

MICROGRAVITY EFFECTS ON WATER FLOW AND DISTRIBUTION IN UNSATURATED POROUS MEDIA

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ABSTRACT

Several aspects of the physical processes of liquid flow and distribution within partially saturated porous media are altered in the reduced gravity conditions (microgravity) of orbiting spacecraft. The objectives of this study were to simulate and test measured flow and distribution in porous media from a microgravity environment using conventional capillary flow theory. Two past microgravity experiments studying water supply and uptake in porous media took place on a U.S. space shuttle, titled ASC-1, and on the Russian space station *Mir*, titled Greenhouse-2. Data from microgravity and ground experiments were simulated using similar physical flow models by elimination of the gravitational contribution to flow in microgravity as a first order approximation. Simulations of flow in the ASC-1 system were matched to data by adjusting media hydraulic parameters to account for apparent pronounced hysteresis and modifications of the substrate-water characteristic (SWC) under microgravity. Qualitative analysis of media parameters indicated narrower pore size distributions and inactive or non-participating large pores in microgravity. Although hysteretic effects were accounted for in the Greenhouse-2 simulations, a medium unsaturated hydraulic conductivity reduction of four orders of magnitude was most effective in matching simulated and measured water content dynamics. Evidence of accentuated hysteresis, altered SWC, and reduced hydraulic conductivity from microgravity simulations may be attributable to proposed mechanisms of air- and liquid-entrapment, fingering flows, particle capturing, separation, and rearrangement, Haines jumps and hydraulic discontinuity. These are likely spawned by enhanced interfacial flows and altered hydrostatic and hydrodynamic forces occurring through sorption and desorption processes.

INTRODUCTION

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. Various systems have been proposed and/or tested, which supply water and nutrients to plants in reduced gravity fields (Morrow et al., 1992, 1993, 1994; Ivanova and Dandolov, 1992b; Bugbee and Salisbury, 1989; Dreshel and Sager, 1989; Wright et al., 1988). Plant growth experiments have been carried out by U.S. and Soviet or Russian scientists for more than ten years in microgravity (Dutcher et al., 1994; Nechitalio and Mashinsky, 1993). Plants generally developed somewhat abnormally in porous media and it is unknown if the effects of reduced gravity have caused the abnormality or if the cause was due to other sources such as an inadequate supply of either water or oxygen to plant roots.

In studying liquid and gas behavior in porous media under the conditions of microgravity, we have posed several basic questions. The most important is, whether it is possible to adequately model liquid behavior within porous media in microgravity by simply removing the gravitational terms from the unsaturated flow equation (Richards equation)? Additional questions include: Are the SWC conceptual and parametric models transferable to or even applicable in a microgravity environment? Are hysteresis pathways of a SWC more or less pronounced and are there additional mechanisms that contribute to this phenomena? How does liquid propagate through initially dry, particulated, non-cohesive, and buoyant (free floating) media in microgravity? Some of these questions have been only partially addressed in past

microgravity experiments.

An imbibition and redistribution experiment in a porous granular medium (Balkanine, a zeolite), conducted on the Mir space station, revealed free particle movement, especially in loosely packed containers. Podolsky and Mashinsky (1994) consistently found higher media water contents in microgravity from horizontally oriented time-controlled redistribution experiments when compared to ground control experiments. They suggested that magnified inertial and frictional forces in microgravity may counteract capillary forces. Morrow et al. (ASC-1; 1992, 1993) showed water transfer rates through a granular substrate (0.6 - 1.0 mm arcillite) to be consistently higher on earth than in microgravity during the last half of each 120 minute pressure setting, which ranged from -5 to -20 cm. In a second set of experiments (ASC-2; Bula et al, 1993) using fine (0.35 - 0.60 mm) and coarse arcillite granules (0.60 - 1.0 mm), transfer rates were found to be generally higher in the fine as compared to the coarse arcillite under various induced differential matric suctions ranging from - 2.5 to -20 cm. Interestingly, transfer rates in the coarse material were generally higher in microgravity while in the fine material rates were typically higher on earth.

While some of the "flow in porous media" experiments sought to model liquid behavior in microgravity, the limitations of research on a space vehicle have yielded little in terms of general and basic models. Microgravity research has, however, confirmed the notion that capillary forces become dominant as gravitational forces diminish (Antar and Nuotio-Antar, 1993). Therefore, despite some differences in liquid behavior observed between earth bound and orbital experimental results in porous media, the use of conventional unsaturated porous media flow theory, based on capillary forces only, is expected to remain a viable framework for gaining more insight.

The objectives of this study were to 1) use models for unsaturated water flow and distribution in porous media to simulate global water content and flux measurements taken in microgravity, 2) test these models for detailed spatial liquid distributions in microgravity and 3) identify potential mechanisms and their corresponding effects that may account for hydrostatic and hydrodynamic differences observed between earth and microgravity.

