Interpretation of measurements with novel thermal conductivity sensors suitable for space applications

N.I. Kömle[1*], E.S. Hütter[1], E. Kaufmann[2], J. Knollenberg[2], G. Kargl[1] and W. Macher[1]

[1]Space Research Institute, Austrian Academy of Sciences, Graz, Austria
[2]DLR Institute for Planetary Sciences, Berlin, Germany
*Corresponding author: Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Email: *norbert.koemle@oeaw.ac.at*

Abstract: The thermal conductivity of near surface soil layers is a key parameter for understanding the energy balance of planetary bodies, especially those without a surrounding atmosphere. A well-known method to measure this property in soils and granular materials is the *transient hot wire* method. While under laboratory conditions evaluation of such measurements obtained with long and thin needles is straightforward and simple formulae can be used, for space applications other types of sensors have been developed, which are – on the one hand – mechanically more robust and – on the other hand – able to measure to some extent the vertical profile of thermal conductivity as a function of depth. We will present some examples, focussed on the MUPUS instrument and on newly developed *thick needle* sensors, to demonstrate the usefulness of a detailed COMSOL model as a tool to interpret thermal conductivity and heat flux measurements in a planetary environment.

Keywords: Thermal conductivity sensors, planetary applications, modeling.

1. Introduction

In principle there are two ways to obtain information about the thermal properties of a planetary body with instruments that have been delivered and deployed by a landed spacecraft. The first possibility is to perform passive temperature measurements, where natural variations of the temperature profile over a certain depth are measured by an array of sensors arranged in vertical direction over the required depth range. If the absorption properties of the surface and the variation of the solar intensity at the landing place are known, a numerical model can be used to evaluate the thermal conductivity by calculating the expected temperature evolution as a function of time. The thermal properties (k, ρ, c_p) can then be adapted in such a way that the simulated result gives the best coincidence with the measured temperature variation in the domain of interest. The second possibility is to use *active* sensors. In this case needle-shaped rods are emplaced into the soil, which are heated in a controlled way over a part or all of their length and at the same time the temperature increase of the sensor (and its cool-down after the heating phase is finished) is measured. Again, a numerical model taking into account the geometry and the material properties of the sensor along with the applied heating power is useful to evaluate the thermal conductivity of the surrounding material.

2. Sensors for measuring thermal properties

Sensors employing the active heating method for measuring thermal conductivity are being developed for various planetary missions (Kömle et al. 2011). A representative selection is shown in Figure 1. The sensors on the left side (TP02, TP08) are commercial probes suitable for measuring thermal conductivity in fine-grained soils with low cohesiveness and in solids with a pre-drilled, exactly fitting borehole. These sensors allow an easy and quick evaluation of thermal conductivity, because the geometrical dimensions of the needle can be approximated by the model of an infinitely thin and infinitely long heat source. However, such needles are not well suited to be used on a planetary lander mission, because they are mechanically weak and their deployment on a planetary surface is not easily possible. Moreover, they are not suitable to measure the thermal conductivity of coarse-grained materials (in the cm size range) and to detect a potential variation of thermal conductivity with depth.

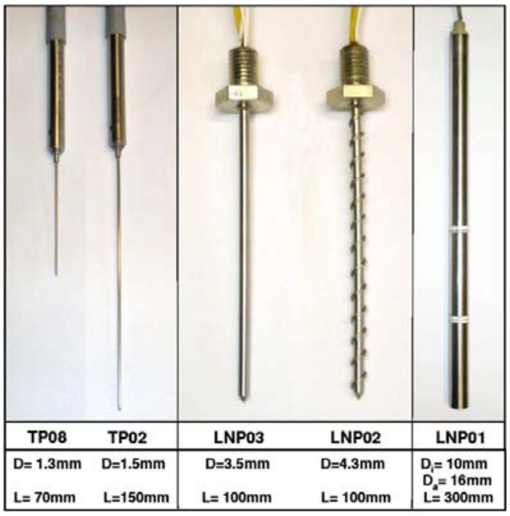


Figure 1. Commercial and custom-made line heat sensors suitable for planetary applications.

