

Abstract

A popular method for measuring the thermal conductivity of solid materials is the transient heated needle method. It allows to evaluate the thermal conductivity of a solid or granular material to be evaluated simply by combining a temperature measurement with a well-defined electrical current flowing through a resistance wire enclosed in a long and thin needle. Standard laboratory sensors that are typically used in laboratory work consist of very thin steel needles with a large length-to-diameter ratio. This type of needles is convenient since it is mathematically easy to derive the thermal conductivity of a soft granular material from a simple temperature measurement. However, such a geometry often results in a mechanically weak sensor, which can bend or fail when inserted into a material that is harder than expected. For deploying such a sensor on a planetary surface, with often unknown soil properties, it is necessary to construct more rugged sensors. These requirements can lead to a design which differs substantially from the ideal geometry, and additional care must be taken in the calibration and data analysis.

In this paper we present the performance of a prototype thermal conductivity sensor designed for planetary missions. The thermal conductivity of a suite of solid and granular materials was measured both by a standard needle sensor and by several customized sensors with non-ideal geometry. We thus obtained a calibration curve for the non-ideal sensors. The theory describing the temperature response of a sensor with such unfavorable length-to-diameter ratio is complicated and highly nonlinear. However, our measurements reveal that over a wide range of thermal conductivities there is an almost linear relationship between the result obtained by the standard sensor and the result derived from the customized, non-ideal sensors. This allows to measure thermal conductivity values for harder soils, which are not easily accessible when using standard needle sensors.

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1 Introduction

Thermal conductivity is one of the key parameters required for modeling the thermal evolution of a planetary body and the interaction between the solid surface and sub-surface layers and the atmospheric and radiative environment. However, it cannot be easily determined by remote sensing, but needs to be measured in situ. The simplest way to do this is to insert a long and thin needle into the material to be measured and to heat this needle with a constant electrical power for a specified time. The thermal conductivity of the surrounding material can then be determined directly from the temperature increase of the needle as a function of time. If the measurement time is long enough, the thermal conductivity can be evaluated without knowing the heat capacity of the material. In this case, the theory of heat conduction in the given axi-symmetric geometry predicts that after a short transient phase at the beginning of the heating period (which depends on the heat capacity of the material and on the thermal properties of the sensor itself) the temperature increase of the sensor versus the logarithm of time ($t = 0$ indicating the begin of the heating period) is linear. Thus the heat conductivity k of the material can simply be determined as

$$k = \frac{Q}{4\pi} \left(\frac{dT}{d \ln t} \right)^{-1} \quad (1)$$

where Q is the heating power supplied to the sensor in [Wm^{-1}] and $\left(\frac{dT}{d \ln t} \right)$ is the measured temperature rise of the sensor as a function of the natural logarithm of time. However, such a simple evaluation is only possible for a very long and thin sensor needle with a length-to-diameter ratio of 100 or more, since the theory behind Eq. (1) assumes an infinitely thin and infinitely long line heat source. The reference sensor used here meets this requirement. However, sensors of this type are not rugged enough to be directly used in harder materials without pre-drilled holes (which may cause other errors for the evaluation of thermal conductivity) or on planetary surface missions, where the properties of the soil to be tested are generally unknown. A more rugged sensor

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is necessarily thicker and shorter and can no longer be considered as “long and thin”. Therefore Eq. (1) is no longer directly applicable.

In order to derive thermal conductivity values from measurements with this type of sensors, there are in principle two possibilities. Either a much more complicated formalism is used, applying the theory of “short and thick” sensors, or the same simple theory is used with an additional calibration function valid over the desired range of conductivities. The first method has been described in much detail in a recent paper by Hütter and Kömle (2012), in Hütter (2011) and most recently in Macher et al. (2012). The second method is the topic of the current paper. A more detailed description of the theoretical background can be found in Wechsler (1992) and in Kömle et al. (2011).

Very few thermal conductivity sensors have so far been successfully deployed in planetary missions. In the framework of the Apollo missions in the early 1970’s a few thermal conductivity measurements were performed on the lunar surface. However, evaluation was largely done along the first line, using the theory of multi-layered hollow cylindrical sensors (Langseth, 1972, 1973). The only space instrument that has measured thermal conductivity on an extraterrestrial body other than the Moon was the TECP-instrument aboard the NASA Phoenix spacecraft, which landed on the Martian polar plains in 2008 (Zent et al., 2009, 2010). The method used to evaluate the thermal conductivity measurements obtained from the TECP-instrument is described in Cobos et al. (2006). The needles used for the TECP measurements had an even greater deviation from the “ideal” geometry than the sensors described in this paper. It may be useful to compare their results with our findings in order to further validate the use of this calibration method for future heat conduction measurements on planetary surfaces. In the following sections we give a description of the sensors used for our calibration measurements, characterize the samples used and discuss the results obtained.

