EFFECT OF GRAIN SIZE AND POROSITY ON SURFACE HEAT INFLUX ON THE MOON

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Introduction: In situ heat flow measurements on the Moon are required to gain insight in to its geophysical characterisation and thermal evolution [1-3]. These measurements are possible by placing subsurface heat-flow probes. But, lunar subsurface heat flow measurements are often perturbed by external thermal forcing due to solar insolation. In order to have an unperturbed heat flow measurement, the probes have to be placed beyond the thermal skin depth of the longest cycle (>2m). The present understanding of lunar heat-flow comes from the two in situ measurements carried out during Apollo 15 and Apollo 17 missions. Apollo in situ measurements were site-specific and profiled temperatures at depths beyond ~30cm to 2.5m [4]. Near-surface behaviour was inferred only from extrapolation [4]. On the other hand, numerical modelling supported by remote sensing observations invoke a two-layer model for lunar surface with an outer-most porous layer of ~2cm followed by a denser layer beneath [5,6]. The outer-most porous layer principally dictates the propagation of solar heat influx to the interior layers and thus needs to be better understood. However, the nature or behaviour of this outer-most layer is not well-constrained due to lack of sufficient experimental data. In this scenario, we have initiated efforts in understanding the behavior of the top few centimetres (~10 cm) of the lunar surface by means of laboratory experiments.

Experimental Setup: We have designed and tested a chamber that can simulate temperature and vacuum conditions close to that of surface of the Moon [7]. The sample/stratigraphy under investigation is placed inside a cylindrical sample holder (shown in Fig. 1) made of Teflon with a copper plate at bottom. Slanted perforations are provided along the walls of sample holder to ensure outgassing of pore gases, without sucking the fine grained material. The sample holder is placed on a copper platform which can be heated or cooled from outside the chamber to lunar day/night temperatures. Thus, the entire setup depicts an inverted regolith column with the sample in contact with bottom copper plate mimicking the lunar surface. A series of eight platinum resistance temperature (PRT) sensors mounted at different heights along one side of the sample holder provide temperature profile within the sample as a function of height. One sensor measures the temperature of the bottom copper plate while all other sensors are placed at heights (mm) of 5, 15, 25, 40, 70, 90 and 100 respectively from bottom for profiling heat flow. A UHV D-type feed through connects these sensors to an external custom-designed temperature measurement electronics that displays and logs the data in real-time. An independent pressure logging system is used to continuously monitor and record the level of vacuum during an experiment.

Samples and Methodology: Using the described experimental setup, we plan to carryout experiments to understand the thermal behaviour/heat exchange within the uppermost (~10 cm) lunar surface layer as a function of various parameters such as pressure, grain size, density/porosity, stratigraphy, composition etc. To start with, experiments were carried out to initially understand the effect of pressure/interstitial gases and grain size on the thermal behaviour of the sample. These experiments were currently carried out with fine grain sand. Experiments with analogues and lunar simulant soils are underway. Experiments were conducted to simulate daytime surface temperature of the Moon (~125^{o}C) for uniform as well as 2-layered stratigraphies. In a 2-Strata case, the bottom layer (*Layer 1 - representing a porous outermost layer of the lunar surface*) extends from the surface upto a height of ~15 mm while the top layer (*Layer 2 - representing a more consolidated layer beneath the outermost porous layer*) extends from ~15-100mm. The nature of layer 1 is varied in all cases while keeping layer 2 unchanged portraying the uppermost porous layer of lunar surface . The grain size/stratigraphic details of the sample are outlined in Table. 1.

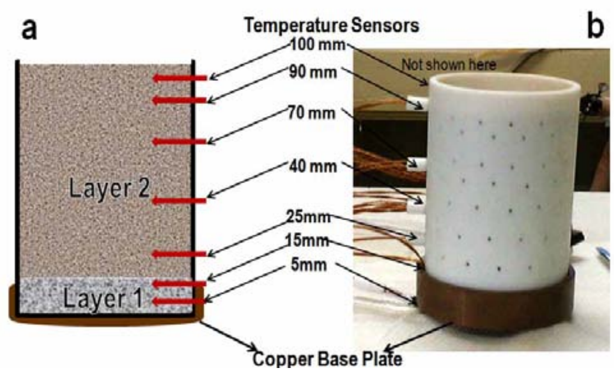

Figure 1: a) A Schematic representation of cross-section of the Sample holder indicating the position of temperature sensors and sample strata b) Picture of the actual sample holder used for the experiment

Table 1: Details of grain size and stratigraphy used in the experiment

Expt.	Sample Stratigraphy	Grain Size (μm)	
		Layer 1	Layer 2
Expt. -1	Uniform	250-1000	250-1000
Expt. -2	2-layer	63 - 150	250-1000
Expt. -3	2-layer	<63	250-1000