Therefore, alternative sensors have been developed for planetary applications, which are shown in Figure 1 (LNP03, LNP02, LNP01) and in Figure 2. All these sensors are mechanically robust enough, so that they can be pushed or hammered into the soil of the Moon, an asteroid or a cometary nucleus. The LNP01 sensor is particularly useful to measure the thermal conductivity of coarse-grained granular materials (Kömle et al. 2010) and the MUPUS probe is designed to measure the variation of thermal conductivity over the length of the probe (approximately 32 cm). This instrument is part of the payload of the comet lander *Philae*, which was launched in January 2004 together with ESA's Rosetta mission and is expected to land on its target comet Churyumov-Gerasimenko in November 2014 (Glassmeier et al. 2007). It consists of a glass fiber rod inside of which 16 individual heaters and temperature sensors are installed on a thin Kapton foil (Spohn et al. 2007). Figure 2 shows the MUPUS ground reference model in a compact configuration, as the original device is mounted on the *Philae* lander. At the top the hammering device (golden box) can be seen. The slender rod on the left is the thermal probe containing heaters and temperature sensors. On the right side the deployment device including a spring mechanism is visible.

3. Use of COMSOL Multiphysics

All these custom-made sensors described above have one disadvantage. Their geometry deviates significantly from an ideal line heat source and this fact demands a more complicated evaluation procedure. At this point the usefulness of setting up a *COMSOL Multiphysics* model comes into play.

Figure 2. MUPUS experiment aboard the Rosetta comet lander *Philae*.

Instead of using a simple analytical formula, modelling of the complete heat transfer problem from the thermal sensor into the medium to be measured is necessary, if one wants to derive the thermal properties of the surrounding medium (and possibly their variation with depth) from measurements. This includes consideration of the complicated geometry, heat loss through cables, radiative interactions with the surroundings, and the thermal resistance between the probe and the surrounding medium. All these features can be met by using the *COMSOL Heat Transfer Module* as a modeling tool. Basically, for the following applications we have used the heat conduction equation for solids including the option that selected domains in the geometry can be homogeneously heated.

4. Results for non-ideal sensor geometry

In this section we show the results of some representative calculations concerning the heat

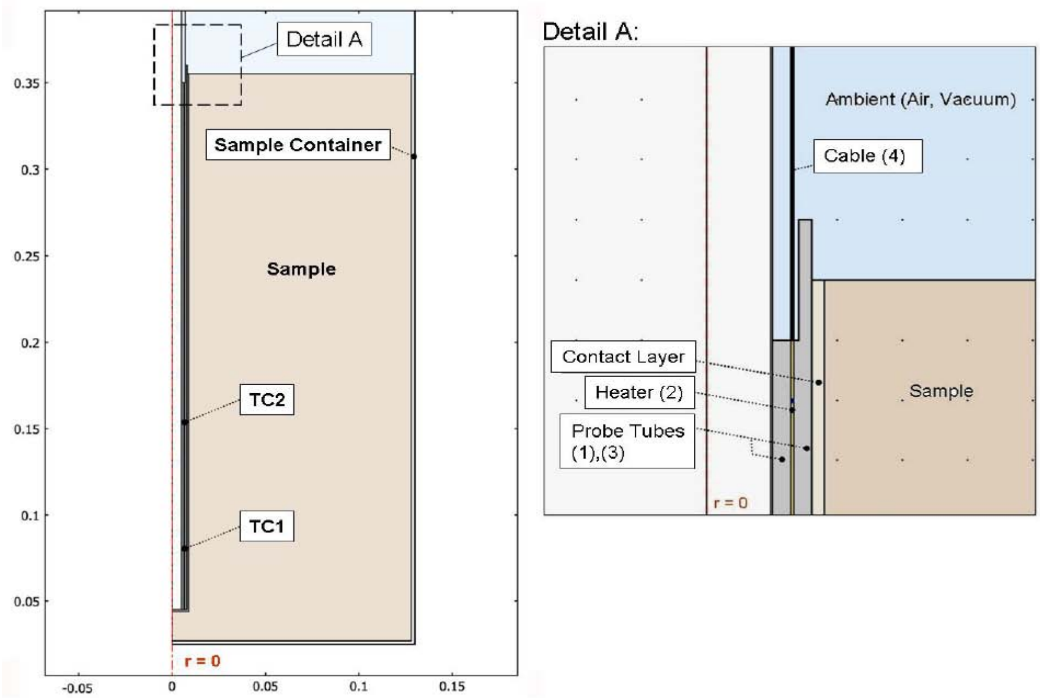


Figure 3. Modeling geometry for the hollow cylindrical sensor LNP01.

transfer in the non-ideal sensors described above.

