MEASUREMENT OF ICY REGOLITH PERMEABILITY AND PORE SIZE ESTIMATION.

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Introduction: Ice bearing lunar regolith is a resource of great interest for future missions planning to capitalize on the benefits of in-situ water. Water on the lunar surface is located in high concentrations at the lunar polar regions where permanently shaded craters reach temperatures cold enough for water ice to remain in a stable solid form for geologic timescales. This sequestrated ice can be harvested and processed into usable water. Water that can be used for crew life support needs and to create rocket propellant for return trips to earth and to enable missions further into the solar system.

Various collection and desiccations processes have been proposed as possible technologies to enable in-situ resource utilization (ISRU) of available water ice. However, many aspects of the sequestrated water ice are unknown. With no ground truth data, every proposed technology must make assumptions related to the morphology of lunar ice reserves. While some geotechnical and thermal properties have been studied for some of the proposed ice morphologies, characteristics are still unknown. One of these uncertainties is mass transport of sublimated vapors.

Background:

Mass transport in porous media is dictated by multiple flow regimes, defined by a dimensionless parameter called the Knudsen number. The Knudsen number (Kn) is a ratio between the mean free path of a gas and the characteristic void diameter of the porous media. At low Knudsen numbers ($Kn \ll 1$), convective flow occurs where bulk gas transport occurs by gas particles interacting with other gas particles. As pressure drops and pore size decreases, the Knudsen number increases. With an increasing Knudsen number ($Kn \gg 1$), the gas flow transitions to the Knudsen diffusion regime where gas transport is on a concentration basis - dominated by particles impinging on walls.

While most of the terms in the Knudsen diffusion regime are clearly defined, pore size distribution in regolith is not. Recent CT scans of icy regolith have shown a large variance in the pore size distribution, exacerbated in icy regolith where ice has gone through sintering. Pore sizes can vary by orders of magnitude.[1], [2] In both Johnson's and Ricardo's investigations, void spaces were estimated range between 1-.01 µm. Of the two, Ricardo's data had a higher resolution. Resolution data was limited by voxel sizes of 15µm in chilled tests. Though a very high resolution, the resolution achieved did not have the capability to differentiate between some void spaces and solid particles. Ricardo reports that particles surrounding a pore needed to be > 40µm for a void space to be detected; accounting for only the upper 60% of simulant LHS-1's particle size distribution.[2]

With the large range of varied pore size distributions, gas transport within the porous media would yield a large variance of Knudsen numbers. During regolith thermal mining and desiccation, increased temperatures and pressures could cause some areas within these pores to move out of the Knudsen diffusion regime and into the transition, or even continuum flow regime.

Investigation into gas permeability in icy regolith could be used to estimate effective pore size and distributions and be used as a comparison to current measured values.

Methods: The following section outlines the planned preparation and testing methods to be used to determine the permeability of icy regolith mixtures. All samples are to be prepared and tested within a -4.4C freezer container.

Permeability Test Setup. Permeability will be measured following a modified version of ASTM D5856-95(2002)e1.[3] Modifications to the standard include the replacement of water as a working fluid with compressed air. The change of working fluid is necessary due to the need for sub-zero temperatures, and relevancy of gas as a working fluid. This modification to the standard has precedent in LaMarche's work on permeability measurements of JSC-1A. [4]

The permeability test setup is described in Figure 1. The test setup includes a Humboldt permeameter H-4146, mass flow controller, and compressed air source. A digital pressure gauge will be used to measure the pressure drop from the gas inlet to the outlet at atmospheric pressure. Porous filter stones separate the sample from the inlet and outlet valves. A calibration pressure is determined by recording the pressure gauge reading with no sample present to determine the base pressure drop of the test setup and the porous stones.

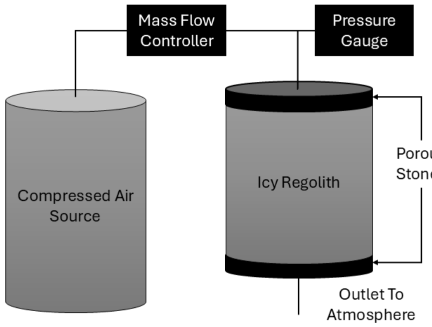

Figure 1. Diagram of Permeability Test Setup

Icy Sample Preparation. Granular icy regolith simulant was prepared using the procedure outlined in Zimmermann et al.[5] using MTU-LHT-1A. Ice contents of 1.5, 3, and 6 weight percent will be created by mixing shaved ice with chilled regolith. Shaved ice will be sieved to a particle size less than 600 µm and mixed with simulant in 2 kg increments. Samples will then be transferred to the permeameter where they can be hand compacted to the desired compaction level. Total sample height will be measured and recorded for bulk density and permeability calculations.

Test Procedure. After samples have been prepared, the second porous stone is placed on the prepared regolith and the top of the permeameter is secured. The mass flow controller will then be used to pass varying volumetric flowrates through the sample and pressures recorded at steady state.

Results and Analysis: Using Darcy's law, effective permeability of each sample can be calculated with mass flowrate, pressure drop, and kinematic viscosity of air.

A parallel capillary estimation can be used to determine valid pore size distributions. The parallel capillary estimation has previously been used to determine permeability. This approach incorporates the continuum and transition mass transfer regimes by accounting for tortuosity, adsorption, and slip effects. This approach has seen success in the oil and gas industry.[6]

With the gathered icy regolith data set, a mean pore size can be determined. However, determining a pore size distribution will be more uncertain. It is expected that various pore size distributions may yield valid permeability values matching datasets (Fig 2). Still, the parallel capillary model factors in mean free path of a gas particle, so collecting permeability values at varying average pressures may provide the additional datasets needed to narrow down possible distributions.

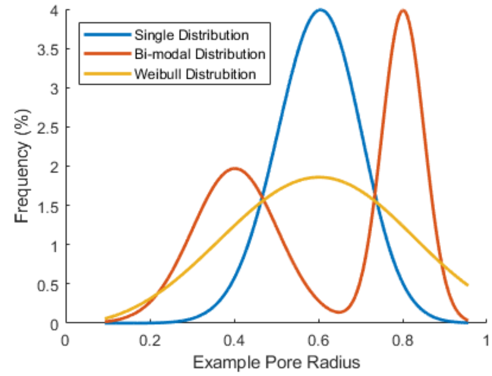

Figure 2. Various Pore Size Distribution Forms

Conclusions and Future Work: While this work has not yet been completed, initial testing is expected to begin soon. Results from this testing will produce permeability values of icy regolith simulants at varying compaction and ice contents. Future work may also investigate how various ice morphologies such as cemented and pressure sintered icy regolith impact permeability.

Using permeability values, effective pore size can be determined. Additionally possible pore size distributions can be estimated. Future work may include using available CT scan data from other published work to better refine pore size estimations. Other work has also used network models to determine permeability from pore size distributions, and the same method may be able to be applied here to reverse the process.[7]

References:

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