THEORETICAL CONSIDERATIONS

The pore-size distribution of a medium or substrate may be characterized by means of the substrate-water characteristic (SWC). This hysteretic relationship describes the amount of water held in the medium as a function of energy level or matric head, h [L]. The van Genuchten (1980) equation for volumetric water content, θ [$L^3 L^{-3}$], as a function of h is given as

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

where α [L^{-1}] and n are empirical parameters and the subscripts s and r refer to saturated and residual water contents, respectively. Fig. 1 illustrates the effect of particles of different size distributions on the SWC, where eq. (1) was fit to measurements from three different particle size ranges of Balkanine, a zeolite used in the Svet growth chamber on the Mir space station. Sorption and desorption pathways (hysteresis) of the 1 to 2 mm particles used in the Greenhouse-2 experiment are indicated by arrows. The relationship between matric head and water content provides valuable information for predicting liquid behavior in porous media, especially in microgravity where water content control can become a critical factor. The unsaturated hydraulic conductivity, $K(h)$ [$L T^{-1}$], of a porous medium may also be expressed

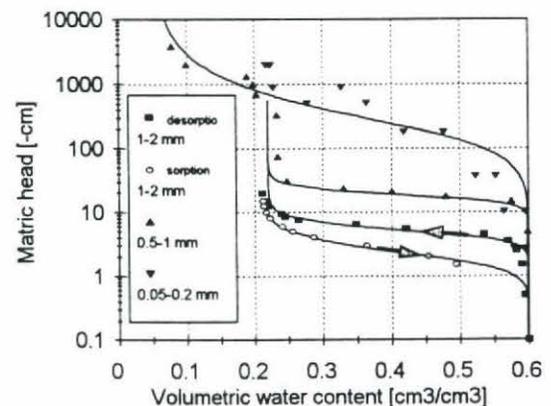


Fig. 1. Measured and fitted substrate-water characteristic (SWC) of three different particle size ranges of Balkanine (a zeolite) with sorption and desorption pathways shown for the 1-2 mm size.

in terms of α and n combining van Genuchten's (1980) equation and Mualem's theory (1976), given by

where K_s [$L T^{-1}$] is the saturated hydraulic conductivity of the medium. These expressions for water retention and conductivity may be incorporated in the unsaturated flow or Richards equation, which is the basis for many simulation

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

models used to describe liquid behavior in porous media. The Richards equation for two dimensional flow may be written as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(K(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K(h) \frac{\partial h}{\partial y} \right) - \frac{\partial K(h)}{\partial y} \quad (3)$$

where t [T] is time and x [L] and y [L] indicate horizontal and vertical coordinate positions. For conditions of microgravity the last term, representing the gravitational contribution to flow, is assumed negligible.

MATERIALS AND METHODS

A finite element model for simulating two-dimensional water movement in variably saturated media, HYDRUS-2D (IGWMC, Golden, CO), was used to simulate water retention and flow data collected both in microgravity and on earth. The program incorporates a finite element model to solve the Richards equation (eq. (3)) for saturated-unsaturated water flow. Microgravity simulations were run by defining a horizontal flow condition, which eliminates the gravity gradient in the Richards equation. The unsaturated soil hydraulic properties are described by a set of closed-form equations (eqs. (1) and (2)) whose parameters are given in Table 1.

Root modules (media containers) from both ASC-1 and Greenhouse-2 experiments possess a similar geometry (Fig. 2). A cross-section of the root modules shows the approximate location of the water supply tubes embedded in the growth media. The porous media and water supply materials were assigned

different water flow parameters and saturated hydraulic conductivities as outlined in Table 1. Time-variable boundary conditions were used in the simulations to account for the hysteretic nature typical of porous media sorption and desorption cycles.

ASC-1

The ASC-1 flight experiment, flown on the space shuttle Columbia (STS-50) from June 25 to July 9, 1992, tested the porous tube nutrient delivery system used to control water movement in particulated porous media (Morrow et al. 1994). The ASC-1 root module consists of two sintered porous stainless-steel tubes embedded in a porous medium (0.6 to 1.0 mm arcillite, a baked and crushed clay) with a pumping system which draws liquid through the porous tubing under negative pressures to induce suction in the porous medium. One tube was considered the supply (tube 1) and the other the recovery (tube 2), with the recovery tube either operating at a suction equal to or greater than the supply tube (Fig. 2). A series of seven different negative pressure configurations were operated in series for a period of 120 minutes each. Liquid transfer rate data from one of the two ASC-1 root modules (30 μ m pore-sized tubing) was digitized for purposes of comparison to simulated data. Stages of desorption, sorption, and desorption are designated as a, b, and c, respectively, for the microgravity (0g) and earth-based (1g) experiments shown in Table 1. The time-

