of the ground-based unit for chamber and substrate lengths using a modified cross-section. The advantage of a water supply tube for maintaining water within the substrate is that air is less easily trapped in tubing than in a large reservoir used in the ground-based unit. A critical part of making gas diffusion measurements in microgravity is to maintain hydraulic continuity in the system necessary to maintain uniform water distribution. Sending the substrate into orbit in a lightly wetted state will aid initial wetting and reduce particle separation and rearrangement. Several past microgravity experiments have suffered due to particle separation or hydrophobic surfaces (Podolsky and Mashinsky, 1994; Yendler et al., 1996). The existence of liquid bridges between particles improves the uniformity of wetting and minimizes particle rearrangement and separation (Jones and Or, 1999).

RESULTS

DIFFUSION IN OTTOWA SAND

Gas diffusion measurements, relative to diffusion in air, were made in Ottawa sand that was previously sieved to between 0.5 and 0.6 mm diameter. Measurements were made over a range of water contents from dry to nearly saturated. Diffusion coefficients were calculated using two different methods discussed previously. The divergence in the two methods with increasing water content suggests a potential violation of the assumptions used in the Currie technique for the scale of chamber and soil sample used here. This will be further considered by adjusting the chamber volumes to determine the effect on the resulting diffusion coefficient calculations. Two different diffusion models are illustrated in Figure 4, one being the WLR model eq. (3) and the other, the Millington and Quirk (1961) diffusion model given as

$$D_G^S = D_a \frac{\varepsilon^{10}}{\phi^2} = D_a \frac{(\phi - \theta)^{10}}{\phi^2} \quad (6)$$

Since these diffusion models have been thoroughly evaluated in a variety of soils where the expected trend

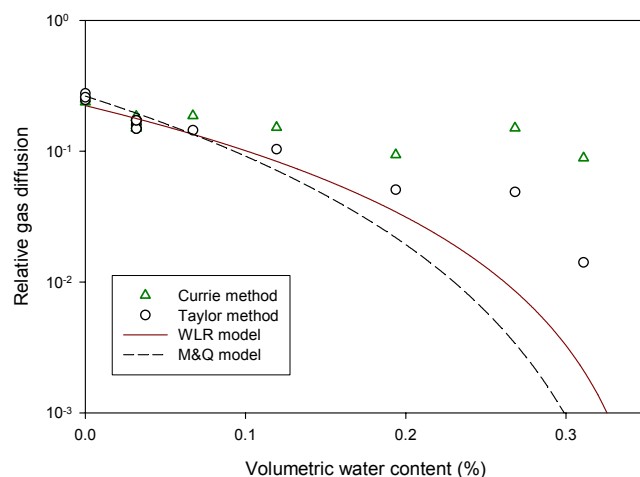


Figure 4. Relative oxygen diffusion measured in the prototype ground-based diffusion cell using Ottawa sand (0.5 – 0.6 mm) shown as a function of volumetric water content ($D_a = 0.153 \text{ cm}^2 \text{ s}^{-1}$).

in diffusion as a function of air-filled porosity is well known, the disparity between our measurements and these models leave in question the validity of the measurements in Figure 4. We expect the diffusion coefficient to be reduced with increasing water content by 3 to 4 orders of magnitude over the water content range as predicted by the models. The fact that diffusion coefficient values close to saturation are similar to those at median moisture contents, suggests a possible leak or open pathway that maintains diffusion at a level similar to mid-range diffusion values. One possible source is from edge effects where a lack of wetting between the container edge and the sand would lead to significant gas diffusion along the wall. A leak in the diffusion chamber itself (between fittings) is another possible problem, which is difficult to pinpoint with the prototype single chamber design. The dual chamber system will be more easily tested for leaks (and subsequently sealed). Edge effects can be examined using wall linings or other similar approaches.

