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Laboratory Measurements of Thermal Properties of Icy Regolith Analogs

M. A. Siegler (1), N. Schorghofer (2), O. Aharonson (3), S. Xu (3,4), M. Choukroun (5)

(1) UCLA Dept. of Earth and Planetary Sciences, Los Angeles, CA, 90095,(2) Institute for Astronomy, University of Hawaii, Honolulu, Hawaii,(3) Division of Geologic and Planetary Sciences, California Institute of Technology, Pasadena, California,(4) Department of Astronautical Engineering, University of Southern California, Los Angeles, California (5) NASA Jet Propulsion Laboratory, Pasadena, CA, 91109 (siegler@ucla.edu)

Abstract

The thermal properties of ice-rich regolith on Mars, the Moon, and other bodies is currently poorly known. Thermal conductivity (and thermal diffusivity) are strongly dependent on the geometry assumed by pore-filling ice between regoith grains. On Mars, and other bodies with atmospheres below the triple point of water, ice may assume a distinct geometry from icy soils on Earth where melting is ubiquitous. Here we present new laboratory data of thermal properties of icy regolith analogs created by vapor diffusion and ice deposition under Martian atmospheric conditions.

1. Background

Models for thermal properties of icy regolith exist [1,5], but few have been verified by measurements, especially under non-terrestrial conditions. Models of thermal conductivity can vary by orders of magnitude with ice content [5], depending on how ice effects the cross-sectional area available for heat conduction. Here we examine some common models spanning the range of thermal conductivity models.

A model commonly used for estimating thermal conductivity is to assume ice forms necks, which link grains to their immediate neighbors [1]. This is hypothesized to occur by vapor deposition due to the vapor density gradient above a curved surface. The gradient is proposed to drive ice from convex grain surfaces to grain contacts (which are points of extreme concavity) [2]. Equations (1) and (2) summarize this model as a function of pore filling fraction F, where ϵ_0 is the soil porosity, λ_s is the conductivity of the grain material and λ_p is the conduction across the pores. λ_{p0}, the conduction across the pores with zero ice content, λ_{ice} to the conductivity of pure ice.

A second model class is based on purely empirical measurements of icy soils on Earth. These models are often based on data from Kersten (1949) [3], which included water in a liquid state. Other authors [4,5] have performed fits to this data and assumed the water component can be removed, as in Equations (4) and (5). λ_{dry} refers to the bulk conductivity of the dry, porous soil, λ_s to that of the solid material of which it is composed.

A third model is assumes ice takes a geometry that adds to the conductivity in direct proportion to the volumetric ice content, in analogy with the effect on heat capacity. This method results in weak dependence on the material of which the dry regolith is composed as λ_{dry} is controlled dominantly by grain geometry. This represents an opposite end-member case to the ice necks in that the effect of ice on soil thermal properties is minimal.

These models are summarized:

1) Ice neck (Mellon *et al.*, 1997):

$$\lambda_p = (1-\sqrt{F})\,\lambda_{p0} + \sqrt{F}\lambda_{ice} \quad (1)$$

$$\lambda = \frac{\lambda_s \lambda_p}{(1-\epsilon_0)\lambda_p + \epsilon_0 \lambda_s} \quad (2)$$

2) Geometric mean (Johansen, 1975):

$$\lambda_{(F=1)} = \lambda_s^{1-\epsilon_0} \lambda_{ice}^{\epsilon_0} \quad (4)$$

$$\lambda = (\lambda_{(F=1)} - \lambda_{dry})F + \lambda_{dry} \quad (5)$$

3) Volumetric mixing:

$$\lambda = \lambda_{dry} + \epsilon_0 \lambda_{ice} F \quad (6)$$

2. Experimental Methods

The experiment here measures the thermal conductivity, thermal diffusivity, and volumetric heat capacity of icy soils created by vapor diffusion. The initial experiment was designed to form ice rich soil by vapor diffusion at 6 mbar (CO_2/H_2O) total atmospheric pressure and sub freezing temperatures [6]. A sample of regolith simulant, 500 μm glass spheres, is kept under a relatively strong thermal gradient ranging from 268 K at the surface to ~200 K at 5 cm depth. As water vapor enters the vacuum chamber, it deposits within the pore space of simulant at depths where temperatures fall below those required for saturation.

