Manuscript revised and submitted to the Advances in Space Research on April 2, 2014

No. of pages: 27 (including figure captions); figures: 8; tables: 2

Modeling Gravity Effects of Water Retention and Gas Transport Characteristics in Plant Growth Substrates

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Key Words: Plant growth media, reduced gravity, gas diffusivity, percolation threshold

ABSTRACT

Growing plants to facilitate life in outer space, for example on the International Space Station (ISS) or at planned deep-space human outposts on the Moon or Mars, has received much attention with regard to NASA's advanced life support system research. With the objective of in situ resource utilization to conserve energy and to limit transport costs, native materials mined on Moon or Mars are of primary interest for plant growth media in a future outpost, while terrestrial porous substrates with optimal growth media characteristics will be useful for onboard plant growth during space missions. Due to limited experimental opportunities and prohibitive costs, liquid and gas behavior in porous substrates under reduced gravity conditions has been less studied and hence remains poorly understood. Based on ground-based measurements, this study examined water retention, oxygen diffusivity and air permeability characteristics of six plant growth substrates for potential applications in space, including two terrestrial analogs for lunar and Martian soils and four particulate substrates widely used in reduced gravity experiments. To simulate reduced gravity water characteristics, the predictions for ground-based measurements (1-g) were scaled to two reduced gravity conditions, Martian gravity (0.38-g) and lunar gravity (0.16-g), following the observations in previous reduced gravity studies. We described the observed gas diffusivity with a recently developed model combined with a new approach that estimates the gas percolation threshold based on the pore size distribution. The model successfully captured measured data for all investigated media and demonstrated the implications of the poorly-understood *shift in gas percolation threshold* with improved gas percolation in reduced gravity. Finally, using a substrate-structure parameter related to the gaseous phase, we adequately described the air permeability under reduced gravity conditions.

1. INTRODUCTION

The successful landing of NASA's Curiosity Mars Rover on August 2012 in search of microbial life in Martian soils has brought renewed scientific and public interest on space exploration and the establishment of human outposts on Moon and Mars. NASA's future space program envisions revisiting the moon, getting astronauts onto a near-earth asteroid by 2025, and conducting the first-ever manned mission to Mars by the mid-2030s (NASA, 2012). A permanent lunar base and deep-space stations facilitating such long-duration interplanetary space missions have also become key topics among space scientists while a permanent Mars base may mark the culmination of the historical endeavor of space exploration. Despite the profound experience obtained from continuous human presence in short term life-support systems (e.g., on the low earth orbit ISS), the prolonged maintenance of a self-sustaining deep-space human outpost, such as a Mars base, will pose far greater challenges to mankind in the future.

Growing plants in reduced gravity environments on space outposts may be beneficial for astronauts in two ways; *psychological* and *functional*. Russian cosmonauts witnessed the pleasure they experienced on space missions by growing plants, watering and watching the plants grow (Nechitailo and Mashinsky, 1993), suggesting that plants can provide a significant psychological benefit for the people onboard (Bates et al., 2009; Marquit et al., 2013). Recent studies in space psychology further recognized the *perception of earth* as a key psychological factor for astronauts involved in short-term missions, which was evidenced by the large number of self-motivated photographs of the earth taken aboard the ISS during space missions (Robinson et al., 2011). The conclusions of these studies indicate "intensive feeling of isolation" once the earth is out of view during future extended-duration missions (e.g., Mars exploration), and emphasized the importance of substitute leisure activities for the crew at unscheduled times.

1 Growing and tending to plants can be a promising substitute leisure activity for long-duration
2 missions. The functional benefit of space-grown plants is related to the potential of plants to
3 regenerate air and water and to supply food for self-sustained operation of a remote human base
4 (NASA, 2002). The role of plants in close-loop systems in relation to space-based applications
5 has been discussed in detail in e.g., Wheeler et al. (2003).

