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Compressional stress effect on thermal conductivity of powdered materials: Measurements and their implication to lunar regolith

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ABSTRACT

Thermal conductivity of powdered materials under vacuum conditions is a valuable physical parameter in the context of planetary sciences. We report results of thermal conductivity measurements of 90–106 μm and 710–1000 μm glass beads, and lunar regolith simulant using two different experimental setups for varying the compressional stress and the temperature, respectively. We found the thermal conductivity increase with the compressional stress, for example, from 0.003 to 0.008 $\mathrm{W\,m^{-1}\,K^{-1}}$ for the glass beads of 90–106 μm in diameter at the compressional stress less than 20 kPa. This increase of the thermal conductivity is attributed the areal enlargement of the contacts between particles due to their elastic deformation. The thermal conductivity increased also with temperature, which primarily represented enhancement of the radiative heat conduction between particles. Reduction of the estimated radiative conductivity from the effective thermal conductivity obtained in the first experiment yields the relation between the solid conductivity (conductive contribution through inter-particle contacts) and the compressional stress. We found that the solid conductivity is proportional to approximately 1/3 power of the compressional stress for the glass beads samples, while the regolith simulant showed a weaker exponent than that of the glass beads. We developed a semi-empirical expression of the thermal conductivity of the lunar regolith using our data on the lunar regolith simulant. This model enabled us to estimate a vertical distribution of the lunar subsurface thermal conductivity. Our model provides an examination for the density and compressional stress relationships to thermal conductivity observed in the in-situ measurements in Apollo 15 and 17 Heat Flow Experiments.

1. Introduction

From the past to the present in the Solar System, powdered materials have existed ubiquitously. For example, the planetesimals formed in the early solar nebula were composed of micron-sized dust particles. Many planetary bodies including moons and asteroids are covered by fine grained material called “regolith”. Under vacuum conditions, the powdered materials have much lower thermal conductivity than intact rocks, so that the powdered materials act as thermal blanket on the bodies. Determination of the thermal conductivity of the surface regolith and its distribution in depth direction is one of the key issues for understanding thermal processes within planetary bodies.

Concerning the Moon, the thermal conductivity of the surface regolith layer was measured as a part of Heat Flow Experiments in Apollo 15 and 17 missions (Langseth et al., 1972, 1973). It serves as an informative reference of thermal conductivity structure of lunar and other planetary regolith layers. In these experiments, two heat flow probes were emplaced in drilled boreholes at each site. Direct measurements of the thermal conductivity were carried out by activating electrical heaters on the probes. The resultant thermal conductivity of subsurface regolith ranged from 0.0141 $\mathrm{W\,m^{-1}\,K^{-1}}$ at the depth of 35 cm up to 0.0295 $\mathrm{W\,m^{-1}\,K^{-1}}$ at 233 cm depth. On the other hand, Langseth et al. (1976) estimated thermal diffusivity of the regolith using data on attenuation of probe’s periodic temperature induced by the annual temperature wave from the surface. Assuming a constant density and a constant specific heat of the regolith with depth, they revised the thermal conductivity values downward between 0.0091 and 0.0132 $\mathrm{W\,m^{-1}\,K^{-1}}$. The higher thermal conductivity deduced from the heater-activated measurements (Langseth et al., 1972, 1973) was considered to be affected by compression of the regolith (which means increase in bulk density of the regolith and compressional stress stored in the regolith media) due to the drilling process in the probe installation (Langseth et al., 1976; Grott et al.,

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2010). At present, the thermal conductivity around 0.01 W m^{-1} K^{-1} as estimated by Langseth et al. (1976) has been believed to be the typical thermal conductivity of the lunar subsurface regolith.

The thermal conductivity of the lunar regolith can be also estimated from cooling history of surface nighttime temperature. Keihm and Langseth (1973) reported that the thermal conductivity of upper a few centimeters of the lunar regolith layer is in the order of 0.001 W m^{-1} K^{-1}, and suggested that the there is rapid conductivity increase by an order of magnitude from the surface to a few tens cm depth. The subsurface thermal conductivity seems consistent with the conductivity inferred from the annual temperature wave analysis by Langseth et al. (1976). Vasavada et al. (2012) also found the similar abrupt change in the thermal conductivity using surface temperature data of lunar equatorial region obtained from Diviner Radiometer on-board Lunar Reconnaissance Orbiter. These previous works considered that the rapid change in the conductivity is related to the density increase with depth, and they derived empirical relationships between the density and conductivity to fit the surface temperature data. However, the derived density dependence and absolute values of the conductivity is not consistent with the thermal conductivity of regolith samples returned by the Apollo missions and measured in laboratories, which was lower than the subsurface conductivity by several factors even at a possible maximum density of 1950 kg m^{-3} (Cremers, 1971). A possible explanation of the depth dependent thermal conductivity is that the thermal conductivity of the deeper regolith is enhanced by self-weighted compressional stress in addition to the density (Horai, 1981). However, the quantitative dependence of thermal conductivity on compressional stress has not been investigated experimentally. This would give an important information for the determination of the thermal conductivity distribution in vertical direction of the lunar and other planetary surface regolith layers.

