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Improved data reduction algorithm for the needle probe method applied to *in-situ* thermal conductivity measurements of lunar and planetary regoliths

Seiichi Nagihara[a,*], Magnus Hedlund[b], Kris Zacny[b], Patrick T. Taylor[c]

[a] *Department of Geosciences, Texas Tech University, Lubbock, TX 79409, United States*
[b] *Honeybee Robotics, Pasadena, CA 91103, United States*
[c] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, United States*

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ABSTRACT

The needle probe method (also known as the 'hot wire' or 'line heat source' method) is widely used for *in-situ* thermal conductivity measurements on terrestrial soils and marine sediments. Variants of this method have also been used (or planned) for measuring regolith on the surfaces of extra-terrestrial bodies (*e.g.*, the Moon, Mars, and comets). In the near-vacuum condition on the lunar and planetary surfaces, the measurement method used on the earth cannot be simply duplicated, because thermal conductivity of the regolith can be ~2 orders of magnitude lower. In addition, the planetary probes have much greater diameters, due to engineering requirements associated with the robotic deployment on extra-terrestrial bodies. All of these factors contribute to the planetary probes requiring a much longer time of measurement, several tens of (if not over a hundred) hours, while a conventional terrestrial needle probe needs only 1 to 2 min. The long measurement time complicates the surface operation logistics of the lander. It also negatively affects accuracy of the thermal conductivity measurement, because the cumulative heat loss along the probe is no longer negligible. The present study improves the data reduction algorithm of the needle probe method by shortening the measurement time on planetary surfaces by an order of magnitude. The main difference between the new scheme and the conventional one is that the former uses the exact mathematical solution to the thermal model on which the needle probe measurement theory is based, while the latter uses an approximate solution that is valid only for large times. The present study demonstrates the benefit of the new data reduction technique by applying it to data from a series of needle probe experiments carried out in a vacuum chamber on a lunar regolith simulant, JSC-1A. The use of the exact solution has some disadvantage, however, in requiring three additional parameters, but two of them (the diameter and the volumetric heat capacity of the probe) can be measured and the other (the volumetric heat capacity of the regolith/stimulant) may be estimated from the surface geologic observation and temperature measurements. Therefore, overall, the new data reduction scheme would make *in-situ* thermal conductivity measurement more practical on planetary missions.

1. Introduction

Measurement of heat released from the interior of an extra-terrestrial body is important in understanding the body's internal structure, composition, and origin (*e.g.*, NRC 2011). The Apollo 15 and 17 missions were the first to measure heat flow on an extra-terrestrial body (Langseth et al., 1976). NASA's *Phoenix* lander was equipped with a probe for measuring thermal conductivity of surface soil of Mars (Zent et al., 2010). ESA's *Rosetta* spacecraft bound to Comet 67 P/Churyumov–Gerasimenko carries a heat flow probe (Marczewski et al., 2004). NASA's *InSight* mission, expected to be launched for Mars in 2016, will include a heat flow probe in its science payload (Spohn et al., 2012). Heat flow is obtained as a product of the thermal gradient and thermal conductivities measurements made beneath the surface. The present study focuses on thermal conductivity measurement.

Regoliths of the Moon, Mars, and comets are much less thermally conductive than soils on the earth, mainly because the atmospheric pressures of these extra-terrestrial bodies are much lower (Presley and Craddock, 2006; Piqueux and Christensen, 2009; Siegler et al., 2012). For example, thermal conductivity of lunar regolith is roughly two orders of magnitude less in the lunar vacuum than in the

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[*] Corresponding author. Tel.: +1 806 742 3102.
E-mail address: seiichi.nagihara@ttu.edu (S. Nagihara).

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pressure of the earth's atmospheric (Horai, 1981). Thermal conductivity instruments for planetary missions must be able to measure this value to less than 0.01 W/m K. Pre-flight development of such instruments involves laboratory tests in a vacuum chamber using regolith simulants. In calibrating the instruments, researchers must be able to independently determine thermal conductivity of the simulant, and its pressure dependency.

Methods used for the thermal conductivity instruments on the aforementioned planetary missions and those used in vacuum chambers are variants of the so-called needle probe method (Presley and Christensen, 1997a; Zent et al., 2010; Kömle et al., 2011). A cylindrical probe containing electric heaters and temperature sensors is inserted into the regolith (or simulant). When the heater is activated, temperature of the probe rises (Fig. 1). Thermal conductivity of the regolith has direct relation with the time-rate of the temperature increase seen by the probe. If the regolith is thermally insulating (*i.e.*, of low thermal conductivity), temperature of the probe rises rapidly as the heat builds up in the vicinity of the probe. If the regolith is highly conductive, the heat dissipates away from the probe quickly, and temperature of the probe rises more slowly.

The needle probe method was developed over 50 years ago for measurements on terrestrial soils, marine sediments, and other materials of similar texture (DeVries and Peck, 1958; Von Herzen and Maxwell, 1959), and it is still widely used by researchers (Beardsmore and Cull, 2001). The method is also known as the 'hot-wire' or 'line heat source' method. A typical needle probe used in terrestrial soil measurements consists of a cylindrical metal tube of 3- to 10-cm length and 1- to 3-mm diameter. It contains an electric heater wire (*e.g.*, nichrome), which runs along the length of the probe, and a temperature sensor (either thermistor or thermocouple) positioned at the mid-point of the probe. The needle probe method is popular among terrestrial researchers mainly for three reasons. First, the experimental hardware is simple, easily transportable, and relatively inexpensive. Second, a needle probe experiment can be carried out very quickly. It takes only 1–2 min to measure a terrestrial soil sample. Third, in this method, the thermal conductivity is obtained as a simple algebraic function of the heater power and the rate of the temperature increases. Knowledge of any additional thermal parameters, such as heat capacity of the material, is not necessary.

