Thermal Measurements of Icy Lunar Regolith Simulant: Water Content Analysis Under Atmospheric Conditions.

G. B. Johnson[1], T. A. Wavrunek[2], and P. J. van Susante[3], J.S.Allen[4], T.C. Eisele[5], [1,2,3,4]Dept. of Mechanical Engineering-Engineering Mechanics, [5]Dept of Chemical Engineering, Michigan Technological University 1800 Townsend Drive, Houghton, MI 49931(contact: pjvansus@mtu.edu).

Introduction:

Recovering water ice located in the PSRs of the lunar south poles has become a primary objective for achieving NASA's strategic goals in space exploration, building a sustainable presence in space. The existence of hydrogen-bearing species in these regions of the lunar south pole was confirmed by the analysis of measurements from the LCROSS impact. However, these measurements offer no insight into the spatial distribution of volatiles within the lunar regolith. This has prompted the need for ground-truthing prospecting missions into these PSRs.

Through NASA's 2020 Lunar Surface Technology Research grant (LuSTR), the Planetary Surface Technology Development Lab (PSTDL) at Michigan Technological University (MTU) has developed a novel prospecting technology known as the Percussive Hot Cone Penetrometer (PHCP) [1]. This instrument utilizes a percussive cone penetrometer to measure geotechnical data of regolith, similar to terrestrial cone penetrometers. The integration of a heater and two thermocouples on the PHCP will allow for temperature profile measurements of the volatile bearing regolith in contact with the cone. Changes in the temperature profiles, seen as inflection points or plateaus, indicate phase change for a specific volatile species. To prove this method of detecting phase change by temperature measurements and utilize these temperature measurements in a method of quantifying the amount of volatile present in a mixed lunar regolith simulant, experimental tests were performed. These tests sought to quantify the weight percentage of water ice in a mixed icy regolith simulant sample using an embedded heat source and buried thermistors around the heater. A series of temperature profiles were recorded for 1.5, 5, 7 and 10 weight percent cemented icy regolith simulant samples.

Methods:

Atmospheric tests were performed using MTU-LHT-1A lunar regolith simulant [2]. Samples with either 1.5, 5, 7 or 10 weight percent water or ice inclusion were mixed in a concrete mixer and water was introduced via a fine mist hand pump sprayer. Once the weight percentage of water was added to the MTU-LHT-1A sample the test setup procedure was started. A modified 5-gallon bucket was used to hold the samples and allow Type-K thermocouples to be inserted from the outer wall. Mixed samples were added to the bucket in layers and compacted by hand using a consistent method and tool for tamping. As the column height of the sample reached a specific layer, thermocouples were inserted and positioned within the bucket relative to the known position of a cartridge heater. The cartridge heater used was 4 inches long, ½ inches in diameter and had a 750-watt capacity with a 21 W/cm^2 energy flux. The thermocouple positioning was 5 mm spacing radially outward at the heater midpoint and endpoint, with 10 mm spacing on the underside of the cartridge heater (Figures 1 - 3).

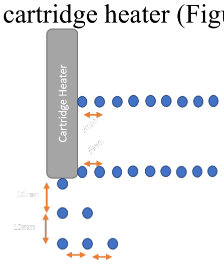

Figure 1: Positioning of the Type-K thermocouples relative to the cartridge heater

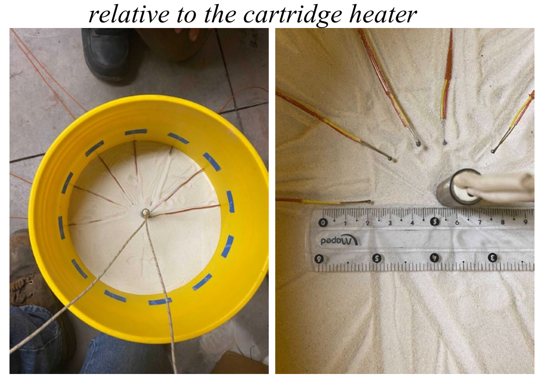

Figure 2 & 3: Modified 5-gallon bucket used for holding the mixed regolith samples and the position of the cartridge heater and Type-K thermocouples

Once the compacted layers of mixed or dry samples were at the top of the cartridge heater, mixed samples to be tested with ice were placed in a -20 ^{O}C chest freezer for a period of 12 hours before testing. Once the samples were ready, constant power was supplied to the cartridge heater at 30 Watts, 50 Watts, or 100 Watts for a period of an hour after which the power was turned off and the temperature measurements continued for at least 30 minutes.

Results:

Temperature profiles of points surrounding the cartridge heater midpoint clearly show regions of water evaporation with an increase in weight percentage of water ice. Desiccated MTU-LHT-1A samples were tested at each power level to determine the baseline thermal response around the cartridge heater midpoint (Figure 4). Figure 5 shows the latent heat of vaporization region for the 10-weight percent mixed ice sample tested with 100-Watt power supply. This region of plateaus in the temperature profiles denotes the energy directed towards phase change instead of a rise in temperature.

