Investigation on the Thermal Properties of an Lunar Icy Regolith Simulant

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1. Introduction

With the moon becoming a more and more important stepping stone for human space exploration, we need to learn more about its properties and resources. The presence of water ice in some Permanently Shadowed Regions (PSR's) on the lunar surface is already certain [1,2] and if extracted, the water could be used for propellant production and as a consumable for astronauts, making future space missions much more affordable.

Knowing the thermal properties of the material beforehand would be highly beneficial to future extraction attempts. This is why in this work thermal conductivity measurements have been done on a lunar highlands simulant (LHS-1) as well as an icy simulant made from LHS-1 and spherical µm-sized granular ice particles to simulate the PSR's icy material.

2. Experimental Setup & Method

Heat flow through granular materials, such as the uppermost layer of the lunar surface material known as regolith, can be explained by three types:

- Thermal radiation
- Solid conductivity
- Gas diffusion

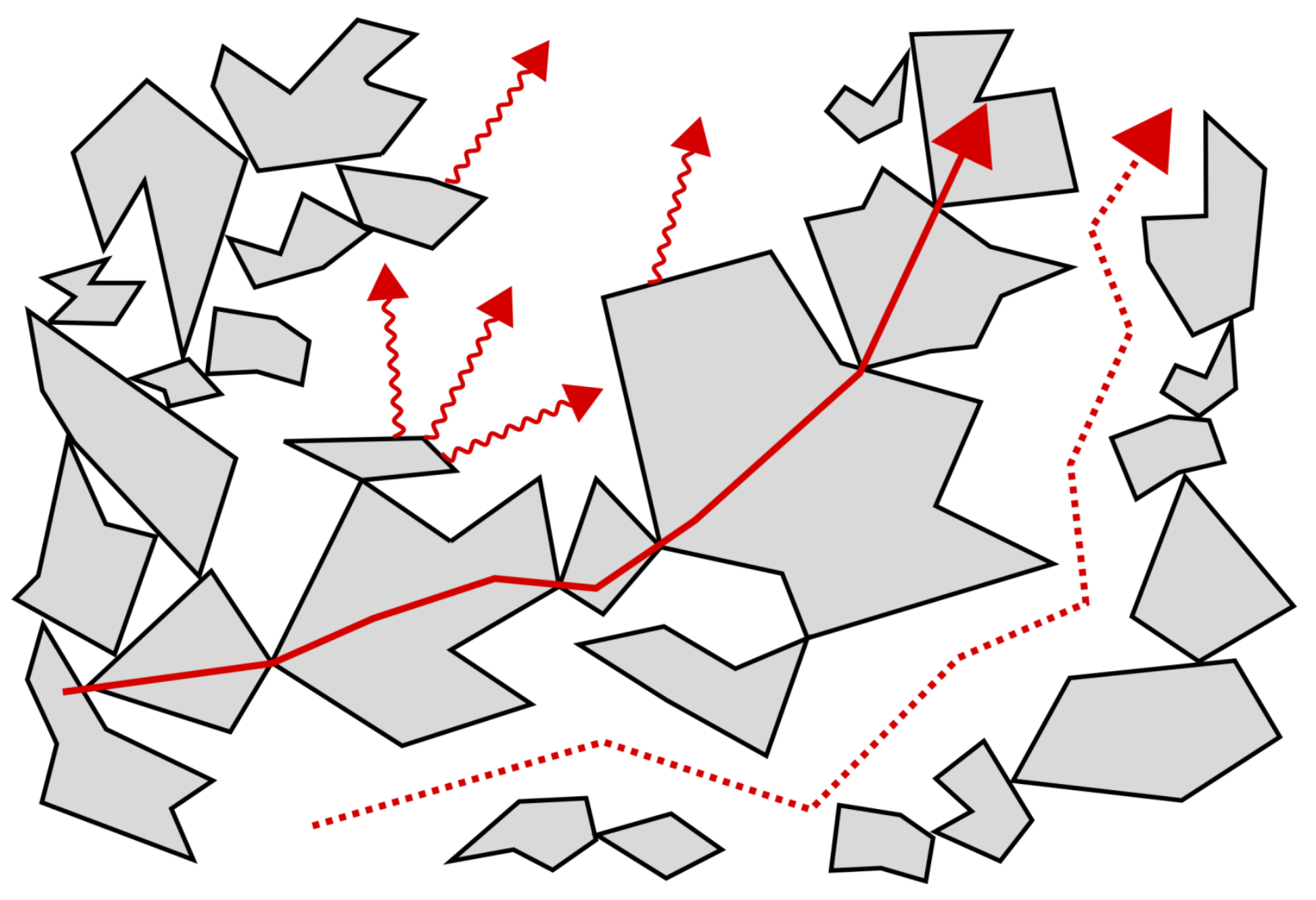

Fig. 1: Options of heat transport through regolith.

To assess the influence of these components, a Thermal Vacuum Chamber (TVAC) was used. Operating at low pressures near 10^{-4} - 10^{-5} mbar, the gas component's contribution becomes negligible and with varying temperatures within the range of 100K - 400K (-173°C to 125°C), the effects of radiation and solid conductivity can be analysed.