MICROGRAVITY PLANT GROWTH SUBSTRATES

The water retention curves shown in Figure 5 illustrate several unique characteristics common for many of the candidate plant growth substrates for use in microgravity. They typically i) are sieved to a narrow particle-size distribution (and consequently exhibits a narrow pore-size distribution), ii) exhibit dual porosity with internal particle porosity in addition to the macro porosity between particles, iii) show significant hysteresis in the water retention curves between wetting and drying (Jones and Or, 1999), iv) release large amounts of air (and heat) from the micropores upon wetting from an initially dry state. This last characteristic poses serious problems for experiments requiring a dry substrate to be wet in microgravity. Upon saturating, microscopic air bubbles are released from the internal pore space over a period of about an hour and in the

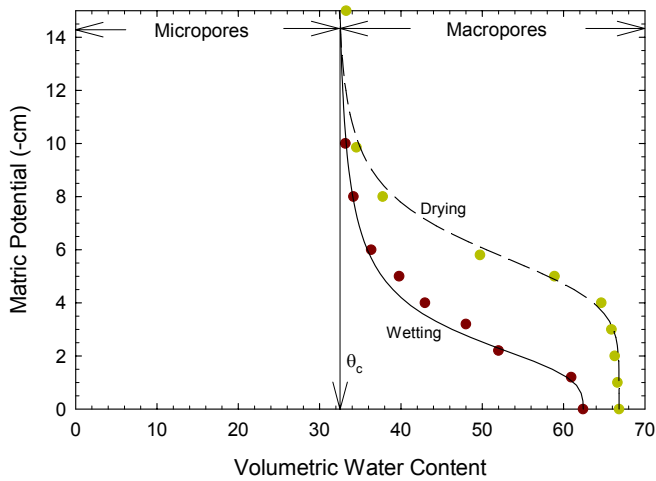


Figure 5. Substrate water characteristic (SWC) curves for Turface (1 – 2 mm) showing both wetting and drying processes. The critical water content, θ_c , separates water internal to particles (micropore) from between-particle water (macropore).

process the fluid volume of the substrate is expanded. This dynamic condition can cause over-saturation of the substrate, and generates large air pockets where smaller bubbles coalesce, which become trapped in large pores. This trapped air may work its way to the surface and in the process cause shifting and rearrangement of particles. The dynamics of this process in combination with subsequent wetting and drying processes can alter the physical packing and consequently the water retention character of the substrate over time. Gravity's force provides a stabilizing influence that buffers much of the particle movement on earth.

In microgravity, the neutral buoyancy of air, water and solid components suggests a more substantial and serious problem because air released from the substrate in any form will simply form along the walls of the particles with no buoyancy force to drive them out of the water phase. Fluid expansion in microgravity has the potential to become a long-term condition. Techniques that may avoid or reduce air entrapment include partial wetting (macropores remain air-filled during air release) prior to saturation or vacuum extracting air in saturated substrate followed by partial drainage prior to space flight.

DIFFUSION IN PLANT GROWTH SUBSTRATES

Relative gas diffusion data were collected in candidate microgravity plant growth substrates shown in Figure 6. Diffusion data were collected using Turface and Isolite, each of two different particle size ranges. Data collected in a relatively dry state (micropore water) were measured using conventional gas diffusion cells, while the wetter media were measured using the prototype

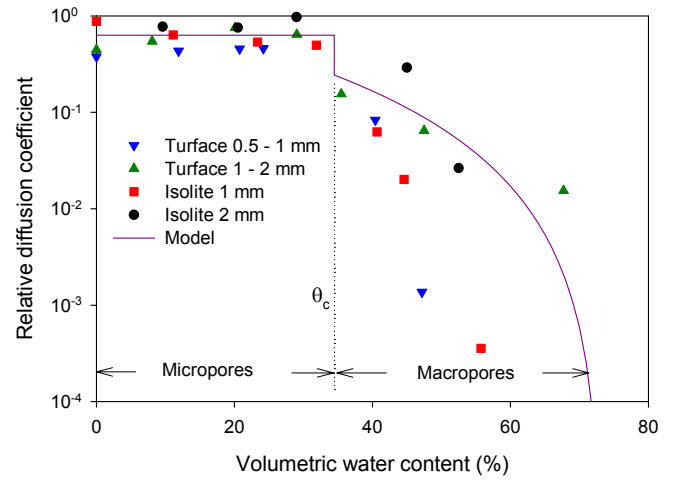


Figure 6. Oxygen diffusion in Turface and Isolite for two particle sizes as a function of water content. Modeled results are modified from Moldrup et al. (2000) ($D_a = 0.153 \text{ cm}^2 \text{ s}^{-1}$).