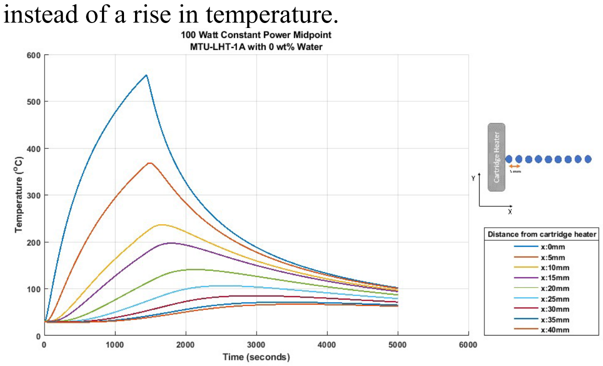

Figure 4: Temperature profiles of desiccated MTU-LHT-1A with constant 100 Watts. 9 thermocouples out to a distance of 40 mm with 5 mm spacing.

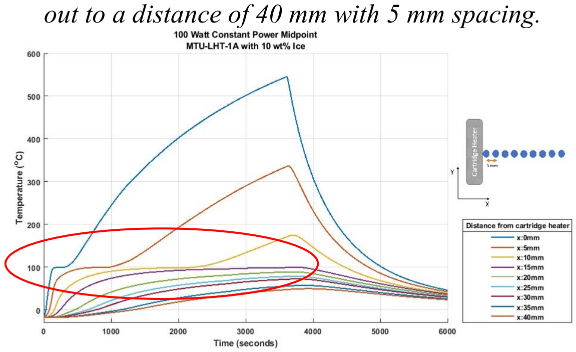

Figure 5: Temperature profiles of MTU-LHT-1A and 10 wt.% cemented ice with constant 100 Watts. 9 thermocouples out to 40 mm with 5 mm spacing.

Discussion:

The goal of atmospheric temperature profile measurement was to develop a method of quantifying the weight percentage of water ice. Analysis of temperature profiles and the rate of temperature change is used in the development of a weight percentage approximation method.

Peaks in the change of temperature plots denote the start and end of a phase change region. The time period of phase change and the associated power supplied over that time period provides the total energy supplied. Each temperature profile also corresponds to a position relative to the cartridge heater that can be used to approximate a volume of the heat affected region, using isothermal lines from the array of thermocouples at the midpoint, endpoint, and underside of the cartridge heater, assuming axis-symmetric thermal behavior. From this volume and the recorded bulk density of the mixed sample, the total mass of the heat affected volume was approximated. The total energy supplied over the time period of phase change was initially used along with the latent heat of vaporization of water to determine the mass of volatile, given the known amount of energy absorbed into the heat affected volume. Dividing the estimated volatile mass from the energy by the total mass of the heat affected volume resulted in a rough approximation of the water ice wt.%. This method closely approximated the weight percentage of a 5 wt.% test within 0.5 wt.% accuracy but diverged at higher weight percentage tests. This method will provide a baseline for correlating results from future tests under vacuum conditions.

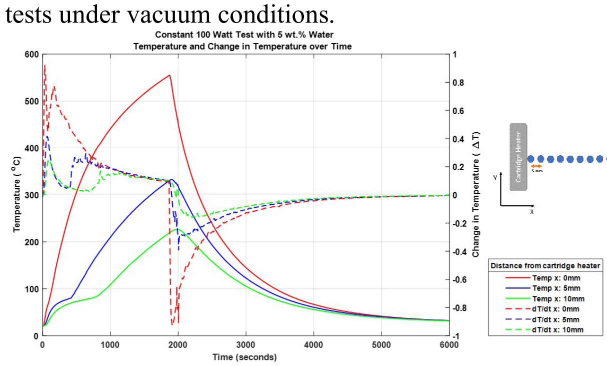

Figure 6: Temperature profiles and change in temperature of MTU-LHT-1A and 5 wt.% cemented ice with constant 100 watts. First three thermocouples positioned at the heater midpoint.

Conclusion:

Based on the results from atmospheric testing of concreted ice and MTU-LHT-1A regolith simulant, temperature measurements can be used to determine the weight percentage of water ice present in a sample. Testing will continue using an instrumented hot cone penetrometer buried in mixed shaved ice and MTU-LHT-1A samples under low vacuum conditions. These tests will measure thermal behavior in a vacuum environment and in samples with discrete ice particles. In addition to tests with the PHCP, a new test setup will be utilized to test water and other volatiles such as CO_2, CH_4, C_2H_4, CH_3OH, and SO_2 under cryogenic temperatures (-180 ^oC) and low vacuum (1-10 mTorr).

Acknowledgements:

This research was supported by NASA's LuSTR 2020 research grant funding 80NSSC21K0769

References:

[1] P. J. van Susante, J. Allen, T. Eisele, and T. Scarlett, K.A. Zacny, "Identifying and Quantifying Volatile Content and Geotechnical Properties in the lunar PSRs", AIAA ASCEND 2021 conference proceedings, Las Vegas, NV, Nov, 2021

[2] C.L. Carey and P.J. van Susante, "Michigan Technological Universities' Lunar Highland Simulant MTU-LHT-1A", SRR, Golden, CO, June 7-10, 2022