6 Most of the essential needs for successful plant growth on earth (e.g., air, water, and nutrients)
7 are strongly linked to the plant growth substrates (Brady, 1974). Compared to field-grown plants,
8 plants grown in controlled volumes have restricted access to these plant needs due to
9 discontinued boundaries (defined by container size and geometry) for mass transport and root
10 penetration. In space, reduced gravity plays an important but poorly understood role in fluid
11 phase configuration within the root zone, demanding proper characterization of growth media for
12 space-based applications. Air and water supply are particularly crucial, as they compete for the
13 same pore space within the root zone. Potential plant growth substrates for reduced gravity
14 environments have been characterized in previous microgravity research, with a specific focus
15 on air (oxygen), water, and nutrient behavior in the root zone of growth modules (Jones and Or,
16 1999; Steinberg et al., 2002; Jones et al., 2003; Steinberg et al., 2005). Despite limited
17 experimental opportunities, many granular growth substrates including balkanine (Ivanova,
18 1997), Zeoponic (Steinberg et al., 2000; Ming et al., 1995), Turface (Blonquist et al., 2006; Jones
19 et al., 2012), and Profile (Blonquist et al., 2006; Jones et al., 2012) have been tested as
20 prospective plant growth media for reduced gravity conditions (e.g., ISS, parabolic flights) and
21 were characterized based on water retention, hydraulic conductivity, and oxygen diffusivity
22 (Heinse et al., 2007). However, time consuming measurements, such as oxygen diffusion under

1 wet conditions (i.e., near gas-percolation threshold), are difficult to perform in reduced gravity
2 (parabolic flight) environments due to insurmountable time restrictions.

3 Following the concept of in situ resource utilization (ISRU) for construction, energy, and
4 resource recovery in space, native materials mined from the lunar or Martian surface will be
5 preferred plant growth media on a future lunar or Martian base (Yamashita et al., 2012). Based
6 on the soil samples returned from lunar missions, the potential of lunar soil as a plant growth
7 substrate has been examined and is not likely to facilitate adequate aeration for plant growth in
8 reduced gravity-drained conditions due to poor physical structure (Ming, 1989). Further
9 characterization and enhanced management is needed to verify the potential of native materials
10 as plant growth media. Characterization of Martian soils for plant growth is still rudimentary
11 (Yamashita et al., 2005) and awaits further studies following future explorations. Among
12 promising terrestrial analogs for lunar and Martian soils, the JSC-1 lunar simulant and JSC-1
13 Martian simulant soils have recently gained attention due to their similarity to the native
14 materials. Despite some studies focusing on measuring water characteristics and dielectric
15 properties on simulant soils (e.g., Robinson et al., 2009), little is known about the gas transport
16 characteristics of these soils.

17 In this study, we discuss the water characteristic and gas diffusivity of six prospective growth
18 substrates, with a main focus on JSC- lunar and JSC -Martian simulant soils. Based on the
19 observations in previous reduced gravity studies, we discuss the possible scaling of the results
20 obtained under full gravity (1-g) to two reduced gravity scenarios, Martian gravity (0.38-g) and
21 lunar gravity (0.16-g). Following a new approach to estimate the gas percolation threshold based
22 on the pore size distribution, we discuss the implications of a shift in the gas percolation
23 threshold in reduce gravity, a difficult-to-estimate parameter under short-term reduced gravity

simulations (e.g., 21s in parabolic flight). Predictions for air permeability measured in four selected substrates will also be discussed with extended scaling to the reduced gravity conditions.

2. THEORETICAL AND MODELING CONSIDERATIONS

2.1 Gravity and Capillary Effects

The equilibrium distribution of a liquid in a finite pore domain of a porous medium is mainly governed by the interplay between the gravitational, F_G , and capillary, F_C , forces (Chau et al, 2005). In weightlessness (i.e., 0-g onboard of the ISS), the liquid phase distribution is predominantly controlled by capillary forces, and gravity plays a progressively important role with increasing gravitational force, for example on the moon (0.16-g), Mars (0.38-g) and on earth (1-g) (Or et al., 2009; Heinse et al., 2009). The relative importance of the two forces in a given gravity environment can be expressed by the gravity/capillary ratio (commonly known as the static Bond number, B_o) which can be expressed as:

$$B_o = \frac{F_G}{F_C} = \left(\frac{\Delta\rho\zeta}{\sigma/r} \right) \mu g \quad [1]$$

where $\Delta\rho$ [kg m⁻³] is the density difference between liquid and gaseous phases, σ [kgs⁻²] is the surface tension, r [m] is mean pore radius, ζ [m] is the characteristic length (which can be approximated by r at the pore scale; Heinse, 2009), μ [-] is the acceleration due to gravity in the environment of interest relative to acceleration of gravity on earth, which is denoted by g [ms⁻²]. Knowing that gravity is a continuum, μ can virtually be any positive value representing a given gravity condition, for example $\mu = 0.16$, 0.38 and 1 for moon, mars and earth, respectively.

