

LABORATORY MEASUREMENTS OF TORTUOSITY AND PERMEABILITY IN MARS ANALOG SOILS. H. G. Sizemore and M. T. Mellon, Laboratory for Atmospheric and Space Physics, University of Colorado, UCB 392, Boulder, CO 80309 (hanna.sizemore@colorado.edu).

Introduction: The martian regolith is a major source/sink in the planet's global water cycle. Diffusion of water vapor in the upper unconsolidated portion of the regolith plays a major role in diurnal and seasonal variations in atmospheric water vapor density [1]; diffusion in the subsurface also plays a key role in the stability of near-surface ground ice in the current epoch and the mobilization and redistribution of that ice during past obliquity cycles [2,3].

Historically, numerical simulations of diffusive processes in the martian regolith have relied on the chemical engineering literature to estimate the diffusive properties of martian soils by analogy with the properties of industrial catalysts. The appropriateness of this analogy has not been tested empirically. Here, we present laboratory measurements of diffusion in four groups of Mars-analog soils – 1) glass spheres (seven size ranges); 2) JSC Mars-1 (bulk soil and eight size-selected sub-samples); 3) Antarctic soils (collected above ground ice in Beacon and Wright Valleys); and 4) an Alaskan loess.

The rate of diffusive transport in soils is controlled both by environmental conditions (temperature, pressure, gas species) and by geometric properties of the soils (porosity, pore size distribution, pore shape, and “tortuosity”). Correct theoretical treatment of diffusion over the broad range of environmental conditions encountered on Mars requires careful separation of environmental and geometric effects in the laboratory. Using a variety of laboratory techniques, we have characterized key geometric properties of the Mars analog soils listed above.

In this work, we focus in particular on soil tortuosity, a geometric property that is invariant with diffusive mode [4,5] and accounts for dead ends and increased path length encountered by diffusing molecules in a porous medium. We describe a laboratory technique for measuring tortuosity and compare our empirical values of tortuosity with values commonly chosen in theoretical studies relevant to Mars.

Additionally, we present coincident measurements of pressure-driven flow and tabulate the permeabilities of the Mars-analog soils.

Background & Theory:

Diffusion: In porous media such as soils, diffusion can proceed in two modes. Normal or ordinary diffusion occurs when the pore spaces are larger than the mean free path and gas-gas collisions dominate. Knudsen diffusion occurs when pore radii are smaller

than the mean free path and gas-wall collisions dominate. When pore radii are on the order of the mean free path, diffusion has a mixed character and is said to be occurring in the transition regime [4].

When two gas species interdiffuse in the normal regime the number flux of either species with respect to a plain of no net transport is given by Fick's first law:

$$J_1 = -D_{12} \frac{\partial n_1}{\partial x} \quad (1)$$

where n_i is the concentration of gas species one and D_{12} is the normal diffusion coefficient. Referencing the flux to the soil rather than a plain of no net transport

$$N_1 = -D_{12}^* \frac{\partial n_1}{\partial x} \quad (2)$$

where

$$D_{12}^* = \frac{D_{12}}{1 - y_1 \alpha_1}, \quad (3)$$

$$\alpha_1 = 1 - \sqrt{\frac{m_1}{m_2}} \quad (4)$$

and y_1 is the mole fraction n_1/n of species one.

Similarly, in the Knudsen regime, the flux is expressed as

$$N_1 = -D_{1K} \frac{\partial n_1}{\partial x} \quad (5)$$

where D_{1K} the Knudsen diffusion coefficient. Significantly, D_{12} is a function of temperature, pressure and the properties of both gases. D_{1K} is dependent upon temperature, pore size and the properties of a single gas species.

In the transition regime, an effective diffusion coefficient D is conventionally defined according to the Bosanquet interpolation formula [4]

$$\frac{1}{D} = \frac{1}{D_{1K}} + \frac{1}{D_{12}^*} \quad (6)$$

and the flux equation is again analogous to Fick's law. In the most general case, the flux through a porous medium is

$$N_1 = -\frac{\epsilon}{\tau} D \frac{\partial n_1}{\partial x} \quad (7)$$

where the porosity ϵ represents the reduction in flux due to the limited pore cross section and the tortuosity τ accounts for dead ends and the generally winding path molecules must follow through the medium.