4.1 Influence of axial heat losses in cylindrical sensors

Axial heat loss along connection wires is usually neglected in the standard evaluation procedure for heat conductivity measurements. However, if conductivity measurements are performed in samples with extremely low thermal conductivity, as they typically exist in the dust layers covering the Moon's or an asteroid's surface, neglecting axial heat loss may lead to big errors in the resulting thermal conductivity, if determined by the standard procedure. To determine the error in such cases it is useful to model the geometry of the sensor embedded in the sample in full detail and to include the isolated copper wires from

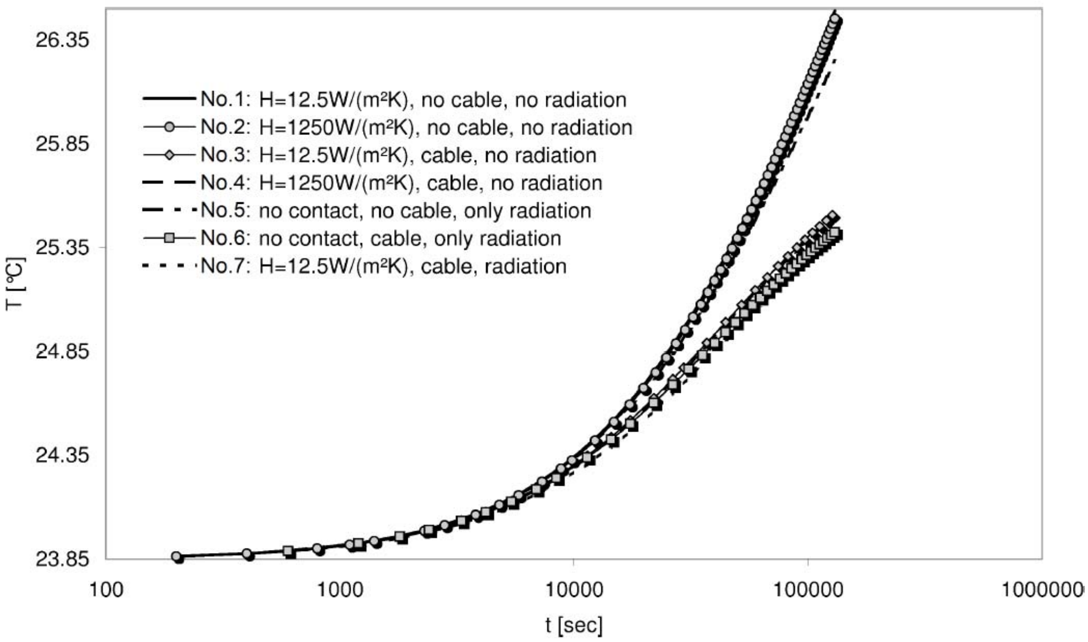


Figure 4. Semi-logarithmic plot of the temperature-time series determined at the position TC2 for a very low sample conductivity $k = 0.002$ $Wm^{-1}K^{-1}$, as appropriate for uncompressed rock powder under vacuum conditions.