To relate the matric potential ψ in pF units ($\text{pF} = \log |-\psi \text{ cmH}_2\text{O}|$; Schofield, 1935) to the corresponding (drained) capillary pore radius r , we invoke the capillary rise equation that, in simplified form for liquid water, can be expressed as:

$$r(\mu\text{m}) = \frac{0.15}{(10^{\text{pF}})\mu\text{g}} \quad [2]$$

Note that the capillary rise r is gravity-dependant (Eq. [2]) whereas the capillary force (i.e., F_C in Eq. [1]) is not.

2.2 Water Characteristic and Pore Size Distribution

The water characteristic (WC) in a porous medium with a unimodal pore size distribution can be described with parametric water retention functions, for example the van Genuchten (vG) model (van Genuchten, 1980) that is given as:

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r) \left(\frac{1}{1 + (\alpha\psi)^n} \right)^m \quad [3]$$

where θ ($\text{cm}^3 \text{ cm}^{-3}$) is the substrate water content, θ_s ($\text{cm}^3 \text{ cm}^{-3}$) is the substrate water content at saturation, θ_r ($\text{cm}^3 \text{ cm}^{-3}$) is the residual water content, α (cm^{-1}) is a scaling parameter that is inversely related to the air-entry pressure, and n, m ($m=1-1/n$) are shape parameters related to the slope of the curve. To extend the predictions for media exhibiting bimodal (two-region) pore size distributions, two vG functions, each with its own set of parameters as in Eq. [3], can be superimposed (Durner, 1994):

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r) \left((1-w) \left(\frac{1}{1 + a_1 |\psi|^{n_1}} \right)^{m_1} + w \left(\frac{1}{1 + a_2 |\psi|^{n_2}} \right)^{m_2} \right) \quad [4]$$

where the subscripts 1 and 2 represent the region-1 (inter-aggregate region) and region-2 (intra-aggregate region), respectively, and $w (-)$ is the weighing coefficient. The equivalent pore size distribution can be derived from the first derivative of the vG function (Eq. [3]) as follows (Durner, 1994):

$$\frac{d\theta(r)}{d \log_{10} r} = \frac{d\theta(pF)}{d(pF)} = \frac{d\theta(\psi)}{d \log_{10} |\psi|} = \quad [5]$$

$$\frac{d\psi}{d \log_{10} |\psi|} = \frac{d\theta(\psi)}{d\psi} = [\log_e 10] \psi C^*$$

where $C^* = d\theta/d\psi$.

Further, the peak of the pore size distribution can be derived from the second derivative of the vG function (Eq. [3]) which will be used later in the study.

$$\frac{d^2\theta}{d\Psi^2} = -(\theta_s - \theta_r) \frac{mn\alpha^n \cdot \Psi^{n-2}}{[1 + (\alpha\Psi)^n]^{m+2}} \left\{ -n(m+1)(\alpha\Psi)^n + (n-1)[1 + (\alpha\Psi)^n] \right\} \quad [6]$$

Based on the water characteristic obtained from ground-based (1-g) and parabolic flight (μ -g) measurements, Jones et al. (2005) noted a shift in air-entry pressure under reduced gravity, and proposed linear scaling of the air entry value, α^{-1} (cm), with respect to gravity:

$$\alpha_{\mu-g} = [\mu(\alpha_{1-g})^{-1}]^{-1} \quad [7]$$

2.3 Gas Diffusivity, Air Permeability, and Gas-Percolation Threshold

Chamindu Deepagoda et al. (2012) proposed a two-region descriptive model to predict gas diffusivity in aggregated media with a distinct gas-percolation threshold, ε_p (the air-filled pore space below which gas diffusion ceases due to pronounced water blockage). They further applied a concept of *inactive pore space* (ε_{in}) to explain the likely variation of inter-connected pore space (Moldrup et al., 2005) with increasing air content for gas diffusivity. The set of equations describing gas diffusivity is given as:

Region-1

$$\begin{aligned} \varepsilon_{in} &= \varepsilon & \varepsilon &\leq \varepsilon_p \\ \varepsilon_{in} &= \left[\frac{\Phi_1 - \varepsilon}{\Phi_1 - \varepsilon_p} \right] \varepsilon_p & \varepsilon_p &< \varepsilon \leq \Phi_1 \end{aligned} \quad [8a]$$

$$\begin{aligned} \frac{D_p}{D_o} &= \alpha_1 \left[\frac{\varepsilon - \varepsilon_{in}}{\Phi_1 - \varepsilon_{in}} \right]^{\beta_1} & 0 &< \varepsilon \leq \Phi_1 \\ \text{where } \alpha_1 &= \frac{D_p}{D_o} \Big|_{\varepsilon=\Phi_1} \end{aligned} \quad [8b]$$