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2 Description of sensors

2.1 Reference sensor

As reference sensor we have used an off-the-shelf thermal conductivity probe manufactured by the Dutch company *Hukseflux* (Type TP02). This sensor is shown in Fig. 1. According to the handbook, it is suitable for standard measurements in the range $0.1\text{--}6\text{ Wm}^{-1}\text{ K}^{-1}$ with an accuracy of $\pm 3\%$ in the final thermal conductivity value. The needle has a diameter of 1.5 mm and a total length of 15 cm. The uppermost 10 cm are actively heated during a measurement. The needle temperature in the heated part and in the unheated tip is measured by two thermocouples. With a length-to-diameter ratio of 100 this sensor fulfils the requirements for an “easy” evaluation of the thermal conductivity without the need for additional calibration.

2.2 Prototype ruggedized sensors

Two slightly different prototypes of custom-made sensors (LNP-A and LNP-B) were tested, and are shown in Fig. 2. They differ only in one detail: LNP-A has a mounting stud with a screw thread at the top which could be used to mount it into a deployment device (for example a robotic arm on a planetary lander spacecraft). Because of the small dimensions of the needle such a part could influence the measurements due to its relatively large mass and heat capacity. Therefore a second prototype (LNP-B) was built, which consisted only of the needle and the necessary connection wires without such a mounting stud. Both sensors were also built by *Hukseflux* and had a needle length of 100 mm and a diameter of 3.5 mm. This implies a length-to-diameter ratio of 28. In these sensors the heating wire inside the needle extends over the whole needle length of 100 mm. Temperature is recorded at three positions, as indicated in Fig. 2: in the centre of the needle, close to the tip and close to the upper end. The readings of the central sensor are used for the evaluation of the thermal conductivity value. The temperature sensors are platinum resistance thermometers (PT1000) and

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temperatures are measured with a 4-wire technique.¹ Due to their larger diameter and their shorter length these sensors are by far more robust than the TP02 and easily withstand penetration into harder soils without damage.

3 Characterization of calibration samples

5 The calibration materials used for our measurements have been selected in order to cover the range of thermal conductivities from 10^{-1} to about $2 \text{ Wm}^{-1} \text{ K}^{-1}$. The lower end corresponds to granular materials under normal pressure. As a representative of such a kind of material we have chosen silica glass beads with a grain size in the range 0.25–0.5 mm. For the range $0.3\text{--}0.5 \text{ Wm}^{-1} \text{ K}^{-1}$ the solid plastic material polyethylene (PE) was used. The range $0.5\text{--}0.6 \text{ Wm}^{-1} \text{ K}^{-1}$ is typical for the thermal conductivity of water. However, since water is a fluid, it may undergo convection when heated by the sensor, which strongly increases the heat transfer between sensor and sample and therefore would lead to large errors in the determined thermal conductivity. To circumvent this problem, a small amount of Agar (50 g per liter of water) is added and dissolved in the water. This mixture is then heated up and boiled for several minutes. Upon cooling the solution back to room temperature a transparent, highly viscous gel is obtained, in which any form of convection is suppressed. However, its thermal properties are the same as those of water. When the agar is frozen and kept in a thermally stable environment, one obtains another useful calibration material, covering the range around $2 \text{ Wm}^{-1} \text{ K}^{-1}$, i.e. at the upper limit of our range of interest. However, there is a lack of easily accessible materials in the range between 0.7 and $2 \text{ Wm}^{-1} \text{ K}^{-1}$. To bridge this gap, we used a thermally conducting paste as sample material (Kerafol-KP96). This grease is viscous enough that convection is suppressed, but at the same

¹For an explanation of the four wire measurement technique with platinum resistance thermometers refer e.g. to the National Instruments webpage, <http://www.ni.com/white-paper/7115/en>.

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time soft enough that sensors can be easily inserted. Its bulk conductivity is close to $1 \text{ Wm}^{-1} \text{ K}^{-1}$.