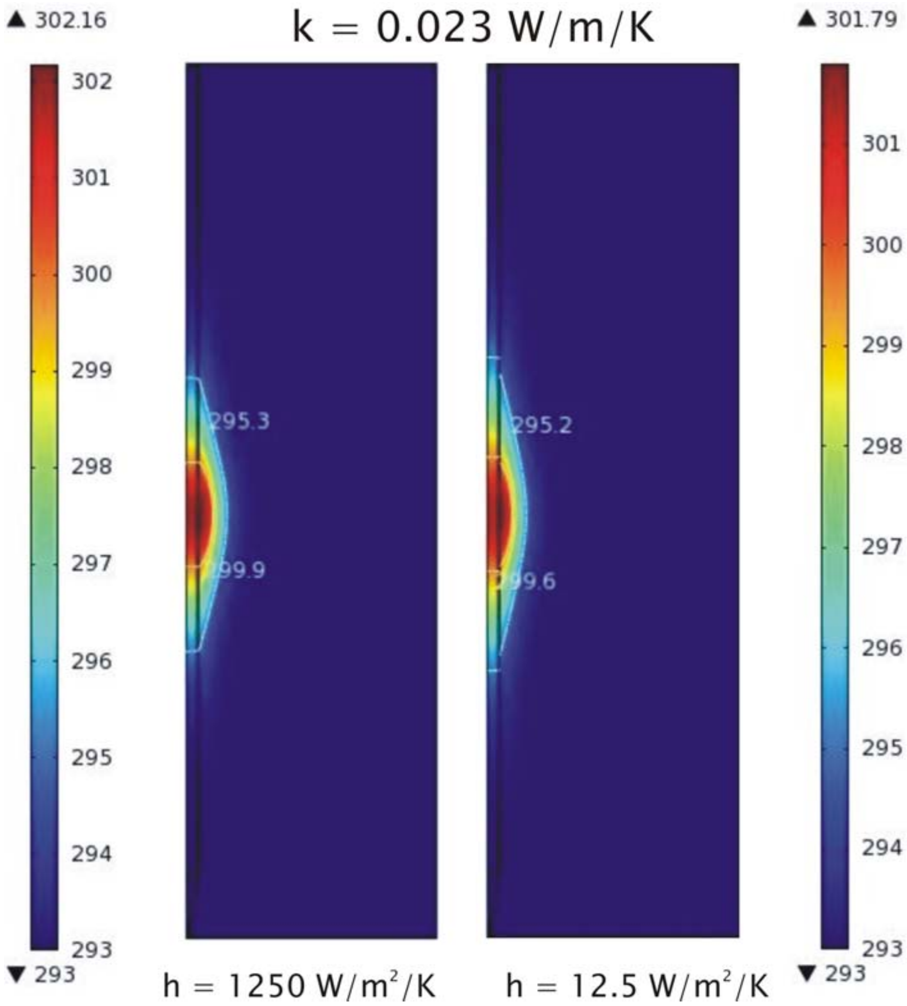


Figure 5. Influence of thermal resistance between conductivity sensor and surrounding soil for a lunar regolith under lunar pressure conditions (vacuum).

the sensor to the attached electronics and power supply into the model. In the following we show a model calculation for the hollow cylindrical sensor LNP01 shown in Figure 1 (right).

For simplicity we have set up an axisymmetric *COMSOL* model including all relevant details of the sensor geometry. The model geometry is shown in Figure 3. It consists of two concentric stainless steel tubes with a heater foil sandwiched between them (Hütter 2011).

The attached cables (copper wires with Teflon isolation) are simulated by concentric cylinders with the same wire cross section area as in the real sensor. The length of the wire in the model is assumed to be 0.5 m and at the end of the wire a constant temperature condition is specified. Figure 4 shows the calculated temperature as a function of elapsed time after the beginning of heating for seven different cases as indicated in the figure legend. As can be seen, the inclusion of axial flow into the model in this very low conductivity case leads to a significantly smaller temperature increase. On the other hand, differences in contact resistance hardly cause a shift of the curve.

4.2 Influence of thermal resistance in a MUPUS-type probe

Next we model the temperature response of a MUPUS-type probe after it has been inserted into a medium. In the following example one of the 16 individual sensor segments is heated for 30 min with a power of 0.7272 W. The geometry is modeled as a 2D-axisymmetric configuration. The individual sensors that can be heated independently have the shape of concentric hollow cylinders with 10 mm outer diameter and 1 mm thickness. Their height increases from 9 mm (Sensor 1 at top position) to 39 mm (Sensor 16 at bottom position). Sensor 12 (heated in our example calculation) has a height of 26 mm. It is assumed in the model that heating is homogeneous within the volume of the chosen probe segment. The sensor is surrounded by a cylindrical sample of 20 cm diameter. This is big enough that the