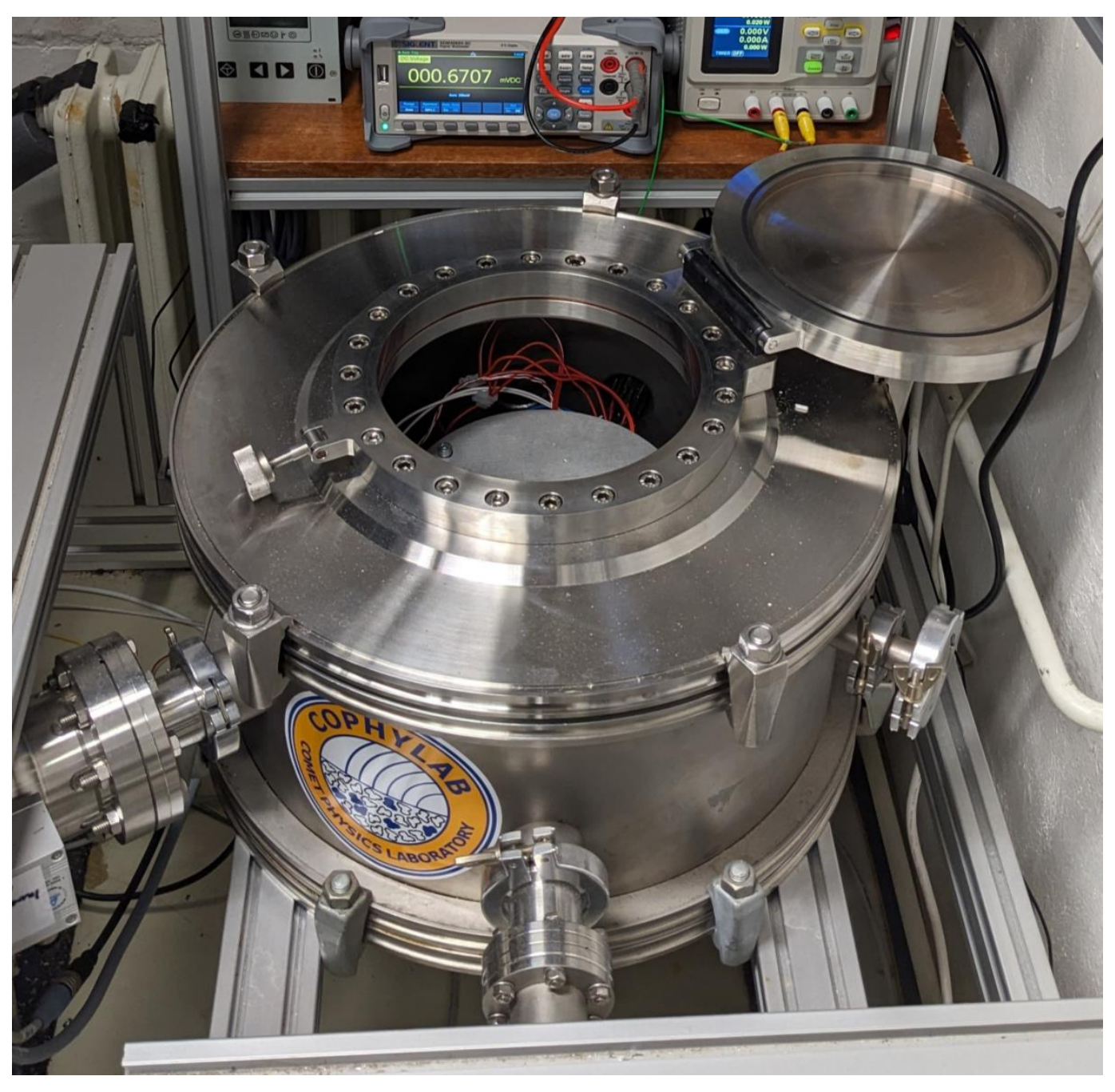

Fig. 2: Thermal Vacuum Chamber.

Using the Transient Hot Strip (THS) technique, the thermal conductivity and thermal diffusivity can be measured simultaneously by observing the temperature response of the material to a