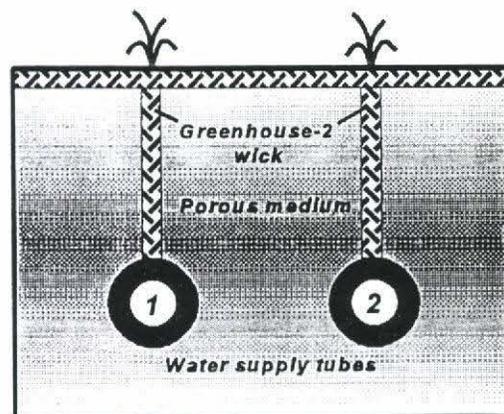


Fig. 2. Generalized root module cross-section showing supply (1) and recovery (2) tubes for the ASC-1 system and for the Greenhouse-2 module, supply tubes (1 and 2) with the wick for supplying water to seeds planted in the surface.

Table 1. HYDRUS-2D model parameters used in the ASC-1 and Greenhouse-2 simulations.

Water flow parameters	ASC-1						Greenhouse-2 (<i>Mir</i>)		
	0g-a	0g-b	0g-c	1g-a	1g-b,c	Sstl. Tube	0g-a	0g-b	Wick
θ_r	0.34	0.34	0.30	0.31	0.30	0.08	0.22	0.22	0.05
θ_s	0.58	0.58	0.47	0.62	0.63	0.43	0.60	0.52	0.48
α [cm ⁻¹]	0.12	0.21	0.12	0.33	0.39	0.04	0.39	0.20	0.14
n	6.3	4.5	6.3	2.2	2.2	1.6	3.7	5.2	1.8
K_s [cm d ⁻¹]	3200	3200	3200	3200	3200	3.6	2.3	2.3	50
Time [min]	Constant head B. C. [-cm]								
0 to 240	10/10			10/10					
240 to 360	10/15			10/15					
360 to 480	10/20			10/20					
480 to 600	5/5			5/5					
600 to 720	5/10			5/10			Potential	Flux	
720 to 840	5/15			5/15			Evaporation	B.C.	
[d]							[cm d ⁻¹]		
7 to 14.4							0.4	0.82	
14.4 to 15.0							0.4	3.7	
15.0 to 30.0								0.4	0

variable boundary conditions (B.C.) used in the five separate simulations are detailed in Table 1 where negative pressure heads are designated for tube 1 and tube 2 (e.g., 10/15), respectively, and the container walls are specified as no flux B.C. The media pressure head was set to -1 cm at the beginning of stage a to create the reported saturated initial conditions of the module. Nodal pressure head values from the final time step of stages a and b were used as the initial pressure head values for stages b and c, respectively.

Greenhouse-2

The "Greenhouse-2" experiment, conducted aboard the Russian space station *Mir* from July 9, 1996 to January 22, 1997, made use of the plant growth unit *Svet* (Ivanova et al., 1993). The *Svet* growth chamber consists of two identical vegetation vessels or root modules where seeds are planted and into which water and air are injected. The module contains two porous materials of interest, the plant growth medium, Balkanine, a naturally occurring zeolite and a

chlorine linen fabric or wick that extends along the top of the module and downward in a double layer from the surface to wrap under each of the supply tubes (Fig. 2). The wick served the purposes of containing the Balkanine to prevent its escape into the cabin and to "wick" water to the seed bed and to the water content sensor. Air flow tubes were installed just above the water supply tubes between the double wick layer to enhance media aeration. A control unit regulated water additions based on the single water content sensor located in the center of each of the two root modules.

A newly added instrumentation system mounted to *Svet* included 16 heat-pulse-based media water content probes designed to provide additional information on the spatial distribution of water in the root module. Eight, 5 mm diameter probes, of various lengths (3, 6, and 8.5 cm), were inserted into each of the two root modules to monitor water distribution and content in the growth media (Bingham et al.,

1996). The area of influence of the 2.5 cm long sensor attached to its stainless steel shaft was found to extend radially approximately 2 to 4 mm from the sensor surface. Sensor readings were dependent on the thermal conductivity of the probe material and the porous media and water in contact with and surrounding each sensor (Yendler, 1996). A 30 day period beginning with a second planting of wheat, was selected for media water content and distribution analysis. The second of the two plantings took place on December 6, 1996 at which time new water content probes were installed to replace some that had stopped functioning. Water content levels at the beginning of the simulation indicated macropores (inter-particle pores) were void of water while micropores (inner-particle pores) were partially water-filled. Over the 30 day period, there were approximately 15 days of gradually increasing water contents, one day in which both root modules became nearly saturated, followed by 15 days of gradual drying. The inability of eq. (2) to account for the dual porosity characteristic of Balkanine illustrated in Fig. 1, made it necessary to begin the simulation at day 7 where sorption had progressed to where the residual water content of the macropores was reached.