Region-2

$$\begin{aligned} D_p / D_o &= \alpha_1 + \alpha_2 \left[\frac{\varepsilon - \Phi_1}{(\Phi - \Phi_1)} \right] & \Phi_1 &< \varepsilon \leq \Phi \\ \text{where} \end{aligned} \quad [8c]$$

$$\alpha_2 = \frac{D_p}{D_o} \Big|_{\varepsilon=\Phi} - \frac{D_p}{D_o} \Big|_{\varepsilon=\Phi_1}$$

An important consideration with regard to above modeling approach is to locate the gas-percolation threshold for cases where measured data are not sufficiently available in the wet region. This is particularly the case when D_p measurements were conducted in reduced gravity (e.g., during parabolic flight experiments) within constricted time (21s). Chamindu Deepagoda et al. (2012) used an empirical linear relationship between percolation threshold and mean particle diameter to determine ε_p . Considering that gas (oxygen) diffusion is not gravity-dependent (Porterfield, 2002) but liquid phase configuration is controlled by gravity (Or et al., 2009), the likely shift in gas percolation threshold in reduced gravity must be associated with the gravity effects on the equilibrium water distribution. With the hypothesis that gas percolation occurs when the majority of large pores starts draining (i.e., by setting Eq. [6] to zero) we propose a vG model-based percolation threshold, denoted pF_p , to describe gas-percolation threshold as:

$$pF_p = \log \left(\frac{1}{\alpha} \left(\frac{(n-1)}{(1+mn)} \right)^{\frac{1}{n}} \right) \quad (n > 1) \quad [9]$$

Since air permeability, k_a (μm^2), is a more structure-controlled parameter when compared to gas diffusivity (Moldrup et al., 1998), predicting k_a often involves a reference-measurement for a given matric potential, for example at matric potentials of -500 cm H_2O (pF 2.7) or 1000 cm H_2O (pF 3) (Eden et al., 2012; Chamindu Deepagoda et al., 2012). In addition, the ratio between air permeability and gas diffusivity was described as a useful parameter representing dominant soil structure characteristics (Eden et al., 2012) and can be used for more accurate predictions of air permeability in structured porous media. We present a dimensionless soil structure parameter, P , for predicting air permeability for the selected substrates:

$$P = \frac{k_a}{k_{a,500} \left(\frac{D_p}{D_o} \right)} \quad [10]$$

where $k_{a,500}$ is the air permeability measured at -500 cm H₂O matric potential.

3. MATERIALS AND METHODS

3.1 Porous media and their properties

We investigated six solid plant growth substrates, each with a narrow particle size range (given in square brackets); JSC-1 Lunar Simulant [0.25–1.0 mm], JSC-1 Martian Simulant [0.25–1.0 mm], two size fractions of Balkanine zeolite; [0.25–1.0 mm] and [1.0 – 2.0 mm], Zeoponic [0.25–1.0 mm], and Profile [0.25–0.85 mm]. The textural differences of the six substrates are shown in Fig. 1.

JSC-1 lunar simulant is a glass-rich basaltic ash, which approximately represents the chemical composition, mineralogy, particle size distribution, and engineering properties of lunar mare soils. Mined from a volcanic air-fall ash deposit located at Merriam Crater in the San Francisco volcano field near Flagstaff, Arizona, the ash undergoes a multistep milling and mixing procedure before being commercially distributed (in different particle size fractions) under oversight of NASA. A detailed characterization of chemical, mineralogical and engineering properties can be found in McKay et al. (1993). Prior to the measurements, we removed via sieving the fraction the < 0.25 mm from the commercially available material of size < 1 mm. JSC-1 Martian simulant also has a volcanic origin and comes from Pu'u Nene, a cinder cone located on a saddle between the Mauna Loa and Mauna Kea volcanoes on the Island of Hawaii. Palagonitic tephra from this cinder cone has a close spectral analogy to the bright regions on Mars (Allen et al., 1998). In addition, the mineralogy, chemical composition, grain size, density, porosity and magnetic properties of the simulant approximately match the properties of Martian soil. As for the lunar simulant, we removed the fraction < 0.25 mm from

commercially supplied material (< 1 mm) before measurements to omit magnetic properties associated with the finer material.