In this work, we measured thermal conductivity of powdered materials under vacuum conditions with controlling compressional stress within the samples. The derived compressional stress dependence of the thermal conductivity was utilized to estimate the vertical thermal conductivity structure of the regolith layers on the Moon.

2. Thermal conductivity of powdered materials

Heat transfer within powdered materials under vacuum conditions contains two contributions. One is thermal conduction within particles and across inter-particle contacts, and the other is thermal radiation through void spaces between the particles. Effective thermal conductivity k is expressed as,

$$k = k_{\mathrm{solid}} + k_{\mathrm{rad}}, \tag{1}$$

where k_{solid} is the solid conductivity, and k_{rad} is the radiative conductivity (Wechsler et al., 1972).

The solid conductivity is controlled by thermal conductance at the contacts between the particles and the array structure of the particles (or networks of the contacts). Significantly low contact conductance of the narrow contact area between the particles reduces the effective thermal conductivity compared to that of the solid material by several orders of magnitude. Some theoretical formulae for the solid conductivity were proposed concerning equal-sized spheres (Halajian and Reichman, 1969; Chan and Tien, 1973). However, they can be applied only to certain selected powders and packing structures, and have not been verified experimentally.

In our previous study (Sakatani et al., 2012), thermal conductivity of glass beads was measured under vacuum and a variation of the thermal conductivity in depth direction was detected in a vertically-extended sample container. The thermal conductivity increased by several factors within a depth range from 1 to 30 cm without effective density variations. A similar trend was identified from a laboratory experiment by Langseth et al. (1974) in a deeper depth range from 39 to 181 cm. Sakatani et al. (2012) concluded that the self-weighted compressional stress increases the inter-particle contact area (or solid conductivity) by elastic deformation of the particles. The experiments by Sakatani et al. (2012) and Langseth et al. (1974) suggested that the solid conductivity is dependent of the compressional stress with an exponent of 0.37–0.50. However, these exponent values were somewhat inaccurate, because the self-weighted stress distribution within the powdered materials packed in a container with finite horizontal dimensions was disturbed by frictional force between the particles and the inner wall of the container, and because evaluation of the radiative conductivity contributing to the measured effective thermal conductivity was insufficient. These issues are addressed in this work.

The thermal conductivity measured by experiments contains both solid and radiative contributions, as indicated by Eq. (1). Determination of each conductivity term is essential for understanding the heat transfer mechanism in the powdered materials. One of the methods for this is measuring temperature dependence of the thermal conductivity. The radiative conductivity depends strongly on temperature. Watson (1964) modeled radiative heat transfer between the particle surfaces as the radiation between multiple parallel plates. According to his model, the radiative conductivity is proportional to the third powder of temperature,

$$k_{\mathrm{rad}} = BT^3, \tag{2}$$

where B is a temperature-independent constant in W m^{-1} K^{-4} unit. An increase in the thermal conductivity with temperature can be primarily interpreted as increase of the radiative conductivity. Most investigators treated the solid conductivity as a constant independent of temperature (Merrill, 1969; Fountain and West, 1970; Cremers et al., 1970). Fitting of the equation of $k = k_{\mathrm{solid}} + BT^3$ to the temperature-dependent thermal conductivity data with k_{solid} and B being the free parameters yields the solid conductivity and the radiative conductivity (or coefficient B) for a given sample. In practice, the solid conductivity is also dependent on temperature, because the thermal conductivity of the solid material and elastic coefficients (Young's modulus and Poisson's ratio) also vary with temperature. According to the model by Halajian and Reichman (1969), the solid conductivity is directly proportional to the thermal conductivity of the solid material, while it varies with 1/3 power of the elastic coefficients. The former effect would be effective on the temperature dependence of the solid conductivity, so that we improve the solid conductivity expression by including the temperature dependence as $k_{\mathrm{solid}} = Ak_{\mathrm{m}}(T)$, where A is a non-dimensional constant independent of the temperature and k_{m} is the temperature-dependent thermal conductivity of the solid material. The temperature dependence of the effective thermal conductivity can be written as,

$$k = Ak_{\mathrm{m}}(T) + BT^3. \tag{3}$$

The values of A and B, representing the solid and radiative contributions, respectively, are estimated by the fitting of Eq. (3) with a known function $k_{\mathrm{m}}(T)$.

3. Experimental method

In order to investigate the effect of the compressional stress on the solid conductivity, two types of experiments were carried out. One is the thermal conductivity measurements under vacuum as a function of the compressional stress. This experiment is called