RESULTS

ASC-1

The water balance output data from simulations was plotted against the digitized microgravity and terrestrial data for comparison. The media parameters were adjusted by iteration to obtain an approximate fit to the digitized data. The simulated data from HYDRUS-2D was matched to the data from both microgravity and ground-based experiments (Fig. 3). Matching was accomplished by adjusting the SWC parameters (α , n) described by eq. (1). For the ground-based simulation, the SWC of arcillite for "stage a" was scaled using α to account for the hysteretic nature of porous media depicted in Fig. 4 (Kool and Parker, 1987). This step was taken due to the over prediction of media-imbibed water when the process shifted from desorption (stage a) to sorption (stage b). No alteration of the slope of the SWC, n , was necessary for the ground simulation and the same SWC curve was used for both stages b and c (Table 1). For the microgravity simulation, however, both parameters n and α were different for the sorption versus desorption curves. Values of n for

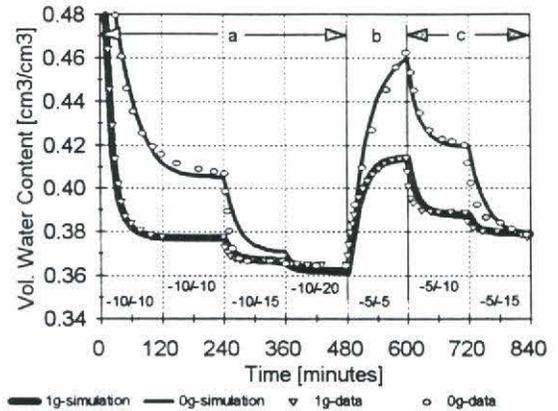


Fig. 3. Simulation of digitized data from the ASC-1 system. Induced pressure heads in tubes 1 and 2 are indicated as, for example, -10/-10 [cm] for each 120 minute time series.

microgravity were 2 and 3 times larger than for ground data, indicating narrower distributions of pores. Smaller α values indicate that the larger pores may have either been absent or not participating in the sorption-desorption process as they did on earth. This may be further evidence of air-entrapment, which, depending on the relationship between the cohesive and adhesive forces, may be more pronounced in certain sizes of pores. A more detailed discussion of mechanisms potentially responsible for the observed differences between earth and microgravity follows the results.

Greenhouse-2

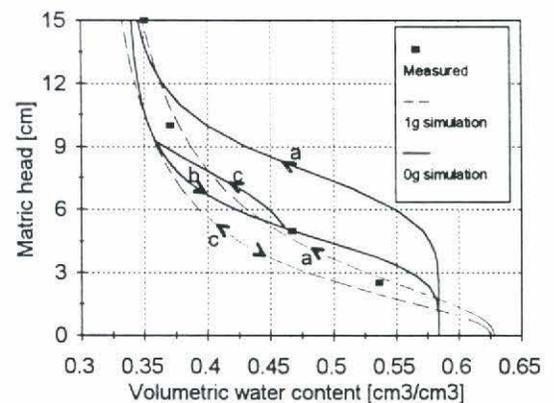


Fig. 4. Substrate-water characteristic curves for arcillite used in the ASC-1 simulations. Sorption and desorption curves are indicated by arrows, illustrating the effects of hysteresis. Measurements are from Morrow et al. (1993).

Simulations of measured water content distributions from microgravity were carried out over a single, 30-day, sorption-desorption cycle from the Greenhouse-2 experiment. Time-dependent water contents were generally consistent between the two root modules and among probes at similar depths in the Balkanine. Using ground-based measured sorption and desorption SWC for Balkanine (Fig. 1), simulations were carried out to recreate water content dynamics as measured by the heat-pulse sensors in microgravity (Fig. 5). Media parameters were determined, which would satisfy the measured water contents, inferred gradients and computed fluxes. Optimization of the parameters yielded two extremes, either a very narrow or a very wide pore size distribution, neither of which were found to satisfy the water content gradients observed in Fig. 5, rather, only uniform water contents throughout the Balkanine were obtained from simulations using these parameters. The sustained higher water contents, after day 15, at the 8.5 cm depth (long probe) compared to those at 6 (medium) and 3 (short) cm are an indication of discontinuity or reduced hydraulic conductivity in the lower portion of the root module (Fig. 5). Such long term hydraulic discontinuities have not been noted using the ground-based root modules.