Balkanine is a natural zeolite-clinoptilolite from the Beli Plast deposit in Bulgaria. Due to its favorable properties (e.g., high nutrient content, granular solidity, long-term usability, weed resistivity, etc.), Balkanine was selected as growth substrate for the Bulgarian-built *Svet* growth chamber onboard the *Mir* Space Station in 1990 (Bingham et al., 2000). A preliminary experiment carried out onboard Salyut-7 OS in 1985 identified beneficial hydrodynamic properties for different fractions of Balkanine (Ivanova, 1997). After *Mir* was deorbited in 2001, Balkanine was further used to grow plants in the *LADA* plant growth unit, an upgraded version of the *Svet* chamber jointly developed by NASA and Russia for plant growth experiments onboard the ISS (Bingham et al., 2001). No detailed measurements of aeration properties of Balkanine have been reported.

Zeoponic (Rocky Mountain Zeolites LLC, Golden, CO) is a NASA-developed zeolite-based synthetic substrate which also includes a few slow-releasing nutrients important for plant growth. It is a promising growth medium that has been tested in many gravity-controlled environments (Steinberg et al., 2000; Blonquist et al., 2006). Profile (Aimcor, Deerfield, IL) consists of stabilized baked ceramic aggregates and has been widely tested as prospective growth substrate in many microgravity plant experiments (Steinberg and Poritz, 2005; Heinse et al., 2007). In this study we consider Zeoponic and Profile as reference substrates to compare with all other investigated substrates.

For the measurements, triplicate 100-cm³ samples were packed with respective substrates at selected bulk densities (Table 1). To measure the water characteristic, initially saturated samples were sequentially drained to matric potentials (in pF) of 1.0, 1.5, 1.7, 2, 2.5, 2.7, 3.0, by means of

1 a hanging water column (for $pF \leq 2$) or pressure plate apparatus (for $pF > 2$). In addition,
2 measurements were conducted for two air-dry steps corresponding to pF 3.5 and 4.0, respectively.
3 At each matric potential step, gas diffusivity and air permeability were measured and the samples
4 were re-saturated before proceeding with the next drainage step.

5 The one-chamber apparatus developed by Klute (1986) was used to measure gas diffusivity.
6 For details of the experimental procedure and calculation of the gas diffusivity coefficient (D_p),
7 readers are referred to Rolston and Moldrup (2002). To measure air permeability (k_a), a known
8 gas pressure gradient of 3~5 cm H_2O (pF 0.3~0.7) was applied across the sample and the
9 resulting air flow was measured under steady-state conditions (Ball and Schjønning, 2002).

11 4. RESULTS AND DISCUSSION

12 Figure 2 shows the variation of the gravity/capillary ratio as a function of matric potential
13 expressed in pF units [log-transformed capillary rise (cm)] for three selected gravity
14 environments; earth ($\mu = 1$), mars ($\mu = 0.38$), and moon ($\mu = 0.16$). Note that for a given
15 capillary height (equilibrium water retention), the gravity effects are more pronounced under
16 reduced gravity (to counter-balance capillary forces). The gravity dominance is more evident at
17 smaller capillary height (due to smaller capillary forces) and declines non-linearly with
18 increasing capillary force, apparently becoming insignificant above $pF \sim 1.5$. We therefore did
19 not consider any gravity scaling above pF 1.5 in subsequent analyses on water and air-phase
20 modeling.

21 The ground-based ($\mu = 1$) water characteristic measurements are shown in Fig. 3 (a-f),
22 together with the parameterized two Region van Genuchten-Durner model (solid line). The

1 extended predictions of water characteristics under lunar ($\mu = 0.16$; dashed line) and Martian (μ
2 $= 0.38$; dotted line) gravity conditions based on the linear scaling of vG parameter α_1 [Eq. (6)]
3 are also shown. Note the smaller water retention for a given matric potential at reduced gravity,
4 which was also observed by Heinse et al. (2007) during parabolic flight experiments. As
5 discussed above, due to capillary-dominated water retention above pF 1.5, we did not consider
6 gravity scaling for α_2 in Region 2. Table 2 presents the detailed vG-Durner parameterization for
7 all investigated substrates.

