MODELLING OF PASSIVE AND ACTIVE L-GIP THERMAL MEASUREMENTS IN THE LUNAR REGOLITH.

Karol Seweryn[1], Roman Wawrzaszek[1], Jerzy Grygorczuk[1], Borys Dąbrowski[1], Marek Banaszkiewicz[1], Clive R.Neal[2], Shaopeng Huang[3], Norbert Kömle[4].
[1]Space Research Centre PAS, 00-716Warsaw,Poland (kseweryn@cbk.waw.pl); [2]Dept. Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA; [3]Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1005, USA; [4]Institut für Weltraumforschung , Österreichische Akademie der Wissenschaften, Graz, Austria.

Introduction: Atop the Moon's crust is a highly comminuted surface layer of lunar regolith. It has been estimated that the regolith thickness varies from about 3–5 m in the maria, and by about 10–20 m in the highlands [1].

The thermal properties of the upper layer of the regolith were determined in the experiments carried out by astronauts during the Apollo 15 and 17 missions when two heat flow probes were inserted into the lunar soil. The determinations of the thermal diffusivity of the lunar regolith down to a depth of two meters were done by studying time series of temperatures recorded by the probes. The analysis of annual temperature variations, which provides the most reliable indication of diffusivities, yield values in the range 0.73 to 1 $x10^{-8}$ m^2s^{-1} [2].

Thermal conductivity estimates derived from a heating experiment were different by a factor of two from the ones resulting from measurements of the annual thermal wave. Independent determinations of heat capacity and regolith density were used to obtain the thermal conductivity value in a range of 0.9 to 1.3 $x10^{-2}$ $Wm^{-1}K^{-1}$ [2].

The value of the heat flow was also obtained from the measurements, but the probes gave different results. The value of the heat flow at the Apollo 15 site was equal to 21 mWm^{-2} and appeared to be higher than that from the Apollo 17 site, where the measured value was equal to 16 mWm^{-2} [2].

The L-GIP team aims at performing new thermal experiments on the lunar surface. Two independent measurements should deliver thermal gradient and thermal conductivity. These two values, when combined, should give a value of the heat flux. Other thermal parameters, like thermal diffusivity or thermal inertia are also of interest. The measurements will be performed by thermal sensors inserted into the regolith. A possible approach is to place the sensors into the soil by using a "mole" hammering device [3], [4]. After being deployed on the surface, such a device could hammer its way down to several meters below the surface [5], [6]. Thermophysical properties would be measured by the mole itself or by sensors embedded in the elastic cylindrical tape dragged by the mole [7].

The L-GIP team identified several problems that can occur during thermal measurements in the regolith: (i) without the thermal contact between the sensor and the medium the heat will be transmitted by radiation, hence the time dependence of the sensor temperature as it slowly relaxes to the medium temperature can only be calculated numerically, (ii) when the sensors are heated in order to derive thermal conductivity from a rate of the temperature increase, even a small gap between the mole and the regolith will result in the thermal resistance that should be taken into account in data interpretation, (iii) the regolith structure will be changed during the mole penetration, therefore the medium thermal conductivity will depend a distance from the medium-mole boundary. In this paper we present numerical thermal models that describe the three cases listed above.

Passive measurements: Temperature measurements are considered as passive. The sensors are located either on the mole or on a tape attached to the mole. In both cases thermal contact between the medium and the sensor is not certain, hence the problem (i) should be investigated.

Fig. 1 The stack of thermal sensors.

Active measurements: In principle, a medium with higher conductivity transfers heat energy faster than a less conductive material. To measure thermal conductivity an active method should be used, in which the heating power applied to the sensor is transmitted to the medium and the change of sensor temperature with time is then analyzed. Theoretical foundations of this method was given by [8].

In practice, it is very hard to ensure all conditions required by theoretical methods. In particular, the energy transfer from the heat source to the surrounding medium can be disturbed by many factors, e.g. by a gap between the heat source and regolith or by the imperfect contact between the two. It is illustrated by an experiment carried out in the vacuum chamber, in which four cylindrical sensors developed in SRC PAS (fig 1) were placed into a hollow cylinder made of Teflon [9]. The borehole diameter varied with depth and the gap width varied accordingly (fig.2, problem (ii)).

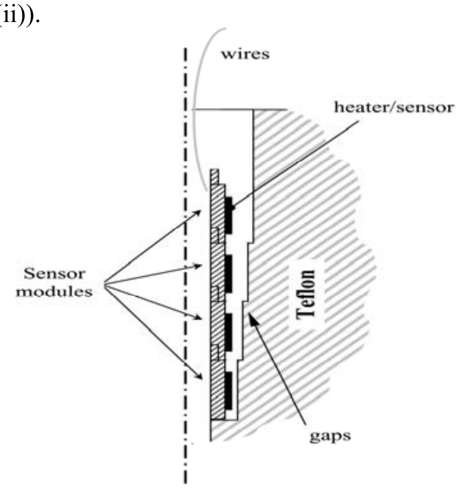

Fig.2 Sensor stack placed inside a Teflon sample.

The results for a heating-cooling cycle are presented in fig.3. It is clear that the influence of the gap width on temperature variations is significant, especially in the initial phase. After a while, the gap does not affects the heat transport anymore and the curves run parallel one to another with the time derivative depending on the medium thermal conductivity.

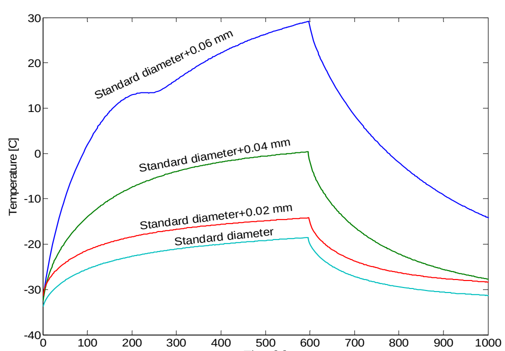

Fig.3 Time dependence of the sensor temperature for the experimental set-up shown in fig 2. Heating power P_H = 0.5W. The kink in the topmost curve results from the power system failure.

Thermal conductivity determination: The linear heat source method assumes that heat generated in an infinitely long cylinder is transported to the surrounding medium. For long heating intervals the slope of the curve Temperature vs ln(Time) can be used to determine thermal conductivity. When the heating element is not long enough as compared with its diameter this approach does not work and one has to use either complicated analytical formulae that are based on Green functions or a numerical finite element method. In either case, the modeled temperature at the sensor depends on the assumed thermal conductivity of the medium. Therefore, the obvious method of determining the value of this parameter is to fit the observed temperature dependence to the modeled one, using the thermal conductivity as a single fitting parameter. In this study we employed numerical method to be able to control also boundary conditions in a complicated model of sensors and the medium [9].

The heat transfer (Fourier) time dependent equation [10] is solved numerically for a geometrically complex system of bodies comprising a stack of sensors, the surrounding medium and interfacing rings. We assume axial symmetry, hence the heat transfer equation is 2-dimensional:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} + \nabla \cdot \left(-k_{eff} \nabla T\right) = Q$$

where, ρ is density, C_p – thermal capacity, k_{eff} – effective thermal conductivity and Q – heat source intensity during heating intervals. The models we present assume that k_{eff} and ρ varies with the radial distance from the borehole wall. In that way we model the effect of the medium material compression during the mole penetration (problem (iii)).

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