Pressure driven flow: Diffusion is mass flux resulting from a *partial* pressure gradient. A total pressure gradient in a porous medium will also lead to mass transport, or bulk flow. So long as this flow is laminar, it is described by Darcy's Law

$$N = -\frac{k dp}{\mu dx} \tag{8}$$

where μ is the dynamic viscosity of the flowing gas and k is the permeability of the porous medium.

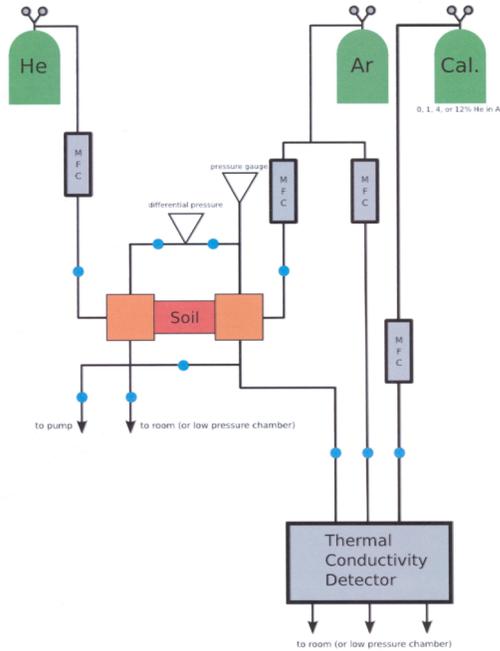


Figure 1. Schematic of experiment hardware.

Experimental Method: We employ a steady state method for determining tortuosity, similar to methods described by Evans et al.(1961) and Scott and Dullien (1962). In our system (Fig. 1) soil is either held inside a straight cylindrical tube and confined by wire mesh, or soil is held in a tube with a u-shaped bend and confined by gravity. In both cases, the two ends of the soil column are exposed to streams of pure helium and argon respectively. We have chosen inert gases so that our measurements aren't complicated by adsorption on the soil grains or chemical reactions.

The two gas streams are connected by a differential capacitance manometer and the gas flow rates can be adjusted to regulate the pressure gradient across the soil. At zero differential pressure, mass flux is purely diffusive. Constant flushing by the gas streams produces steady boundary conditions and, integrating equation (7), a constant diffusive flux

$$N_1 = \frac{\epsilon D_{12}n}{\tau x_o \alpha_1} \ln \left(\frac{1 - \alpha_1 y(0) + \frac{D_{12}}{D_{1K}}}{1 - \alpha_1 y(x_o) + \frac{D_{12}}{D_{1K}}} \right) \tag{9}$$

where x_o is the length of the soil chamber and $y(0)$, $y(x_o)$ are the mole fractions of species one at the ends of the soil column.

Since determination of the pore size distribution and effective pore radius in soils can complicate measurement of tortuosity in the Knudsen and transition regimes [4, 5], we typically operate in the normal mode,

$$N_1 = \frac{\epsilon D_{12}n}{\tau x_o \alpha_1} \ln \left(\frac{1 - \alpha_1 y(0)}{1 - \alpha_1 y(x_o)} \right) \tag{10}$$

and all gas lines in the apparatus vent to the room. However, we have the capability to operate in the transition regime by venting to a continuously evacuated low-pressure chamber.

We measure helium contamination in the argon stream using a Wheatstone bridge thermal conductivity detector. In the steady state, counter diffusion of helium and argon is not equimolar [8]:

$$\frac{N_{He}}{N_{Ar}} = -\sqrt{\frac{m_{Ar}}{m_{He}}} \tag{11}$$

Thus measuring helium in the argon stream gives us maximum sensitivity.

Because the system is dynamic, maintaining a zero pressure gradient across the soil can be difficult. We address this issue procedurally by measuring fluxes at a range of differential pressures and performing a least squares fit to determine the flux at zero differential pressure (Fig. 2). This procedure has the added benefit of allowing us to determine the soils' permeabilities.