8 The pore size distributions derived from the parameterized vG-Durner model (Eq. [4]) are
9 shown in Fig. 4(a-f). Notably, most of the media show strong bimodal (two-region)
10 characteristics, a highly favorable property of plant growth substrates facilitating water and
11 nutrient retention, aeration and root penetration. Among the six substrates, lunar simulant is the
12 least promising with a very narrow intra-aggregate pore region, poor water retention
13 characteristics (see Fig. 3a) particularly under lunar gravity conditions ($\mu = 0.16$). An important
14 implication evident from the pore density - pF plots is the increase of air-filled pore connectivity
15 with decreasing matric potential (and hence increasing air-filled pore space), which can be
16 potentially related to the gas percolation (note that we primarily focus on diffusion-based gas
17 percolation). Importantly, two parameters control the movement/percolation of gases in porous
18 media; the air-filled pore space (ϵ), and the degree of connectivity (typically characterized by a
19 pore tortuosity-connectivity parameter; Moldrup et al., 2001). The gas percolation threshold can
20 be described as the minimum air-filled pore space with the degree of pore connectivity just
21 sufficient to create a continuous pathway across the sample facilitating gas movement. As the
22 applied matric potential (often from the bottom of the sample) exceeds the air-entry value, bigger
23 pores start draining first allowing air to enter the sample. Thus, the air-filled pore space which

1 opens up at the beginning comprises of a small number of large pores and hence exhibits a lower
2 degree of pore connectivity. As the matric potential further decreases and more and more
3 (smaller) pores drain, the air-filled pore space as well as the degree of connectivity increases
4 thereby increasing the probability of gas percolation. The gas percolation, therefore, can be
5 hypothesized to occur when the pore occurrence is maximum, i.e., in the neighborhood of the
6 peak of the pore density vs. pF plot. Based on this, we estimated the gas percolation thresholds
7 (in pF) and used them for predictions of gas diffusivity. We successfully tested the hypothesis
8 using the two reference media, Zeoponic and Profile (Fig. 5a and b), for which observed data
9 very close to the gas percolation threshold were available. We applied the concept for the other
10 four substrates to estimate the percolation threshold and also to predict gas diffusivity (Fig 5c
11 through f). The most important implication of the presented approach is its applicability to
12 different gravity environments, as shown in Fig. 5 for Martian ($\mu = 0.38$; dashed line) and lunar
13 ($\mu = 0.16$; dotted line) conditions. Reduced gravity apparently shifts the gas-percolation
14 threshold and thereby leads to air entering the substrates at higher matric potentials (smaller pF)
15 and thereby provide improved early aeration conditions. However, note that the reduced gas
16 percolation threshold does not necessarily ensure better-aerated plant rhizosphere in reduced
17 gravity, as the diffusive gas movement to the root zone will be primarily controlled by the inter-
18 connectivity of air-filled pore space under the gravity of interest.

19 The critical condition for plant growth with respect to aeration occurs when the substrate is at
20 near-saturated conditions due to the small air-filled pore space and high water-induced tortuosity.
21 In addition, as many studies have shown before, the critical aeration conditions for plants can be
22 better represented by the critical gas diffusivity than by air-filled porosity (Paul and Lee, 1976;
23 Allaire et al., 1996). Critical air-filled porosity can therefore be described as the air-filled

1 porosity corresponding to the critical gas diffusivity. Linking to the critical air-filled porosity,
2 Chamindu Deepagoda et al. (2012) presented the concept of a *critical window of diffusivity*,
3 which represents the ‘safe’ diffusivity range for a given substrate. The observed shift in gas
4 percolation threshold in reduced gravity therefore will result in a larger window of diffusivity, an
5 important observation with respect to reduced gravity growth media characterization.

6 To test the sensitivity of the pF-based percolation threshold to changes in $vG-\alpha$, we
7 examined the variation of percolation threshold with α for selected $vG-n$ parameter values
8 ranging from $n = 1.01$ (representing fine-textured substrates) to $n = 5$ (representing coarse-
9 textured media) (Fig. 6). Note that for natural soils $vG-n$ increases steadily with increasing
10 particle size upto nearly 70% sand content, followed by a rapid increase for coarser fractions
11 (Minansny and McBratney, 2005). Typical unconstrained $vG-n$ values were observed to vary
12 from $n = 1.01$ (clayey soils) to 5 (sand) (Leij et al., 2005). The percolation threshold decreases
13 nonlinearly with increasing α (i.e., moving to reduced gravity conditions). A sharp decline can be
14 seen for fine-textured substrates (with smaller n values) when compared to coarser media.
15 Furthermore, for a given α , the gas percolation threshold increases nonlinearly with increasing n
16 (substrate particle size) and shows a larger increase of percolation threshold in finer materials
17 (for smaller n) when compared to the coarser materials (for larger n). This is due to the fact that
18 the probability of pore connectivity near the percolation threshold is higher in finer-textured
19 materials (dominated by smaller pores) compared to the coarser-textured materials (dominated
20 by big pores) as discussed before. However, with ground-measured D_p data for media with
21 different particle fractions, Chamindu Deepagoda et al. (2012) observed a linear increase in air-
22 filled porosity-based percolation threshold with increasing particle size. We await detailed D_p

measurements for differently-sized substrates at different gravity conditions to arrive at a clear conclusion.