4 Calibration of the ruggedized sensors

For the calibration of the custom-made sensors the following procedures were performed:

- Reasonably large-sized samples were prepared, which were big enough in diameter and height that all three sensors could be inserted without disturbing each other during a measurement and making sure that no influence from the sample boundaries could disturb the measurements. For estimating minimum sample sizes, refer to the formulae given in Hütter and Kömle (2012).
- The samples (with sensors inserted) were kept for at least several hours in a thermally stable environment to make sure that they were isothermal at the beginning of a measurement series. All measurements were performed at room temperature, i.e. at an ambient temperature in the range $20\text{--}25^\circ\text{C}$, apart from those in Agar-ice, where the samples were stored in a deep-freezer at -22°C .
- Thermal conductivity measurements were made by heating each sensor separately, allowing for long enough time periods between two subsequent measurements (at least several hours). The chosen heating periods of the sensors were between 300 s and 900 s, depending on the sample used.
- The thermal conductivity was evaluated using the following standard procedure:
 1. Removal of any temperature trend from the data not associated with the active heating of the sensor.
 2. Identification of the suitable interval of the measured temperature profile (linear part on the T versus $\ln t$ graph).

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3. Calculation of the thermal conductivity according to Eq. (1).

The general setup of the measurements is shown in Fig. 3 for two of the used samples, the glass beads and the PE-block. The Agar sample was prepared in the same 30 cm diameter steel container as the glass beads sample. For performing the measurements in the Agar-ice, this sample was placed in a deep freezer with the sensors inserted and frozen at a temperature of -22°C . In this way it was ensured that the sensor needles were firmly frozen into the ice and thus had a good contact to the sample with negligible thermal resistance. For the Kerafol-KP96 sample the sample container was smaller (diameter of 16 cm) but still large enough to ensure that there was no influence of the container walls on the measurement results. The active heating times of the sensors used for the thermal conductivity measurements were typically 900 s. The heating powers were in the range 100–500 mW, depending on the estimated conductivity of the sample material. An example for the evaluation procedure as described above is shown in Fig. 4.

5 Results

The results of our calibration measurements with the ruggedized thermal conductivity sensors are summarized in Table 1 and in Fig. 5. All measurements were repeated two times or more (the scattering of the measurement results can be seen from the table) and the average value from the individual results (bold numbers in the table) was used to calculate the calibration factor.

Using the measured average values with both types of sensors (the reference sensor TP02 and the ruggedized sensors (LNP-A and LNP-B) a correction factor was calculated per sample and hence conductivity range. This allows the true thermal conductivity to be obtained from a measurement with one of the ruggedized sensors according to the formula:

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$$k_{\text{TP02}} = f_{\text{cal}} \cdot k_{\text{LNP}}. \quad (2)$$

The calibration factors derived for the different materials and sensors (LNP-A and LNP-B) as calculated from the measurements are listed in Table 2. As can be seen from Fig. 5, the measured thermal conductivity values can be well fitted by a linear relationship (constant calibration factor), at least within the range $0.2\text{--}2\text{ Wm}^{-1}\text{ K}^{-1}$. The average value of the calibration factor calculated from the values given in Table 2 is $f_{\text{cal}} = 0.8$. Scattering of individual measurements indicate a maximum error of $\pm 15\%$.

6 Conclusions

The measurements reveal that the prototype sensors give consistently higher values of the thermal conductivity when evaluated in the same way as the measurements with the standard sensor. However, we found an almost linear relationship between this apparent thermal conductivity derived from the measurements with the ruggedized non-ideal sensors and the true thermal conductivity of the material derived from the measurements with the TP02 sensor. This result confirms that suitable measurements with the rugged prototype sensors, which have strongly non-ideal geometry, can be made for any unknown material (in the appropriate thermal conductivity range) by applying a constant calibration factor.

Acknowledgements. This paper is a late result of the project L317-N14 supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung. The custom-made sensors used for the measurements described here were designed and manufactured under the funding of this project.

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Table 1. Thermal conductivity measurement results for the different calibration materials and sensors. The bold numbers at the bottom of each section represent the average of the individual measurements listed above. (These numbers have been used for the plot in Fig. 5.)