Calculations showed that the high saturated hydraulic conductivity of the 1 to 2 mm Balkanine ($K_s = 20,000 \text{ cm d}^{-1}$) combined with the shape of the intrinsic conductivity function (eq. (2)) used in simulations, required extremely small matric head gradients to facilitate fluxes on the order of those computed from daily changes in water content measurements. Unsaturated hydraulic conductivity values were then optimized to satisfy computed fluxes passing probe positions and leaving the surface. The van Genuchten (1980) expression (eq. (2)) for unsaturated hydraulic conductivity was scaled using the K_s parameter, to fit the optimized data by reducing K_s from a value of 20,000 to 2.3 cm d^{-1} (Fig. 6). Reduction of the K_s parameter facilitated simulation of water content gradients that were previously not achieved using the measured value of the Balkanine saturated hydraulic conductivity. Additionally it was found that a two fold reduction in K_s parameter (from 5,000 to 50 cm d^{-1}) for the wick further improved the fit to data. We find no evidence that the saturated hydraulic conductivity of porous media differs in microgravity, however, it may be that a differently shaped conductivity

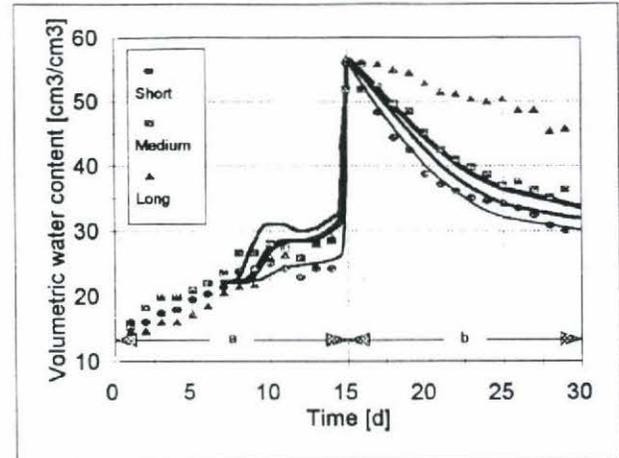


Fig. 5. Comparison of spatial and temporal measured (symbols) and simulated (lines) water contents at 3, 6, and 8.5 cm depths in 1 to 2 mm Balkanine in root module 1.

function would fit both the measured and computed hydraulic conductivities shown in Fig. 6, unfortunately the HYDRUS-2D model only allows for the use of the van Genuchten conductivity function. One potentially better fitting model was presented by Gardner (1957), given as

$$K(h) = \frac{C_1}{C_2 + h^4} \quad (4)$$

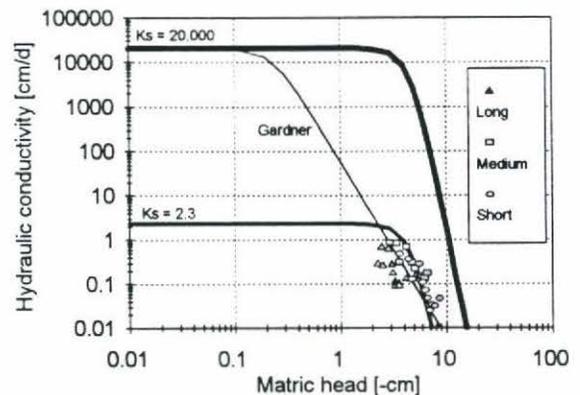


Fig. 6. Unsaturated hydraulic conductivity functions inferred from measured and fitted saturated hydraulic conductivities using (2) and the other is by Gardner (1957). Data points are computed conductivities taken from short, medium and long probe water contents.

where C_1 [$L^3 T^{-1}$] and C_2 [L^2] are empirical fitting parameters and h [L] is the matric head. This function, plotted in Fig. 6, was fitted ($C_1 = C_2 = 0.003$) to the original measured saturated hydraulic conductivity and the $K(h)$ values taken from the inferred gradients and calculated fluxes at matric heads between -2 and -9 cm as shown. This lack of fit lends some evidence to the idea that conventional capillary flow models may not adequately describe liquid retention and flow in microgravity. However, we feel the reduction in the K_s parameter for matching purposes does not indicate a reduction of the saturated hydraulic conductivity of porous media in microgravity. It simply provided a means for fitting the intrinsic hydraulic conductivity function to the data set available and likely implies the need for a different conductivity function as illustrated in Fig. 6.

Spatially variable water content distributions are presented in Fig. 7, showing a length-wise cross-section of root module 1. Fig. 7a portrays sensor locations and shows sensor depths from the near wall toward the far wall (15 cm across), which are noted below each symbol. Water from the porous supply tubes passed through the wick before contacting the Balkanine in which the sensors were located (Fig. 2). Water content distributions four days before flooding, during sorption (Fig. 7b), and eight days after flooding, during desorption (Fig. 7c), show erratic water content distributions. During the sorption process, there are signs of preferential wetting toward the back (right side) of the module, which could also be a result of higher evapotranspiration near the inlet of the air supply tube due to preferential airflow. A similar, though, less pronounced trend is observed during desorption. Water contents during sorption indicate transitioning from inner-particle water ($\theta < \theta_i$) to inter-particle or pendular water ($\theta > \theta_i$). At this residual water content matric head spans almost two orders of magnitude shown in Fig. 1. Evidence of potential mechanisms leading to observed differences between earth and microgravity will now be presented and discussed using the ASC-1 and Greenhouse-2 results and other past microgravity experiments.