Since induced gas movement across a pressure gradient occurs preferentially through the largest and least tortuous pore networks, air permeability (k_a) is a highly macropore (structure)-dependent parameter when compared to gas diffusivity. Due to the difficulty to distinguish air-permeability-based percolation thresholds experimentally, modeling air permeability, particularly for media with large percolation thresholds, can be described as linking to analog D_p/D_0 measurements through a structure parameter (Kawamoto et al., 2006; Eden et al., 2012; Chamindu Deepagoda et al., 2013). We use the dimensionless structure parameter, P (Eq. [10]), to describe substrate air permeability. Figure 7 shows the variation of P with pF for four substrates (excluding Zeoponic and Profile). Note that P shows an increase with increasing pF until the bigger pores controlling advective flow are drained, and remains largely constant with further increase of pF as the smaller pores drained thereafter do not play a significant role in the macropore-dominated flow. Also note the markedly high average P values ($P \approx 5$) observed for the four substrates (Fig. 7, dotted color lines) implying higher macropore-dominated flow compared to the reference- P ($P \approx 2$) reported by Kawamoto et al. (2006) considering a wide range of undisturbed natural soils (Fig. 7, dotted gray line). This provides useful information for cases where pressure-controlled aeration systems are integrated in plant growth modules for rapid root zone aeration, as critical aeration conditions may potentially occur in localized root zone areas, which are far from the macropore pathways. Measured air permeability data plotted as a function of matric potential (in pF) are shown in Fig. 8 ($\mu = 1$) together with predictions based on the calculated average P values. The predictions look promising despite a higher degree of uncertainty as typically observed in air permeability predictions compared to gas diffusivity

1 due to high dependence on structural properties. The scaled simulations to Martian ($\mu = 0.38$)
2 and lunar ($\mu = 0.16$) gravity conditions are also shown in Fig. 8, implying better or more
3 favorable early aeration conditions under reduced gravity.

5 **5. CONCLUSIONS**

6 Six prospective plant growth substrates were characterized for earth- and space-based
7 applications using measured water retention and gas transport properties. We proposed a model
8 to estimate the gas percolation threshold from parameterized water characteristic data and the
9 pore size distribution, and applied the model to predict substrate gas percolation by diffusion.
10 The proposed model is particularly helpful when the percolation threshold is difficult to estimate
11 due to lack of measured data or experimental limitations (e.g., limited time for parabolic flight
12 measurements). Combining the percolation threshold model with a recently developed gas
13 diffusivity model, we successfully described observed substrate gas diffusivity data. Using a
14 substrate structure parameter linking to gas diffusivity, we adequately described the measured air
15 permeability for four substrates. We further discussed the implications of scaling the water
16 characteristic, gas diffusivity, and air permeability to two reduced gravity conditions, Martian
17 (0.38-g) and lunar (0.16-g) gravity with an emphasis on the shift of the gas percolation threshold
18 which likely results in improved early aeration conditions under reduced gravity. The predictions,
19 however, need to be validated with gas transport measurements under sustained reduced gravity
20 conditions (for example on the ISS) with specific focus on measurements in the wet region.

22 **ACKNOWLEDGEMENTS**

This study was conducted as part of the Gas Diffusivity in Intact Unsaturated Soil (“GADIUS”) project and the large framework project Soil Infrastructure, Interfaces, and Translocation Processes in Inner Space (“Soil-it-is”), both sponsored by the Danish Research Council for Technology and Production Sciences. This research was also partly supported by the Japanese Core Research Evolutional Science and Technology (CREST) program sponsored by the Japan Science and Technology Agency (JST). We gratefully acknowledge the assistance of Innovative Research Organization at Saitama University, Japan.

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Figure Captions

Fig. 1 Textures of considered growth substrates: (a) JSC Lunar Simulant [0.25-1.0 mm], (b) JSC Martian Simulant [0.25-1.0 mm], (c) Balkanine [0.25-1.0 mm], (d) Balkanine [1.0-2.0 mm], (e) Zeoponic [0.25-1.0 mm], and (f) Profile [0.25-0.85 mm].