Sensor/ λ	Glassbeads $\text{Wm}^{-1} \text{K}^{-1}$	PE $\text{Wm}^{-1} \text{K}^{-1}$	Agar $\text{Wm}^{-1} \text{K}^{-1}$	Kerafol KP96 $\text{Wm}^{-1} \text{K}^{-1}$	Agarice $\text{Wm}^{-1} \text{K}^{-1}$
TP02	0.1684	0.4126	0.5874	0.8477	2.1064
	0.1707	0.4479	0.6251	0.8709	1.9281
	0.1688	0.3755	0.5411	0.8743	1.9631
	.....	0.4560	.....	0.8554	1.8860
	.....	0.3680	.....	.....	.....
	.....	0.3779	.....	.....	.....
	.....	0.4190	.....	.....	.....
	.....	0.4127	.....	.....	.....
	0.1693	0.4087	0.5845	0.8621	1.9709
LNP-A	0.1841	0.5125	0.7396	1.1125	2.7702
	0.1859	0.5119	0.7529	1.1201	2.8757
	0.1850	0.5092	0.7462	1.1161	2.7835
	.....	.....	0.7373	1.1139	2.9208
	0.1850	0.5112	0.7440	1.1157	2.8375
LNP-B	0.1865	0.4979	0.7328	1.0957	2.7807
	0.1868	0.4998	0.7228	1.1000	2.7039
	0.1879	0.4994	0.7336	1.0918	2.6502
	0.7255	1.0931	2.8554
	2.8146
	0.1871	0.4990	0.7274	1.0951	2.7609

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Table 2. Calibration factors derived for the different materials and sensors.

Sensor/material	Glassbeads	PE	Agar	Kerafol-KP96	Agarice
LNP-A	0.9151	0.7995	0.7856	0.7727	0.6946
LNP-B	0.9048	0.8190	0.8013	0.7872	0.7139

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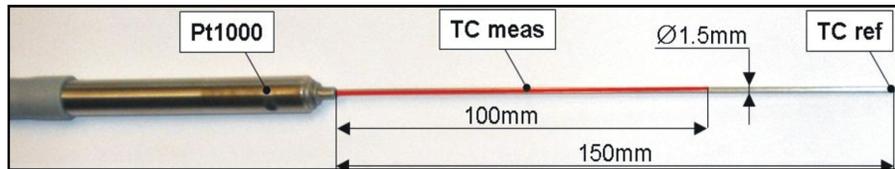


Fig. 1. The commercial TP02 (long needle) thermal conductivity probe produced by the Dutch company Hukseflux. The heated part is indicated in red.

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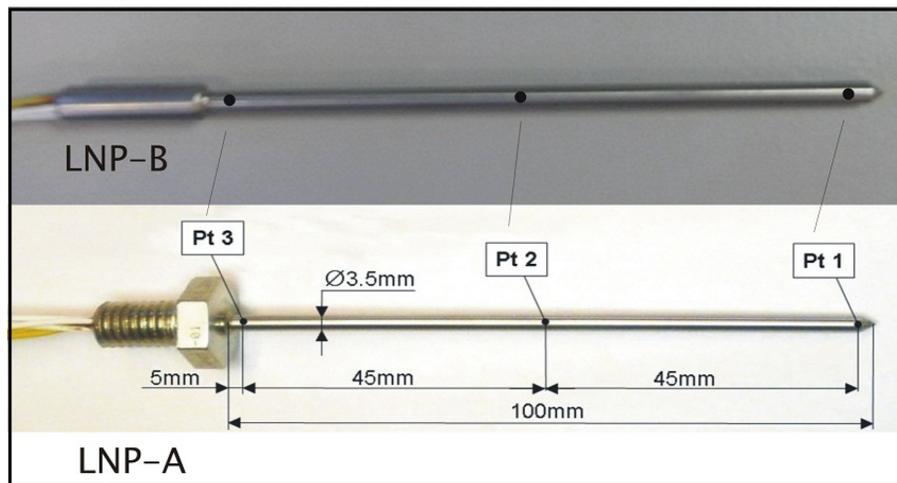
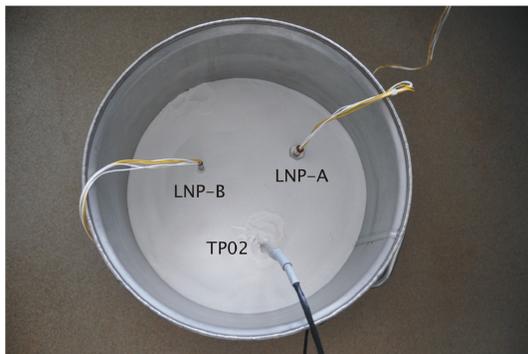
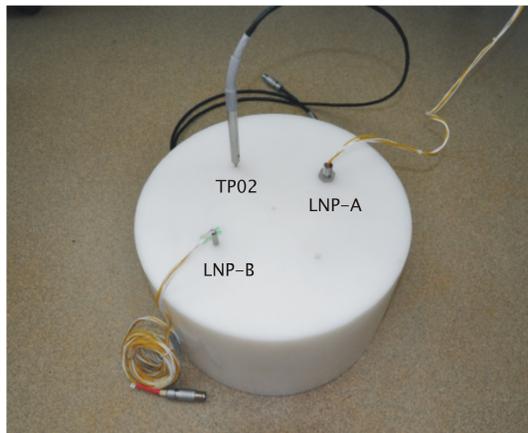