Results and Discussion: Some preliminary results obtained from the experiment are shown in Fig. 2. Fig. 2 shows the temporal evolution of heat flow(Q) within the sample stratigraphy calculated between 5mm (within Layer 1) and 25mm (within Layer 2). The heat flow(Q) is calculated as a product of thermal conductivity of the medium and its thermal gradient, given by Q= -λ (ΔT/z), where 'λ' is thermal conductivity (taken as ~0.25 W/mK for fine grain sand), 'ΔT' is the temperature difference and 'z' is the distance between the measurement points in Layer 1 and Layer 2. In Fig. 2, the temporal evolution of heat flow due to 63μm porous layer is plotted for different pressure conditions - Atmospheric, 7e-2 torr and 8e-5 torr (indicated with solid symbols). Variations due to 150μm porous layer for atmospheric and 8e-5 torr pressures are also shown in the same figure (shown with open symbols).

Effect of pressure/interstitial gases: A pressure dependence of heat flow within the sample stratigraphy is clearly evident from Fig. 2. Under atmospheric pressure, the presence of interstitial gases significantly influence the bulk thermal conductivity of the sample thus exhibiting an exponential rise in the heat flow within the medium until an equilibrium is achieved. As the pressure is reduced, the bulk thermal conductivity is also reduced but still follow an exponential rise. However, at ~8e-5 torr, the exponential variation in bulk conductivity tends to be almost linear. This is because of heat exchange being only due to radiative transfer, as the effect of interstitial gases at these pressures become negligible.

Effect of grain size: Also from Fig. 2, a significant effect of grain size can be seen on comparison of heat flow variation within the sample due to two distinct porous layers (63 and 150 μm). For a porous medium, heat conduction is principally dominated by conduction (due to interstitial gases) and radiation [8]. Conduction due to grain to grain boundary becomes negligible as the porosity is increased. Under vacuum conditions, a porous sample with relatively larger grain size exhibits higher thermal conductivity compared to smaller ones. This is because of the increased bulk conductivity due to the presence of larger contact area at the grain boundaries. Therefore, heat flow due to porous layer of 150μm grains appears to be rapid compared to that of a layer of 63μm grains.

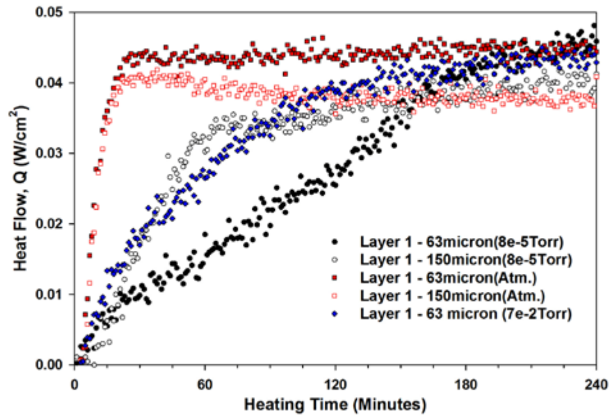

Figure 2: Temporal variation of heat flow within the sample stratigraphy for variable pressures and grain sizes

Summary and Future Work: Qualitative analysis of our preliminary results showed that both the parameters, pressure and grain size, significantly affect the heat flow within the medium. This has several implications in understanding the heat flow within the surface regolith of the Moon. In particular, the results indicate that the behavior of heat transfer within porous media under vacuum is appreciably different from that under atmospheric conditions. We plan to carry out investigations of various other parameters including these for different representative samples and stratigraphies of lunar soil in a simulated lunar environment. Inferences from these laboratory experiments will be iteratively used in conjunction with a model for obtaining an improved understanding of surface heat flow on the Moon.

References: [1] Lyubimova Ye. A. (1974) NASA Report [2] Nafi Toksoz M. et al. (1972) *Moon, 4, 190* [3] Kiefer W. S., (2012) Planet. and Space Sci., 60, 155-165 (1972) *Moon, 4, 190* [4] Langseth M. G. and Keihm S. J., (1974), Proc. of Soviet-AM Conf. on the Cosmochem. of the Moon and Planets [5] Urquhart M. L. and Jakosky B. M. (1997) JGR, 102, E5-10959-10969 [6] Vasavada A. R. et al., (2012), JGR, 117, E00H18 [7] Durga Prasad K. and Murty S. V. S. (2013), Acta Astronautica, 89, 149-153 [8] Paton M. D. et al. (2012), Geo. Sci. Instrum. Method. Data Syst., 1. 7-21