SPECIFIC HEATS AND THERMAL DIFFUSIVITIES OF LHS-1 LUNAR REGOLITH SIMULANT AT LOW TEMPERATURES.

D. H. Austen and E. Shafirovich, Department of Aerospace and Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, eshafirovich2@utep.edu.

Introduction: The development of methods for extraction of water from lunar regolith requires a knowledge of thermophysical properties of dry and icy lunar regolith over a wide range of low temperatures.

Thermophysical properties of lunar regolith samples collected in the Apollo missions have been well documented (see, for example, [1] and references therein). Despite a wide variation in petrology of the samples from different missions, specific heat is virtually independent of composition. With increasing temperature from 100 to 350 K, specific heat increases from 0.3 to 0.8 J/(g·K). Wood-Robinson et al. [1] recommend applying the temperature dependence of specific heat [2] to all lunar materials:

$$C_p(T) = -3.6125 + 2.7431\,T + 2.3616 \cdot 10^{-3}\,T^2 - 1.2340 \cdot 10^{-5}\,T^3 + 8.9093 \cdot 10^{-9}\,T^4 \quad (1)$$

where the units of T and C_p are K and J/(kg·K), respectively. Thermal conductivities of the Apollo samples were measured in the range of 100−400 K, and, in contrast with specific heats, the data depend on the regions where the samples were collected [1]. In general, thermal conductivity of the Apollo samples varies from $(0.5-0.8)\cdot 10^{-3}$ W/(m·K) at 100 K to $(1-3)\cdot 10^{-3}$ W/(m·K) at 400 K [1].

Among various lunar regolith simulants, JSC-1, developed to simulate the lunar mare regolith, and its finer versions JSC-1A and JSC-2A received most attention. Specific heat of sintered JSC-1A, measured by differential scanning calorimetry (DSC), increases from about 0.8 J/(g·K) at 373 K to 1.0 J/(g·K) at 773 K [3]. Specific heat of sintered JSC-2A, also measured by DSC, increases from about 0.6 J/(g·K) at 273 K to about 0.9 J/(g·K) at 423 K [4]. It is seen that the specific heats of JSC-1A and JSC-2A are similar to those of the Apollo samples. The measurements of thermal conductivity of uncompressed JSC-1A under vacuum (10^{-2} Pa) at 240-340 K have shown the values in the range of $(2-3)\cdot 10^{-3}$ W/(m·K) [5], i.e., close to those of the Apollo samples.

However, thermophysical properties of regolith in polar regions of the Moon remain unknown. An additional problem is that ice may affect thermophysical properties of the regolith in those regions.

Currently, two lunar regolith simulants, LMS-1 and LHS-1, are used to develop technologies for processing regolith on the lunar surface. The LMS-1 and LHS-1 were designed to simulate the lunar mare and highland soils, respectively. Recently, various physical properties of both simulants have been determined [6]. However, to our knowledge, their thermophysical properties have not been studied yet.

The objective of the present work was to determine specific heats and thermal diffusivities of LHS-1 (particle size: < 1 mm, volume mean diameter: 90 μm) and its finer version LHS-1D (particle size: < 35 μm, volume mean diameter: 7 μm) over a wide range of low temperatures. Based on these properties and the bulk density of the material, thermal conductivity can be calculated. Specific heats were measured using DSC, and thermal diffusivities were determined by laser flash analysis (LFA). Specific heats of the simulants mixed with water were also measured.

Experimental: Specific heats were determined using a simultaneous thermal analyzer (Netzsch STA 449 F3), equipped with a steel furnace that operates over the temperature range from about −150°C to 1000°C. The STA allows simultaneous DSC and thermogravimetric analysis (TGA). The specific heats were measured in accordance with the ASTM Standard E1269-11 [7] in an alumina crucible. The STA was calibrated using standards under the same conditions as those during the actual test: a heating rate of 20 K/min and helium flow rate of 50 mL/min.

The measurements were conducted with dry simulants LHS-1 and LHS-1D as well as with their mixtures with distilled water, prepared in a resonant acoustic mixer (Resodyn LabRAM).

For the dry simulants, the STA temperature program included three vacuum cycles and purging with helium under atmospheric pressure. For the simulants with added water, no vacuum cycles were used; instead, the furnace was purged for 30 min with helium.

Thermal diffusivities of LHS-1 and LHS-1D at low temperatures were measured using a laser flash apparatus (Netzsch LFA 457 [8]) with a furnace that operates over the temperature range from −125°C to 500°C. The tests were conducted in a helium environment at atmospheric pressure (approximately 90 kPa) and in vacuum (pressure < 1 Pa).

The sample was placed into a graphite-coated sapphire crucible. The bulk densities of LHS-1 and LHS-1D were 1.25 g/cm^3 and 1.05 g/cm^3, respectively. The crucible was then installed in the instrument. In the atmospheric pressure tests, three vacuum cycles were conducted followed by purging with helium at atmospheric pressure, the flow rate of which was maintained at 50 mL/min throughout the test. In the vacuum tests, the furnace was evacuated, and the vacuum pump was kept on throughout the test.

Results and Discussion: Figure 1 shows the specific heats of dry LHS-1 and LHS-1D at 110−320 K. The figure also presents the temperature dependence of the specific heats of the Apollo samples described by Eq. (1). A reasonable agreement of the obtained curves with the Apollo data is observed, which is not surprising as the composition of LHS-1 is similar to those of the Apollo samples [6] and, as noted above, specific heats of different regolith samples are almost identical [1].