ground based diffusion cell. Two aspects of these data stand out: 1) the diffusion coefficient measured in the micropore regime (i.e., below θ_c) is relatively constant and 2) orders of magnitude difference exist between data and model predictions in the wet region where θ is greater than θ_c . A modification of eq. (3) is suggested for this two-pore region substrate, where a constant is used to describe diffusion at the micropore scale and a modified form of Moldrup et al. (2000) describes the macropore region, written as

$$D_g = \begin{cases} D_a \cdot (\phi - \theta)^{1.5} \rightarrow \text{micropores} \\ D_a \frac{(\phi - \theta)^{2.5}}{(\phi - \theta_c)} \rightarrow \text{macropores} \end{cases} \quad (7)$$

The relatively constant diffusion coefficients determined in the micropore filling range is due to the small contribution of the micropores to gas diffusion in comparison to macropore diffusion. Throughout the micropore-filling region, unsaturated hydraulic conductivity is low and a comparison of conventional (vertical flux) diffusion methods was well correlated to our horizontal diffusion measurements. As water begins filling macropores, however, unsaturated hydraulic conductivity is much greater and small gravity gradients are sufficient to produce significant differences in the vertical water content profile for the coarse textured media used here. The effect of this on the gas diffusion measurement is a greater cross-sectional area for gas diffusion in the upper regions of the porous medium compared to the wetter media at the bottom of the sample, thus the need for a thin sample. The effect of particle size is also apparent in the diffusion data for the macropore regime, where smaller particle sizes for each substrate show smaller diffusion values.

EFFECT OF HYSTERESIS ON DIFFUSION

One factor which will have a significant impact on the gas diffusion rates within the substrate is the hysteresis in water retention illustrated in Figure 5. This effect can be hypothetically demonstrated using the water retention for wetting and drying processes coupled with a diffusion equation expressed in Figure 7 as a function of matric suction, which is typically the variable to which water status is maintained within a porous medium for microgravity conditions. For illustration purposes, we select a control point of 3 cm suction for 1 to 2 mm Turface. The two diffusion curves demonstrate a variation in the computed oxygen diffusion coefficient of more than an order of magnitude, which could easily be the difference between a well-aerated or hypoxic root zone.

For long term plant growth conditions, one may begin with a saturated substrate drained to the control point of 3 cm suction. Over time, however, it is possible that localized water may be extracted from individual pores by plant roots while maintaining the 3 cm suction within the substrate (i.e., no change in energy potential). This process could conceivably continue until the water content was reduced to the intersection of the wetting curve at which point water would begin to be re-supplied according to the energy gradient developing within the substrate. Referring to Figure 5, this shift from the drying to wetting curve translates to a difference in water content of 0.2 or more than 50 percent of the available macropore water. The less obvious consequence of this shift is that while oxygen diffusion would be enhanced, hydraulic conductivity is diminished and water supply may become limiting to plant growth under certain scenarios. If water content could be directly monitored and controlled, there would be less uncertainty within the root zone. Unfortunately, restrictions on electromagnetic measurement techniques leave only a few measurement options such as the heat pulse technique, whose