DISCUSSION

Simulation results from the ASC-1 and Greenhouse-2 experiments using the Richards equation suggest that the physical principles relating to capillary flow may operate similarly in

microgravity as they do on earth. There are some doubts, however, regarding the details of the hydrodynamics and hydrostatics in microgravity. Porous media related sorption and desorption processes on earth are known to exhibit such phenomena as, "fingering" or "channeling", air-entrapment, particle rearrangement and hysteresis (Levine et al., 1977). Enhanced hysteresis, alteration of the SWC, and modified hydrodynamics were apparent microgravity effects inferred from parameterization of the capillary flow models. Potential mechanisms for these phenomena that are postulated in this study include enhanced interfacial flow, applicable to both consolidated and unconsolidated media and alteration of the balance of liquid and solid forces in unconsolidated porous media. These primary mechanisms trigger potential secondary mechanisms illustrated in Fig. 8. The illustration is given as a framework for understanding the potential causes of observed and hypothesized

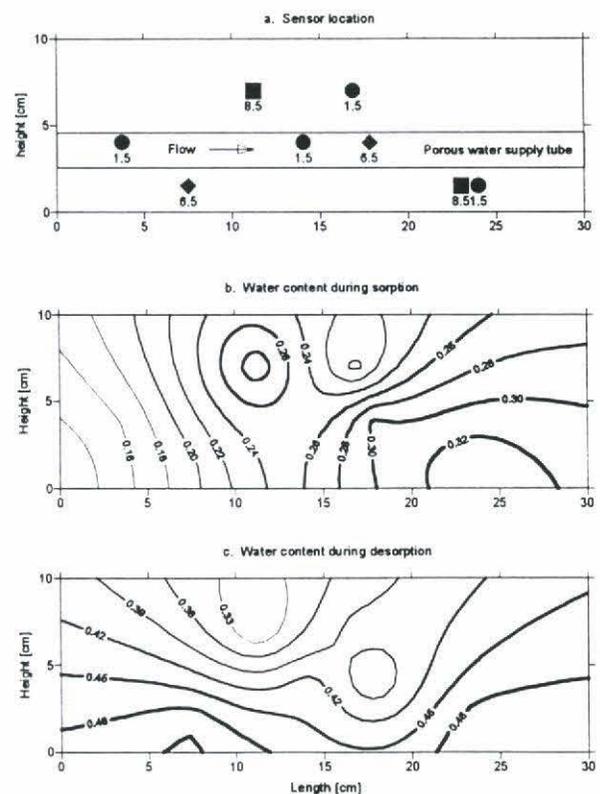


Fig. 7. Water content sensor locations in root module 1, with depth from near wall indicated below each symbol (a). Volumetric water content [$cm^3 cm^{-3}$] distributions during the sorption process (b), four days prior to media saturation and during desorption (c), eight days after sating.