well determined heat source. The THS is capable of functioning as a heat source and thermometer at the same time when inserted into a sample. [3, 4]

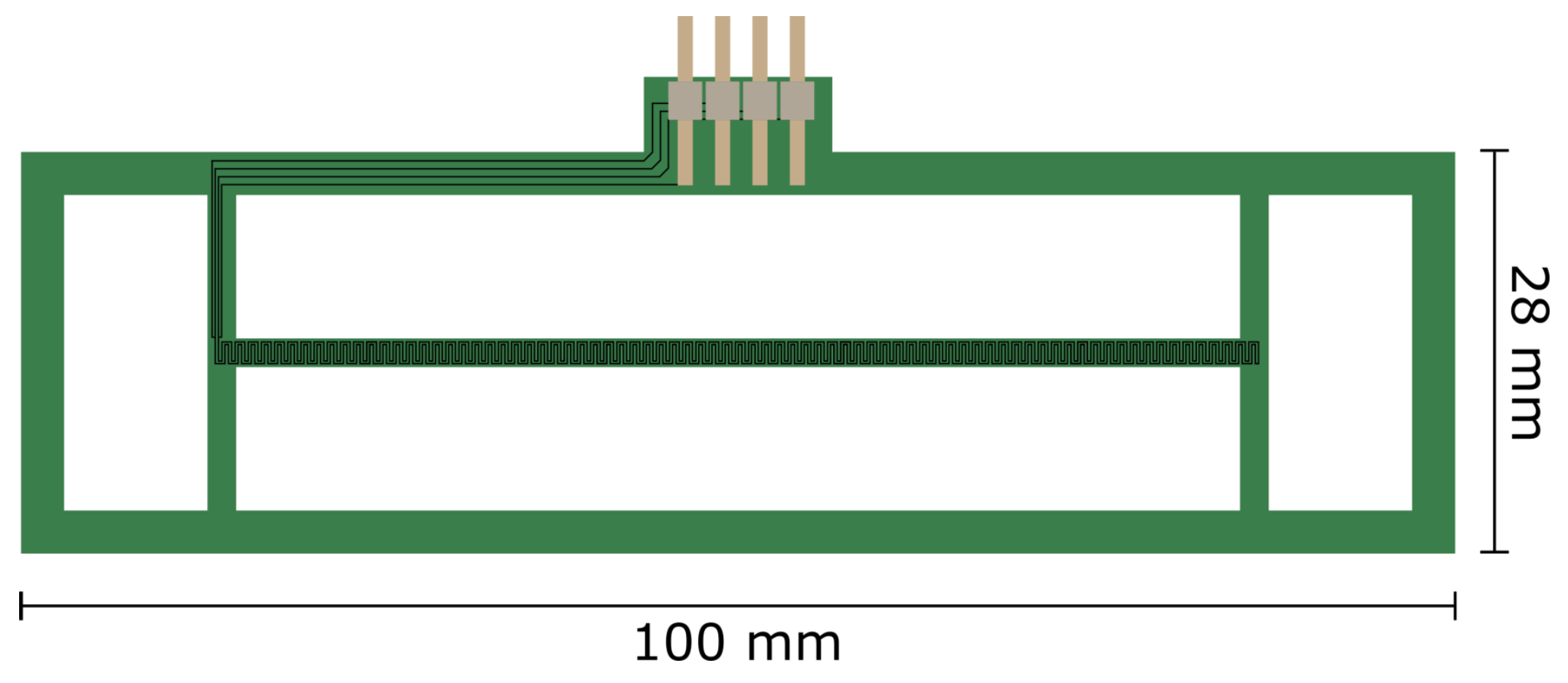

Fig. 2: Transient Hot Strip for thermal conductivity measurements.