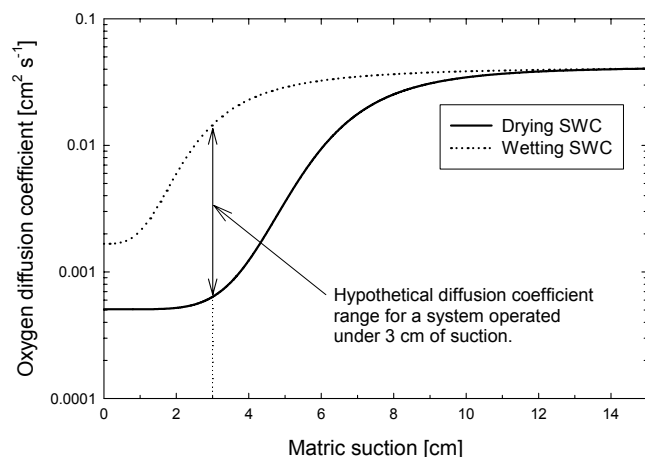


Figure 7. Oxygen diffusion modeled using eq. (3) based on the hysteretic water retention data of Turface (1-2 mm) shown in Figure 5 as described by eq. (1).

accuracy suffers from contact effects.

CONCLUSION

Novel gas diffusion devices for measurements on earth and in orbit have been designed and are being evaluated. The ground-based diffusion cell design optimizes gas and soil chamber dimensions considering substrate characteristics such as particle size and water retention in combination with the water content measurement range of interest. Oxygen diffusion coefficients determined using the prototype ground-based unit were comparable to results from a conventional diffusion cell and are in reasonable agreement with the WLR diffusion model under dry conditions. Further testing is underway to reduce potential sources of measurement error such as edge effects or possible chamber leaks. Accurate characterization of substrate water retention and reduced air entrapment upon substrate wetting are subjects in need further attention. Future work will focus on additional ground-based gas diffusion measurements in a variety of growth media and on the design and testing of automated diffusion measurement flight hardware.

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REFERENCES

- Currie, J. A. (1960). "Gaseous diffusion in porous media. Part 1. A non-steady state method." *Br. J. Appl. Phys.* 11: 314-317.
- Glauz, R. D. and D. E. Rolston (1989). "Optimal design of two-chamber, gas diffusion cells." *Soil Sci. Soc. Am. J.* 53: 1619-1624.
- Jones, S. B. and D. Or (1999). "Microgravity effects on water flow and distribution in unsaturated porous media: Analysis of flight experiments." *Water Resour. Res.* 3(4): 929-942.
- Jury, W. A., W. R. Gardner, et al. (1991). *Soil Physics*. New York, NY, John Wiley and Sons.
- Marshall, T. J. (1959). "The diffusion of gases through porous media." *J. Soil Sci.* 10: 79-82.
- Millington, R. J. and J. P. Quirk (1961). "permeability of porous solids." *Trans. Faraday Soc.* 57: 1200-1207.
- Moldrup, P., T. Olesen, et al. (2000). "Predicting the gas diffusion coefficient in repacked soil: Water-induced linear reduction model." *Soil Sci. Soc. Am. J.* 64: 1588-1594.

Morrow, R. C., R. J. Bula, et al. (1992). "A matrix-based porous tube water and nutrient delivery system." SAE Technical Paper Series Paper No. 921390.

Morrow, R. C., W. R. Dinauer, et al. (1993). "The ASTROCULTURE-1 flight experiment: pressure control of the WCSAR porous tube nutrient delivery system." SAE Technical Paper Series Paper No. 932282.

Podolsky, I. and A. Mashinsky (1994). "Peculiarities of moisture transfer in capillary-porous soil substitutes during space flight." Adv. Space Res. 14(11): 39-46.

Rolston, D. E. (1986). Gas diffusivity. Methods of Soil Analysis. A. Klute. Madison, Wisconsin, Am. Soc. Agron. Monograph 9: 1089-1102.

vanGenuchten, M. T. (1980). "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils." Soil Sci. Soc. Am. J. 44: 892-898.

Yendler, B. S., B. Webbon, et al. (1996). "Capillary movement of liquid in granular beds in microgravity." Adv. Space Res. 18(4/5): 233-237.

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