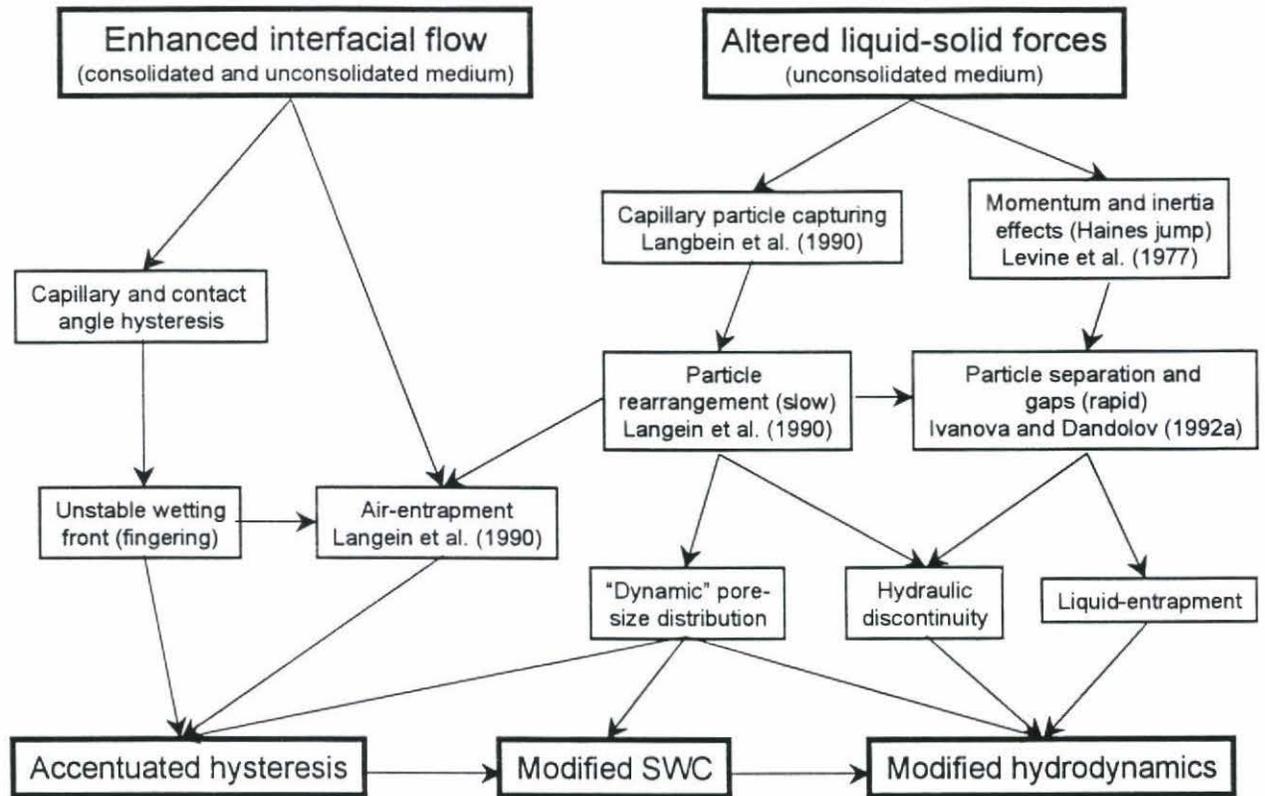


Fig. 8. Mechanisms potentially responsible for the microgravity induced phenomenon of accentuated hysteresis, modified SWC, and modified hydrodynamics inferred from parameterization of the capillary flow models used in microgravity simulations.

differences between porous media water retention and flow on orbit compared to that on earth. Evidence of many of these phenomena are found in results from past microgravity experiments.

Enhanced Interfacial Flow

A potential scenario for liquid imbibition into an ideal pore under conditions of earth's gravity and microgravity shows the potential for increased air-entrapment as film flow rather than capillary flow progresses through a large pore (Fig. 9). Flow along the surface of a "large" pore was demonstrated in a soda water bottle during the approximately 20 seconds of microgravity from the parabolic flight aboard the KC 130 aircraft (Langbein et al., 1990). The half filled bottle's flat liquid surface, normally present in earth's gravity, became rounded in microgravity as liquid ran up the bottle walls and filled in the neck of the open bottle forming a large air bubble which was forced to the center of the bottle. Effervescence along walls showed little tendency for bubbles to coagulate, producing a foam that

effectively forced liquid out of the bottle. Air bubbles which form in saturated porous media are likely to have a similar effect, especially after very dry media is saturated, which has a tendency to slowly release air trapped in micropores.

Whether a pore becomes only partially or completely filled with water is a function of the pore size, relationship between the adhesive-cohesive, and the liquid-solid contact angle. The liquid-solid contact angle was found to be altered in a microgravity environment. Sell et al. (1984), found non-hemispherical menisci having larger contact angles than those measured on earth. They conclude that since hemispherical menisci give rise to maximal capillary pressure, liquid columns having deformed menisci in microgravity rise more slowly than on earth, giving further evidence for reduced hydraulic conductivity in microgravity. Langbein et al. (1990) found surface wettability and speed of penetration a function of contact angle and dihedral angle of the surface. They found the smaller the sum of the

contact angle and half the dihedral angle, the faster the penetration and better the wettability. Hysteresis has been attributed to both "capillary" and "contact angle" effects, and both are likely participants in microgravity. Hysteresis results from variations in the solid-liquid-gas interfaces that form differently in porous media under conditions of sorption and desorption (Hillel, 1980; Jury, et al., 1991). Under conditions of microgravity, liquid spreading over solid surfaces (film flow) is uninhibited by gravity forces and therefore spreading can proceed in all directions (Antar and Nuotio-Antar, 1993). **Altered Liquid-solid Forces**