Fig. 2 The ratio of gravity and capillary forces plotted as a function of pF [pF= log| $-\psi$, cm H₂O|] for three different gravity environments; terrestrial gravity ($\mu = 1.0$, solid line), Martian gravity ($\mu = 0.38$, dotted line), and lunar gravity ($\mu = 0.16$, dashed line). Note that $\mu = g_{\text{obs.}}/g_{\text{Earth}}$.

Fig. 3 Water characteristics (WC) for investigated substrates. The solid line depicts the van Genuchten (vG)-Durner model, Eq. [4], fitted to data measured under unit gravity ($\mu = 1.0$) and the dotted and dashed lines, show the scaled vG-Durner curves for Martian ($\mu = 0.38$) and lunar ($\mu = 0.16$) gravities.

Fig. 4 Pore size distributions of investigated substrates derived from the vG model parameterized based on measured ($\mu = 1.0$) data for the six substrates

Fig. 5 Measured substrate gas diffusivities, D_p/D_o , as a function of matric potential [pF= log| $-\psi$, cm H₂O|] for investigated substrates. The predictions combining the $D_p(\epsilon)/D_o$ model, Eq.[8] to Eq. [9], and vG model, Eq.[4], are shown by the solid line ($\mu = 1.0$). The predictions scaled based on Eq. [7] to two gravity conditions, Martian gravity ($\mu = 0.38$, dotted line) and lunar gravity ($\mu = 0.16$, dashed line) are also shown.

Fig. 6 vG model-based gas percolation thresholds (in pF), Eq. [9], as a function of vG parameter α (cm^{-1}) for selected vG- n values ranging from $n = 1.01$ (representing clay), 1.5, 2 (silty and loamy soils), 3 (sandy soils), 5 (coarse sand and other coarse-textured substrates).

Fig. 7 Variation of the soil structure parameter $P [= k_a/k_{a,500}*(D_p/D_o)]$ as a function of matric potential [$\text{pF} = \log|-\psi, \text{ cm H}_2\text{O}|$] for investigated substrates. The dotted lines in corresponding colors illustrate the average P values while the standard deviations are shown as error bars. The dotted gray line at $P \approx 2$ is based on the results of Kawamoto et al. (2006).

Fig. 8 Measured air permeability, k_a (μm^2), as a function of matric potential [$\text{pF} = \log|-\psi, \text{ cm H}_2\text{O}|$] together with predictions ($\mu = 1.0$, solid line) for investigated media. The dotted and dashed lines illustrate the simulations scaled to Martian ($\mu = 0.38$) and lunar ($\mu = 0.16$) gravities.

Table Captions

Table 1 Physical properties of investigated growth substrates

Table 2 van Genuchten-Durner parameters for investigated substrates

Table 1 Physical properties of six growth substrates

Media	Physical Properties				
	Particle size range mm	Bulk density	Total porosity	Inter agg. Porosity	EGME Surface Area (m ² /g)
		g cm ⁻³	cm ³ cm ⁻³	cm ³ cm ⁻³	
Lunar Simulant	0.25-1.0	1.33	0.57	0.52	4.80
Martian Simulant	0.25-1.0	0.71	0.73	0.45	197.4
Balkanine	0.25 -1.0	0.87	0.61	0.40	NA
Balkanine	1.0-2.0	0.87	0.61	0.40	NA
Zeoponic	0.25-1.0	0.97	0.61	0.44	94.2
Profile	0.25 -0.85	0.65	0.74	0.42	95.8

Table 2 van Genuchten-Durner parameters for the six selected substrates

Media	Particle size range mm	θ_r $\text{cm}^3\text{cm}^{-3}$	van Genuchten-Durner parameters				
			Region -1			Region-2	
			α_1			α_2	
			w	(cm^{-1})	n_1	(cm^{-1})	n_2
Lunar Simulant	0.25-1.0	0.001	0.91	0.082	3.51	0.003	1.87
Martian Simulant	0.25-1.0	0.01	0.61	0.073	3.63	0.002	1.30
Balkanine	0.25 -1.0	0.01	0.65	0.194	5.55	0.0004	1.67
Balkanine	1.0-2.0	0.01	0.66	0.345	1.37	0.0006	1.37
Zeoponic	0.25-1.0	0.027	0.64	8.14	6.92	0.0020	1.54
Profile	0.25 -0.85	0.000	0.57	6.56	7.01	0.00518	1.63

Figure 1

Fig. 1

Figure 2

Fig. 2

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Fig. 8