3. Icy Regolith Simulant

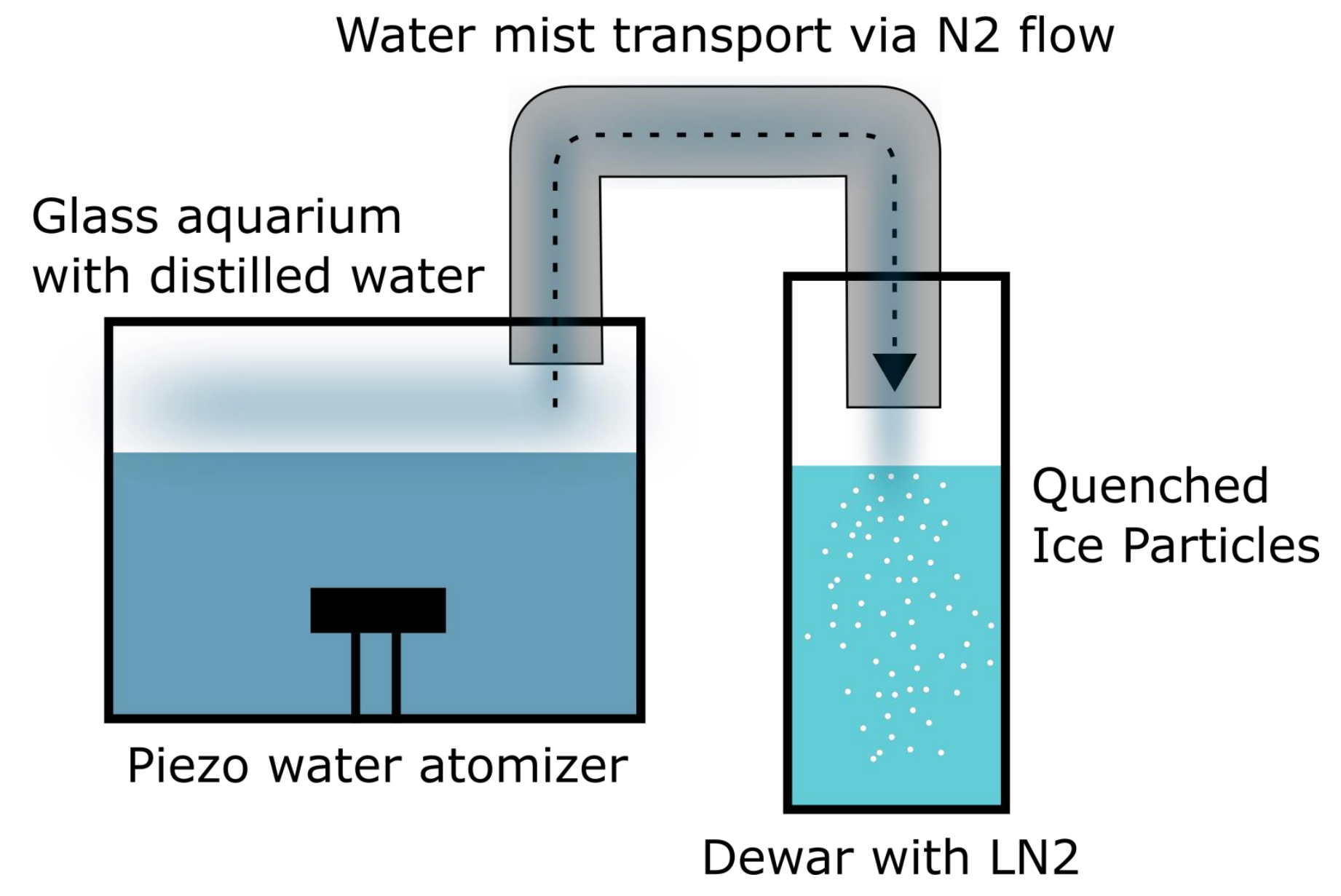

Fig. 4: Ice machine creating granular ice particles by quenching water droplets in liquid nitrogen.