Fig. 2. The custom-made LNP-sensors fabricated by Hukseflux for use on planetary surfaces like on Moon or Mars. They are heated over the whole length.

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Glass beads sample



PE sample

Fig. 3. Experimental setup used for the calibration measurements. Top panel: sensors inserted into glass beads sample; bottom panel: sensors inserted into PE sample.

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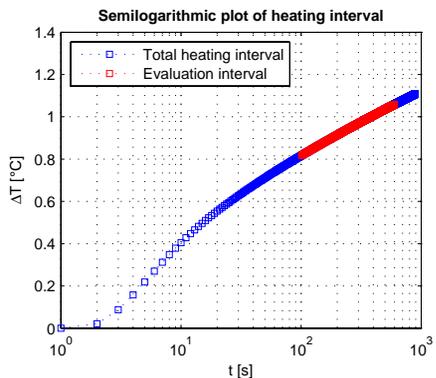
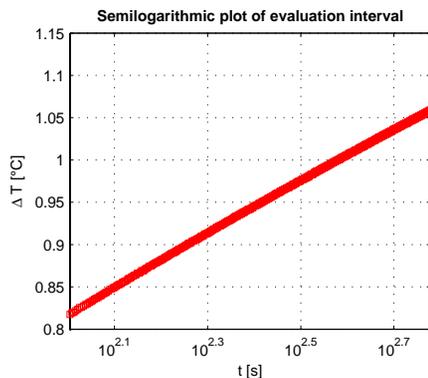
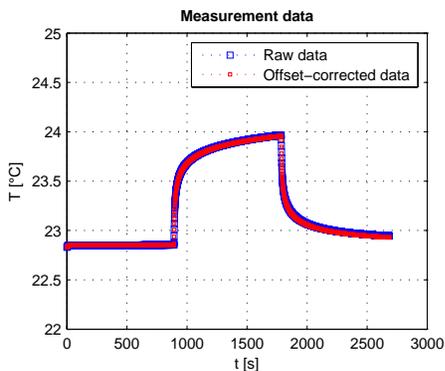


Fig. 4. Illustration of the thermal conductivity evaluation procedure using a Kerafol-KP96 measurement with sensor LNP-B as an example (heating time: 900 s; heating power: 0.215 W). Top left panel: raw data and offset-corrected data of the total measurement (including the decline phase of the temperature which is not used for the evaluation). Bottom left panel: semi-logarithmic plot of the heating interval. Top right panel: semi-logarithmic plot of the interval used for the thermal conductivity evaluation.

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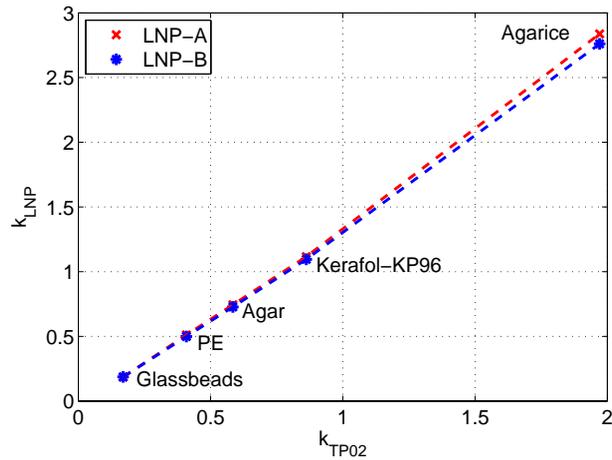


Fig. 5. Calibration of the custom-made LNP-sensors versus the commercial Hukseflux TP02 thermal conductivity sensor, which is considered as the reference sensor.

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