Water vapor densities are maintained such that the surface remains nearly ice free, while an ice table forms at roughly 1 cm depth.

We instrumented the apparatus with an 11-needle thermal properties probe. Each needle 1 mm in diameter, lies horizontally through the 5 cm regolith simulant at 0.5 cm intervals. Each needle contains a resistive wire heater and a thermocouple. The heater is briefly pulsed (~10 s) and heat loss and exchange between neighboring needles is monitored by the thermocouples. The amplitude and rate of temperature change at a source needle or its neighbor will be modified by the thermal diffusivity and heat capacity of the surrounding medium [7].

Measurements using the single needle technique determine only the thermal conductivity. Measuring the dissipation of the heat pulse at both the heated and neighboring needles allows separate determination of thermal diffusivity and heat capacity.

3. Results

In contrast to the expected rapid increase of thermal diffusivity at low ice contents predicted by the ice neck model, the data shows a clear, nearly linear increase with ice content in the diffusivity in the vertical direction κ_z. However, the thermal conductivity and heat capacity were greatly impacted by anisotropic ice structure, leading to $\kappa_z \neq \kappa_x$. Volumetric heat capacity, ρc, depends only on relative density and porportion of the materials. Thermal conductivity, $\lambda_z = \kappa_z \rho c$, may be calculated.

As shown in Figure 1, these results strongly favor the volumetric model, falling just slightly below the expected values adjusted for temperature at 200 K and 273 K. The F=1 data point was not achieved by vapor filling, but by freezing liquid water saturated soil and falls above the trend line of the other measurements.

This lower than anticipated thermal conductivity implies that ice neck structures are not forming between soil grains. Examining the ice structures between grains in detail instead reveals long ice tendrils, linking distant grains (Figure 2).

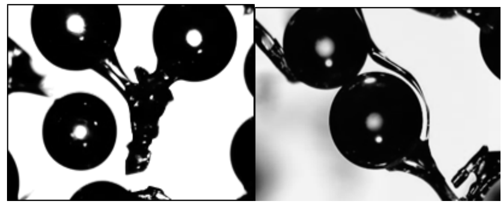

Figure 2: Ice tendril structures formed during an 11 hour experimental run. The beads are 500-600µm for scale.

We attribute these structures to small-scale temperature differences between grains. We show that temperature gradients ~10^{-2} K/m are expected to form such tendrils rather than necks for the 500 µm grains examined here. Such small gradients are likely common in the Martian subsurface and in other bodies where icy regolith is expected to form by vapor migration, and are required for ice to be mobile. Therefore, this pore-filling structure and associated thermal properties may prove common throughout the solar system.

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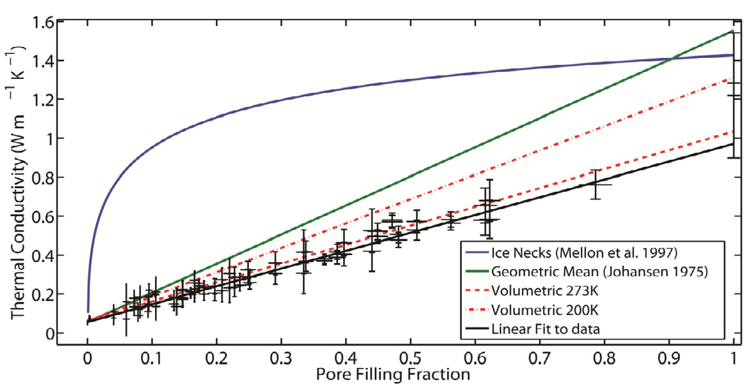

Figure 1: Thermal conductivity as a function of ice content (in the vertical direction) as measured in icy regolith created by vapor diffusion at 6mbar total pressure.