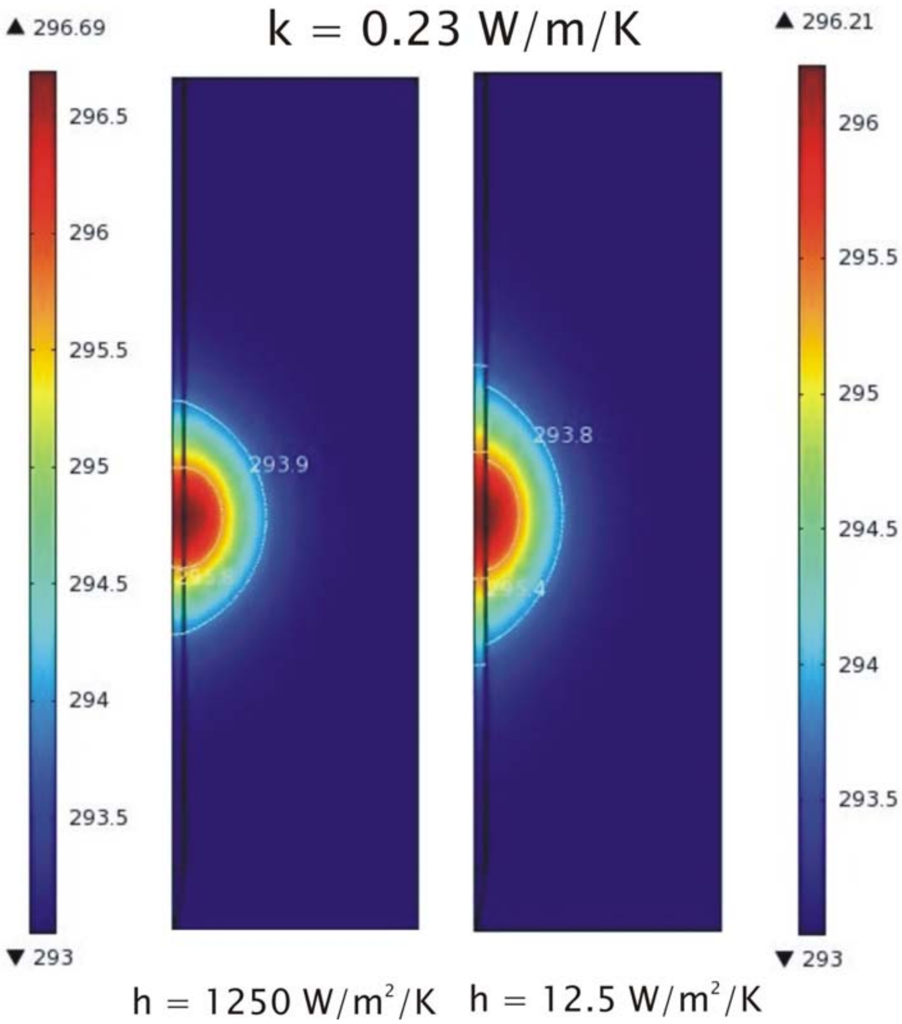


Figure 6. Influence of thermal resistance between conductivity sensor and surrounding soil for dry sand under terrestrial air pressure conditions.

influence of the outer boundary on the thermal evolution can be ignored.

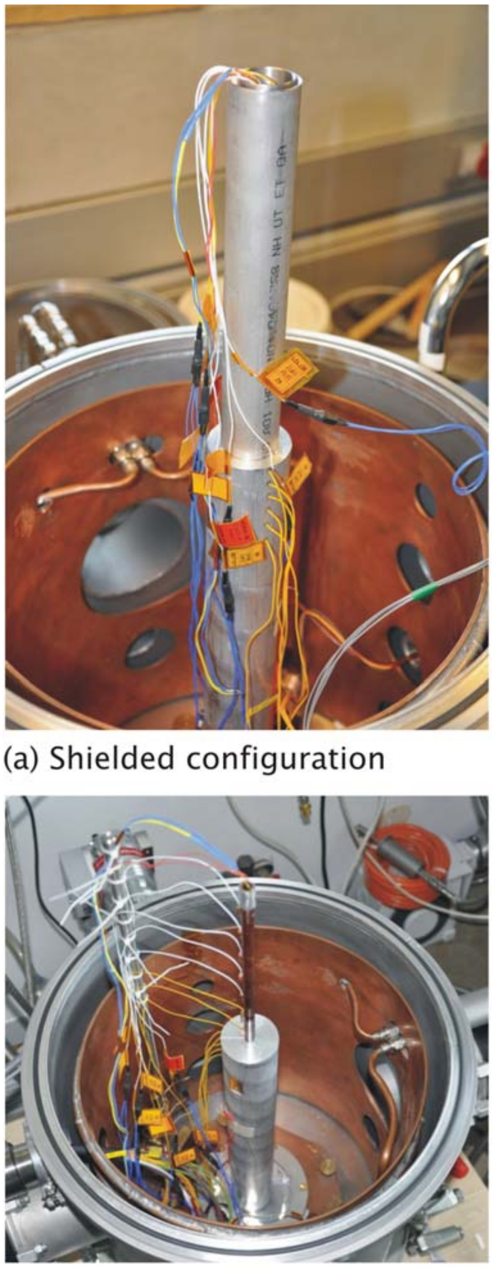
The MUPUS probe and its variant EXTASE developed for terrestrial measurements (Schröer 2006) are mainly designed for planetary and field applications, respectively. Therefore it is important to understand in detail the role of the heat conductance between the probe and the surrounding material, which depends on the contact pressure between sensor and soil as well as on the surrounding air pressure.