To produce granular ice, a fine mist of water droplets is generated using a piezo water atomizer. The mist is then quenched in liquid nitrogen as shown in Figure 4, producing ice particles with a mean radius of 2.4 ± 0.1 µm. [5] These particles can then be mixed in any ratio with a regolith simulant to create an icy regolith simulant. The mixing can be done either with the liquid nitrogen ice slush as produced by the ice machine or in a desiccated form. When liquid nitrogen is removed, the ice shows strong adhesive forces, which means that larger ice chunks might form. With a slush, one can reach much better homogeneity but the liquid nitrogen has to boil off before using the simulant for experiments. Additionally, this type of ice allows the incorporation of water soluble contaminants such as Methanol to the simulant.

The real form of ice on the lunar surface is to date mostly unknown, leaving one to speculate what it might look like. Due to constant bombarded by micrometeorites and exposure to solar radiation, the surface material is rough and highly granular. One could expect the ice to share similar characteristics.

The easiest way of creating an icy regolith simulant by just freezing wet regolith (the so called mud-pie) is certainly not reflecting the reality of the lunar surface since there is no possibility of liquid water there. The next simplest approach to simulate ice in a granular form is to add premade granular ice particles to the regolith simulant. The resulting material consist of discrete, unfused ice particles intermixed with the regolith grains as shown in Figure 5. For lunar water extraction projects like LUWEX, this represents a worst case scenario since the thermal conductivity is lowest for such kinds of materials compared to fused or embedded ice.