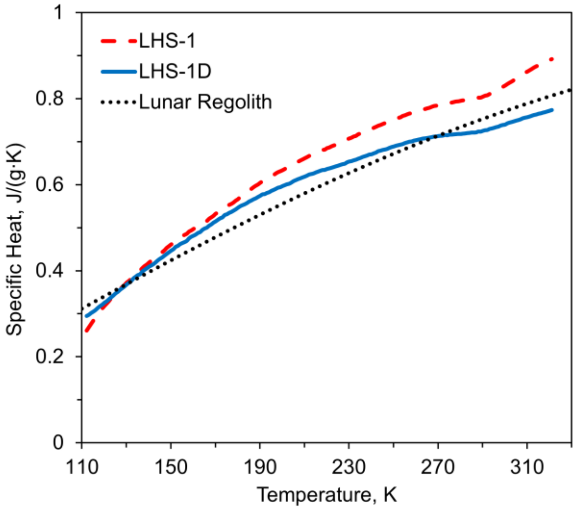

Fig. 1. Specific heats of LHS-1, LHS-1D, and the Apollo samples vs temperature.

Figure 2 shows the specific heats of LHS-1/water mixture in comparison with the data for dry LHS-1. The two consecutive peaks in the C_p curve correspond to the melting of ice and the evaporation of water. It is seen that below 250 K the addition of ice did not increase the specific heat. The thermogravimetric curve shows that the mass of the sample dropped by about 5%, which is explained by evaporation of water. It is also seen from both C_p and mass curves that with approaching a temperature of about 340 K, all water was vaporized. Therefore, the concentration of water before the heating was about 5 wt%.

Figure 3 shows the thermal diffusivities of LHS-1 and LHS-1D at 90 kPa of helium and LHS-1 in vacuum at 148−300 K. A downward trend is observed with increasing temperature. It is seen that the values at 90 kPa are much higher, which is explained by a significant contribution of helium to the heat transfer, in addition to the thermal conduction and radiation. Thermal conductivity calculated using the obtained values of thermal diffusivity in 1 Pa vacuum is two orders of magnitude higher than the thermal conductivities of the Apollo samples or JSC-1A measured in 10^{-2} Pa vacuum [1, 2, 5]. It is also seen that the finer simulant has a lower thermal diffusivity, which was expected.

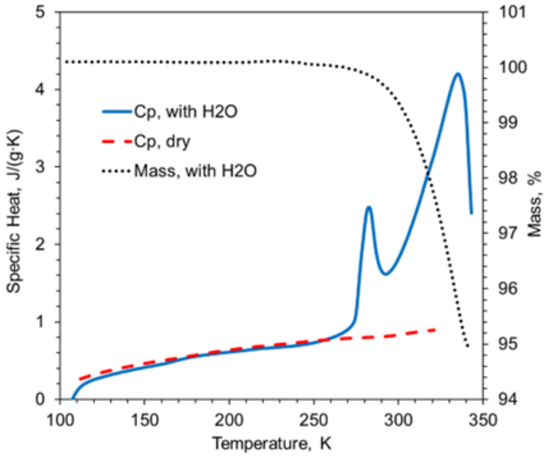

Fig. 2. Specific heats of LHS-1 with and without water and the thermogravimetric curve of LHS-1 with water.

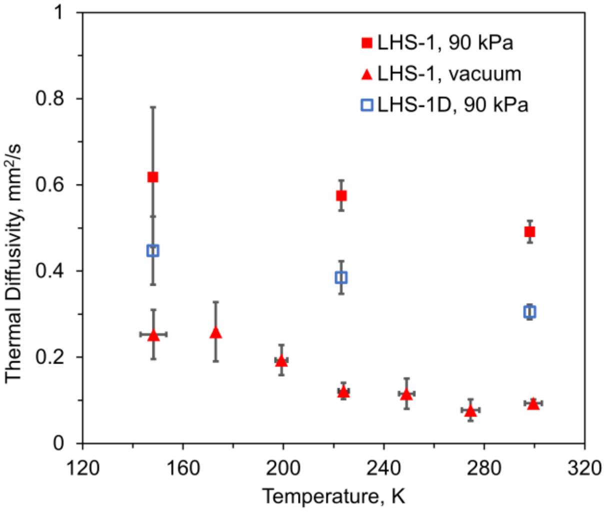

Fig. 3. Thermal diffusivities of LHS-1 and LHS-1D vs temperature.

Acknowledgments: The material presented in this work is based upon the work supported by National Aeronautics and Space Administration (NASA) under Grant #80NSSC21K0768.

References:

[1] Woods-Robinson R. et al. (2019) *Journal of Geophysical Research*, 124, 1989-2011. [2] Hayne P.O. et al. (2017) *Journal of Geophysical Research*, 122, 2371-2400. [3] Ferguson R.E. and Shafirovich E. (2018) *Combustion and Flame*, 197, 22-29. [4] Fateri M. et al. (2019) *International Journal of Applied Ceramic Technology*, 16, 2419-2428. [5] Sakatani N. et al. (2018) *Icarus*, 309, 13-24. [6] Isachenkov M. et al. (2022) *Icarus*, 376. [7] ASTM E1269-11 (2018) *ASTM International*. [8] Min S. et al. (2007) *Thermochimica Acta*, 455, 45-49.