The sensitivity of the temperature field developing in the sensor as well as in the soil is an important aspect to be investigated by modeling, before such an instrument can be used for field measurements on a routine basis or on a planetary mission. Therefore we have studied the influence of thermal resistance for a low conductivity lunar regolith material under lunar (vacuum) conditions and for a typical terrestrial soil (dry sand under normal air pressure conditions). The former case is illustrated in Figure 5, the latter case in Figure 6. The range of the thermal conductance *h* is varied from 1250 $Wm^{-2}K^{-1}$ (representing a reasonably good material contact between the probe and the grains composing the soil), and 12.5 $Wm^{-2}K^{-1}$, which is the lowest possible conductance, assuming that heat can only be transferred from the sensor into the soil by thermal radiation interaction (no air, no direct material contact). Looking at Figure 5 one can see that for the low conductivity material (lunar regolith) the highly different conductance values have no visible influence. On the other hand, for materials with a higher conductivity (Figure 6), the shape of the isotherms is visibly different and more circular for the same sensor heating profile. In the lunar regolith case the high thermal resistance (low thermal conductance) causes the generated heat to be channeled along the sensor and to flow more in upward and downward direction rather than flowing into the soil.

4.3 Calibration measurements with a MUPUS-type sensor

In the MUPUS as well as the EXTASE probe thermal sensors are fixed inside a hollow cylindrical tube. This tube is made of fiber glass bound together with cyanato-ester. Since there are no data available for thermal conductivity and specific heat of this composite tube, its thermo-physical properties were measured using a dedicated measurement setup. In order to determine the thermal conductivity of the tube in vertical direction, the temperature gradient along the tube was measured in vacuum using two different configurations, which are shown in Figure 7. In the first one the tube's outer mantle surface was shielded against thermal radiation from the surroundings inside the vacuum chamber by an aluminium tube positioned concentric around the glass fiber tube, while in the second configuration the glass fiber tube was open to the environment inside the vacuum chamber. The temperature values obtained from these measurements are compared with the results of 2D-axisymmetric simulations done with *COMSOL Multiphysics*. Hereby the setup where the probe is shielded against the radiation from the environment is simulated by using *surface-to-surface* radiation as boundary condition at the tube's outer mantle surface and the inner surface of the aluminium tube. The *COMSOL* model geometry used to represent this case is shown in Figure 8.

For the second configuration a *surface-to-ambient* radiation boundary condition was used, setting the ambient temperature equal to the wall temperature of the vacuum chamber (approximately room temperature in these tests, because no active cooling of the system was performed). As an example for the results obtained by the measurements with radiation shielding, Figure 9 shows the time dependent temperature profile at equidistant points along the tube in vacuum.



(a) Shielded configuration

(b) Unshielded configuration

Figure 7: Two different setups used for calibration measurements of the MUPUS and EXTASE probes in a vacuum environment. The tube is heated at the top position. Temperature sensors (PT0, PT1, PT2, PT3,PT4,PT5) where attached to the tube at the positions marked by the white wires.

For the case of free radiative interaction with the surroundings inside the vacuum chamber a comparison of the measured and simulated temperature profile along the tube after a heating time of 3 hours is shown in Figure 10.