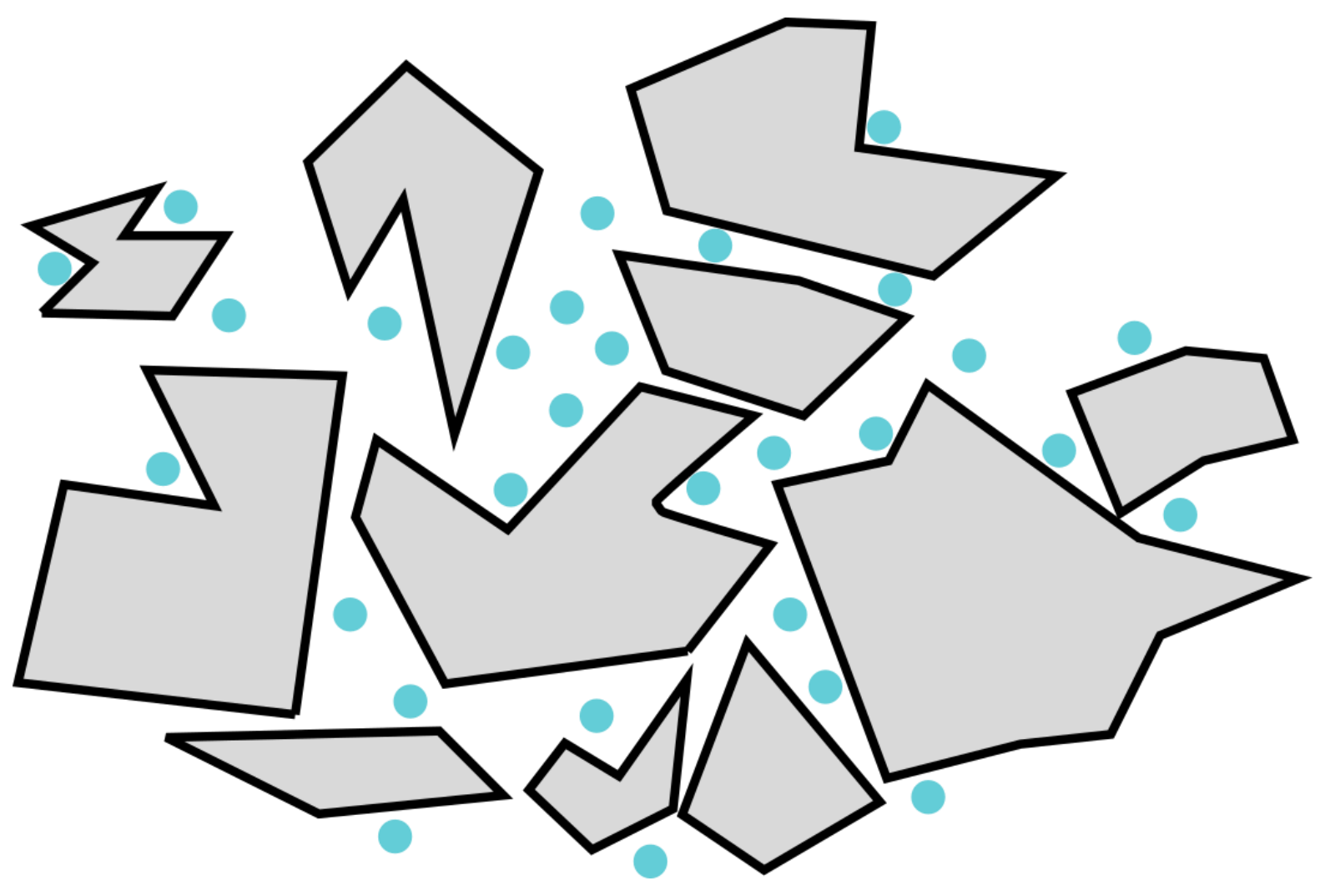

Fig. 5: Schematic of discrete unfused µm-sized ice particles in regolith.

4. Thermal Conductivity Measurements

First, the thermal conductivity measurements were performed on dry simulant. For this purpose the Lunar Highlands Simulant LHS-1 by Exolith Labs was used at two different bulk densities as shown in Figure 6 (top). The data is fitted with a $a + bT^3$ fit where a represents the solid conductivity and bT^3 the radiative one. The red solid line shows measurements of Apollo 11 samples from [6].

The measured simulant's thermal conductivity is in good agreement with the Apollo sample, although the temperature dependence is slightly different, which could be caused by small differences in grain size, composition and the degree of compaction. With an increase in bulk density, the solid thermal conductivity increases because of the particles being closer together. The radiative term might reduce slightly because of pore spaces shrinking with higher levels of compaction.

Next, an icy regolith simulant was created by using the method presented in Section 3 with 2.2 ± 0.3 wt. % of granular ice particles mixed in LHS-1.

To assess the thermal conductivity, the cooled sample was heated in the TVAC gradually up to 380K over an 8 day period while measuring the thermal conductivity. Figure 6 (bottom) shows this data compared to the lower density sample from above.

With rising temperatures, the icy sample's thermal conductivity increases drastically. Above approximately 200K, this is most prominent due to the sublimation of ice, leaving water gas in the pores space between the regolith. This gas is able to transport heat much faster than only solid and radiative thermal conductivity could do at the given temperatures.

Because of the vacuum pumps, there is a strong pressure fluctuation and gradient in the TVAC, which also influences the vapor pressure in the pore space. The maximum TVAC pressure was reached at 240K with 0.01 mbar.

Above 250K, most of the water is gone which leaves a mostly dry sample with very similar thermal conductivity to the dry sample.

For future water extraction approaches, this means that heating times might be shortened drastically with the presence of water gas from sublimation within the pore space of the granular regolith. Even with a vacuum on the outside, some gas might stay trapped inside the pores even over multiple days.

Future measurements will also analyse changes made from higher water ice contents, delivering reference points for possible ice content variations in PSR's on the lunar surface.