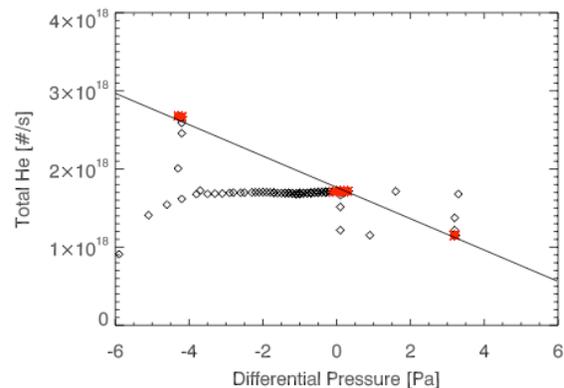


Figure 2. Example of line fitting procedure to find tortuosity and permeability. Black points represent data acquired while gas flow rates and instrument responses were in the process of equilibration. Red

points indicate data acquired under steady operating conditions; the line fit is performed on these data only.

Results and Discussion: Table 1 shows porosity, tortuosity and permeability measurements for two representative soil samples, bulk JSC Mars-1 and an Antarctic sample collected in Beacon Valley. Figure 3 shows tortuosity as a function of porosity in the same two samples. Tortuosity varies from about 1.5 to 1.9 over the range of porosities we considered for these soils, and τ decreases with increasing void space. The behavior of these soil samples is typical of all of the soils we investigated. We examined soils with grain sizes ranging from < 32 to $>800 \mu\text{m}$ and porosities ranging from 20% to $>70\%$. Our measured tortuosities were always less than 3, and typically less than 2.

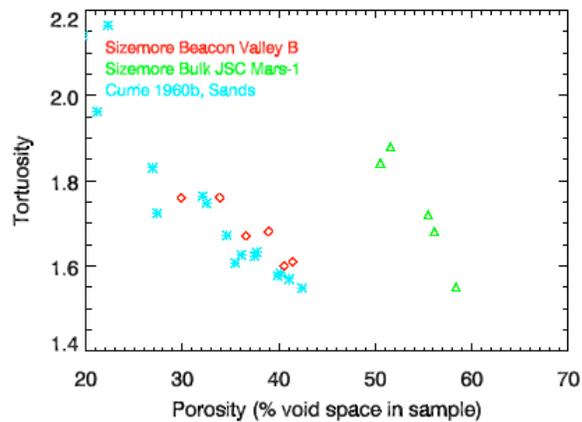


Figure 3. Tortuosity of JSC Mars-1 (green) and an Antarctic soil (red) measured using our steady state method. Tortuosity of coarse-grained sands measured by Currie (1960b) using a non-steady state method are shown in blue for comparison.

The range of measured tortuosities and their functional behavior with porosity ϵ are in excellent agreement with previous measurements of τ in dry unconsolidated particulate materials [8,9,10,11,12], (Fig. 3). However, the tortuosities we have measured are significantly lower than values measured in many industrial catalysts or values assumed in theoretical studies of water vapor diffusion on Mars. Values of τ reported in the chemical engineering literature range from 1.4 (glass spheres) to >16 (ceramic pellets) [8,4]. Following Smoluchowski (1968), Clifford and Hillel (1983) assumed $\tau = 5$ for martian soils. Mellon and Jakosky (1993,1995) chose $\tau = 3$, the theoretical tortuosity of an isotropic distribution of straight round capillaries [15].

These two choices ($\tau = 5$, $\tau = 3$) have guided subsequent theoretical work related to diffusion in martian

soils, although they are up to a factor of 3 greater than measured values. The choice of lower tortuosity values in numerical simulations of ground ice dynamics [e.g. 2,3,14] and of vapor adsorption [e.g. 1] would result in a small but potentially significant correction to existing theoretical results. Thus, the disagreement between commonly assumed and measured values of tortuosity points to a need for further laboratory validation of diffusive processes in Mars analog materials.

Porosity ϵ	Tortuosity τ	Permeability k [m^2]
Beacon Valley		
0.3386	1.76	3.22e-13
0.4052	1.60	8.83e-13
0.3896	1.68	6.91e-13
0.2990	1.76	1.63e-13
0.3655	1.67	7.54e-13
0.4146	1.61	9.44e-13
JSC Mars-1		
0.5053	1.84	1.15e-12
0.5547	1.72	2.61e-12
0.5837	1.55	5.47e-12
0.5610	1.68	3.36e-12
0.5156	1.88	1.04e-12

Table 1. Summary of results for a typical Antarctic soil sample and bulk JSC Mars-1.

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