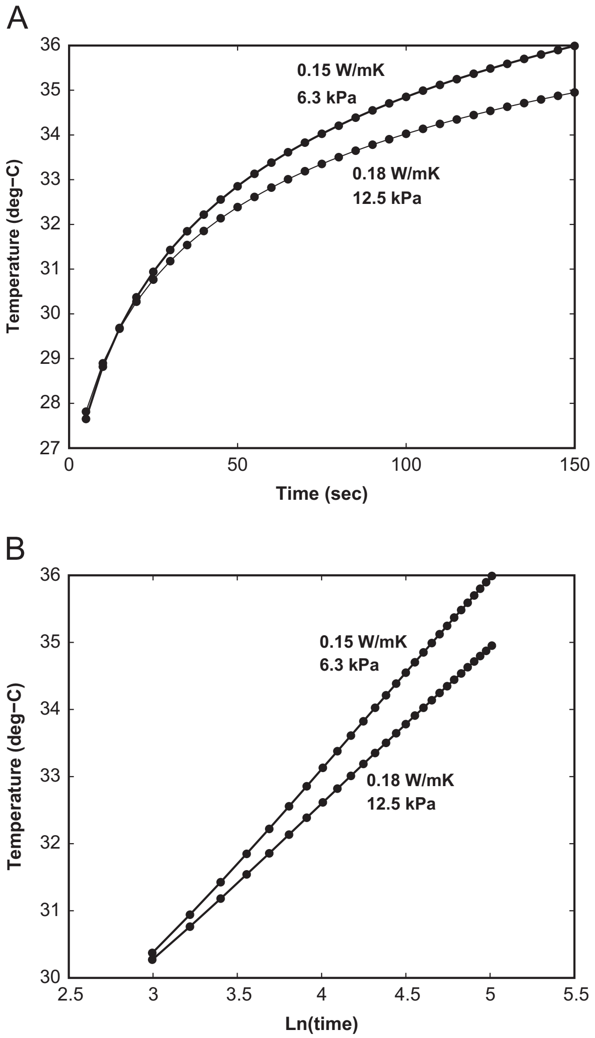

Fig. 1. (A) Temperature (°C) versus time (s) for the needle probe experiments on JSC-1A conducted at two different pressures (6.3 kPa and 12.5 kPa). Thermal conductivity obtained from each experiment is also shown in W/m K. Heater power was 5.30 W/m and 5.26 W/m, respectively. B: Temperature (°C) versus the natural logarithm of time (s) for the same set of experimental data with only the measurements after $t=20$ s were used.

Some of the advantages of the needle probe method are not applicable to planetary missions and vacuum chamber tests. Because of engineering requirements driven by the robotic deployment on planetary bodies, the thermal conductivity instruments on planetary missions deviate from the well established configuration of the needle probe used on earth (*e.g.*, Kömle et al., 2011; Zacny et al., 2013). Most notably, these probes are of greater diameter (1–2.5 cm) and length (30–50 cm). In addition, these probes are used for measuring materials that are ~100 times less thermally conductive than the earth's soils, for which the method was originally intended.

As we explain in detail in the next section, when a large-diameter probe is used for measuring materials of very low thermal conductivity, it requires a much longer measuring time, several tens (if not over a hundred) of hours. In case of the Apollo heat flow experiments, they used a 2.5-cm diameter probe and heated it for 40 h (Langseth et al., 1972). The long duration of experiment also causes a large portion of the heat emitted by the probe to travel along the probe itself and escape into the mechanism that deploys it. That negatively impacts the accuracy of the thermal conductivity determination (Blackwell, 1954; Presley and Christensen, 1997a). Because of these additional complexities, it is nearly impossible for the instruments on the aforementioned planetary missions to obtain the thermal conductivity as simple algebraic function of the heater power and the time rate of temperature increase. Sophisticated computer simulations of the heating experiments on the surfaces of the extra-terrestrial bodies, which involve a number of loosely-constrained parameters, are necessary for determination of the thermal conductivity of the regolith on these planetary missions (*e.g.*, Grott et al., 2010).

The present study proposes improvement in the data reduction scheme of the needle probe method so that much less time is required for measurements, even for large-diameter probes and low-conductivity (<0.01 W/m K) materials. Because of this improvement, *in-situ* thermal measurement of planetary regolith would become more practical for missions in which time management on the surface is critical. The improved data reduction algorithm would also help researchers expedite and simplify thermal conductivity measurements in vacuum chambers. We have carried out a suite of needle probe experiments on JSC-1A lunar regolith simulant (Schrader et al., 2010) in a vacuum chamber, and reduced the data using this new data reduction algorithm.

2. Theoretical basis for the needle probe method

Here we summarize the mathematical heat conduction model which serves as the theoretical basis for the thermal conductivity