The lack of body forces in microgravity creates a condition where capillary, momentum and inertial forces exhibit greater influence on liquid-solid interactions within porous media. At the two water content extremes of completely dry or completely saturated media, where capillary forces are minimal, particles in microgravity are free-floating. It is the transition from these extremes to partial saturation where the greatest opportunity for particles to rearrange creating a "dynamic" pore size distribution. The rearrangement of particles is even more likely to occur at the wetting front of an initially dry porous medium where particles are drawn into the advancing water front by adhesive and capillary forces, creating air gaps between particles. This temporary loss of particle continuity would increase the chances for unstable fingering flows and perhaps necessitate near saturation behind the front before water film thickness could extend to adjacent free-floating particles to further advance the wetting front. Langbein et al. (1990), performed liquid imbibition experiments in close-packed glass beads in the temporary (< 20 seconds) microgravity environment of the KC-130 aircrafts parabolic flight. They stated that, "each time, it (water) wets another sphere, the video recordings show a local rearrangement of adjacent spheres due to capillary forces." This process likely caused imbibition in a less densely packed container of Balkanine in microgravity, to cease after only 4 hours while wetting in the other three containers continued beyond 24 hours (Ivanova and Dandolov, 1992a). The imbibition process is likely made up of both "capillary particle capturing" described by Langbein et al., (1990) and Haines jumps. The Haines jump (Haines, 1930), which results from unstable fluid configurations in pores leading to rapid filling or draining of the pore, causes particle

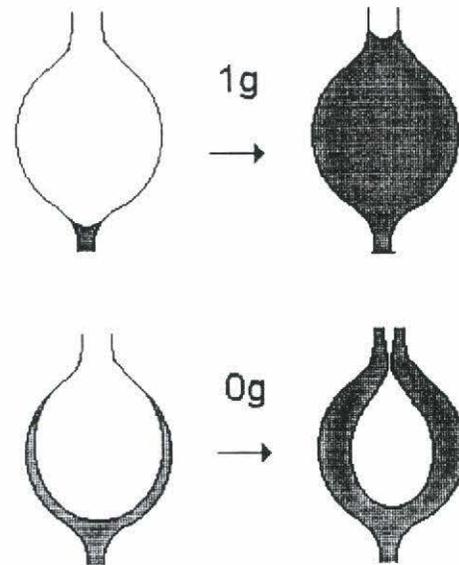


Fig. 9. Wetting of an ideal pore under conditions of gravity and microgravity illustrating the potential increased hysteresis due to air-entrapment.

rearrangement and possibly separation (liquid entrapment) in microgravity. Its effects are more pronounced as pore (particle) size increases due to increased inertial and momentum forces, which on earth are held in check by body force or particle weight. These phenomena of particle rearrangement and separation, which lead to alteration of the pore size distribution and reduced flow pathways, may partially explain the greater difference between the sorption and desorption SWC curves from microgravity as well as the modified hydrodynamics.

Evidence of potential mechanisms leading to enhanced hysteresis and reduced unsaturated hydraulic conductivity in microgravity can be seen in past microgravity experiments. The mechanisms are enhanced interfacial flow leading to air-entrapment and fingering and alteration of the liquid-solid force picture, which leads to particle capturing, separation, and rearrangement, Haines jumps, dynamic pore size distribution, hydraulic discontinuity, and liquid- and air-entrapment. Effects of these mechanisms are accentuated hysteresis, modified SWC and altered hydrodynamics. Phenomenon of particle

separation may be one of the key problems for the use of unconsolidated porous media as a growth substrate in microgravity. The resulting reduction in cross-sectional flow area from discontinuous pathways is a possible reasons for the differences of liquid imbibition into initially dry media noted in microgravity as compared to Earth.

SUMMARY AND CONCLUSIONS

Simulations of water retention and flow within porous media in both microgravity and on earth were obtained by capillary flow models adjusted to account for probable hysteresis in the SWC. Compared to ground-based results, media parameters from microgravity indicate narrower pore size distributions that may be a result of particle rearrangement and increased air-entrapment. Enhanced interfacial flows and altered liquid-solid forces are proposed phenomena in microgravity likely leading to secondary mechanisms and effects. These secondary mechanisms are likely responsible for the enhanced hysteresis and modified SWC inferred from media parameterization using microgravity data. Evidence of reduced unsaturated hydraulic conductivities from parameterization and simulations along with slower propagation rates observed in porous media from past microgravity experiments as compared to horizontal flows on earth give indications of modified hydrodynamics in microgravity. Water content distributions measured in microgravity were spatially and temporally erratic with isolated incidences of sustained large water content gradients indicating hydraulic discontinuity (particle separation, air-entrapment). While the applicability of conventional soil physical models for simulating porous media behavior in microgravity remains questionable, these simulations and results provide valuable evidence of potential mechanisms causing observed differences. Further research using media with solid-phase continuity may alleviate some of these problems such as physical and hydraulic discontinuity.

ACKNOWLEDGMENTS

Partial funding from the Rocky Mountain NASA Space Grant Consortium is gratefully acknowledged. Special thanks is extended to Dr. Ray Bula of the Wisconsin Center for Space Automation and Robotics and Dr. Gail Bingham of

Space Dynamics Laboratory for providing experiment information.

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