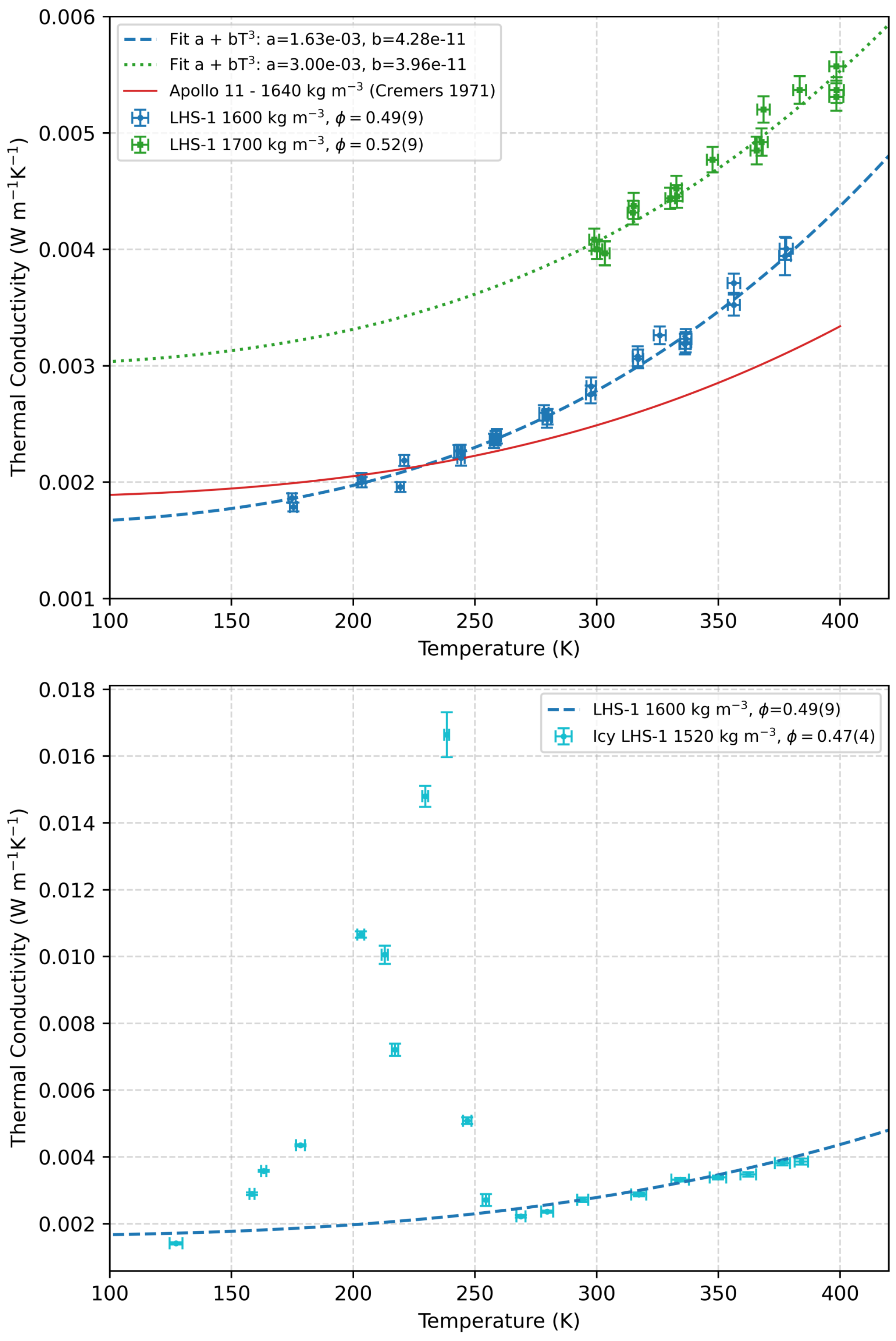

Fig. 6: Thermal conductivity measurements of dry LHS-1 (top) and icy LHS-1 (bottom) with 2.2 ± 0.3 wt. % of ice.

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LUWEX

The project LUWEX - Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production – aims to display the thermal extraction, capturing and purification of water from the here portrayed type of icy regolith simulant.

To recreate lunar conditions, the simulant will be placed in a TVAC where the material is heated until sublimation occurs. Since the thermal conductivity of regolith is very low, the material is stirred to distribute the heat equally. Water gas will then travel to a cold trap and deposit there. The collected water will then be purified outside of the vacuum chamber and could be further used as propellant or as consumable.

Funded by the European Union

Visit https://luwex.space/ or scan the QR code!

This work is part of the DLR internally funded young investigator group "Synergetic Material Utilization" (SMU) established 2021 at the Institute of Space Systems in Bremen, Germany. The group focuses on research and development of ISRU technologies for Moon and Mars exploration.

The experimental parts of this work were carried out in the CoPhyLab at TU Braunschweig.

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