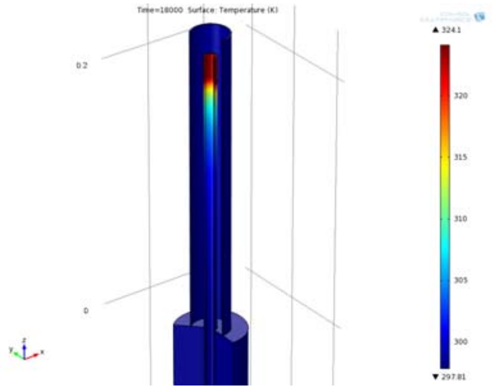


Figure 8: *COMSOL* model of the "shielded configuration" as shown in Figure 7a.

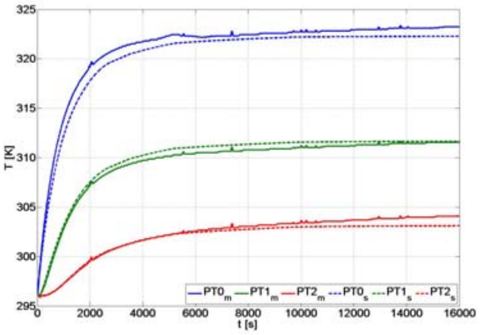


Figure 9: Comparison of the measured temperature of the three upper temperature sensors PT0, PT1 and PT2 (solid line) with the results of a 2D-axisymmetric-simulation (dashed lines) in case of radiation shielding (*surface-to-surface* radiation).

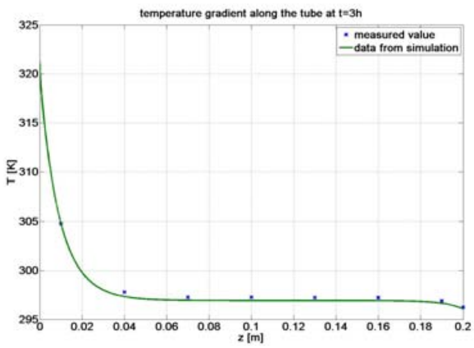


Figure 10: Temperature profile along the tube after 3 h of heating in case of *surface-to-ambient* radiation.

5. Summary

We have demonstrated by three examples how the capabilities offered by the *COMSOL Heat Transfer Module* can be applied to develop accurate thermal models for describing the behavior of heat conductivity sensors with a geometry strongly deviating from the standard shape of a long and thin needle. With such detailed models, along with calibration measurements in well-known media, a sound interpretation of the heat conductivity measurements to be performed by space-borne sensors will become possible.

Acknowledgements. The reported results are based on theoretical and experimental work conducted in the frame of the FWF-TRP project L317-N14.

References

Glassmeier K.H., Böhnhardt H., Koschny D., Kührt E., Richter I.: The ROSETTA Mission: Flying towards the Origin of the Solar System. *Space Sci. Rev.* **128**, 1-21 (2007), *DOI:10.1007/s11214-006-9140-8*

Hütter E.: *Development and Testing of Thermal Sensors for Planetary Applications.* PhD-Thesis, Karl-Franzens-University Graz (2011).

Kömle N.I., Hütter, E.S., Feng, W.J: Thermal conductivity measurements of coarse-grained gravel materials using a hollow cylindrical sensor. *Acta Geotechnica* 5, 211-223 (2010), *DOI:10.1007/s11440-010-0126-z*

Kömle N.I., Hütter E.S., Macher W., Kaufmann E., Kargl G., Knollenberg J., Grott M., Spohn T., Wawrzaszek R., Banaszkiewicz M., Seweryn K., Hagermann A.: In situ methods for measuring thermal properties and heat flux on planetary bodies. *Planet. Space. Sci.* **59,** 639-660 (2011), *DOI:10.1016/j.pss.2011.03.004*

Spohn T., Seiferlin K., Hagermann A., Knollenberg J., Ball A.J., Banaszkiewicz M., Benkhoff J., Gadomski S., Gregorczyk W., Grygorczuk J, Hlond M, Kargl G, Kührt E., Kömle N., Krasowski J., Marczewski W., Zarnecki J.C: MUPUS - A Thermal and Mechanical Properties Probe for the Rosetta Lander Philae. *Space Science Reviews* **128**, 339-362 (2007), *DOI:10.1007/s11214-006-9081-2*

Schröer K: *Eine kompakte Sonde für Temperatur- und Wärmeleitfähigkeits-messungen in den Geowissenschaften.* PhD-Thesis, Westfälische Wilhelms-Universität, Münster (2006).