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Thermal conductivity of lunar regolith simulant JSC-1A under vacuum

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ABSTRACT

Many air-less planetary bodies, including the Moon, asteroids, and comets, are covered by regolith. The thermal conductivity of the regolith is an essential parameter controlling the surface temperature variation. A thermal conductivity model applicable to natural soils as well as planetary surface regolith is required to analyze infrared remote sensing data. In this study, we investigated the temperature and compressional stress dependence of the thermal conductivity of the lunar regolith simulant JSC-1A, and the temperature dependence of sieved JSC-1A samples under vacuum conditions. We confirmed that a series of the experimental data for JSC-1A are fitted well by our analytical model of the thermal conductivity (Sakatani et al., 2017). Comparison with the calibration data of the sieved samples with those for original JSC-1A indicates that the thermal conductivity of natural samples with a wide grain size distribution can be modeled as mono-sized grains with a volumetric median size. The calibrated model can be used to estimate the volumetric median grain size from infrared remote sensing data. Our experiments and the calibrated model indicates that uncompressed JSC-1A has similar thermal conductivity to lunar top-surface materials, but the lunar subsurface thermal conductivity cannot be explained only by the effects of the density and self-weighted compressional stress. We infer that the nature of the lunar subsurface regolith grains is much different from JSC-1A and lunar top-surface regolith, and/or the lunar subsurface regolith is over-consolidated and the compressional stress higher than the hydrostatic pressure is stored in the lunar regolith layer.

1. Introduction

The thermal conductivity of planetary surface materials is important for controlling the near-surface temperature distribution. Most planetary surfaces, including that of the Moon, are covered by fine grains called regolith. The thermal conductivity of regolith-like powdered materials is extremely low (on the order of 0.001 W m^{-1} K^{-1}) under vacuum, where thermal conduction and/or convection by remnant gas molecules are negligible. In situ measurements of the lunar surface temperature and thermal conductivity values measured by Apollo 15 and 17 heat flow experiments (HFEs) showed that the surface regolith layer has insulating characteristics (Langseth et al., 1976). Because of the low thermal conductivity of the surface regolith layer, the surface temperature of the Moon in the equatorial regions widely varies from 400 K in the daytime to 100 K or below during nighttime.

The planetary surface temperature is a good indicator of the surface thermal conductivity, and it can be used to estimate the physical properties of surface materials, such as grain size and density (or porosity), because the thermal conductivity of powders depends on several parameters of the grains. For example, Keihm and Langseth (1973) analyzed lunar surface temperature data acquired during Apollo HFEs, and they concluded that there are rapid increases in the thermal conductivity and density within a depth of a few centimeters of the lunar regolith layers. A similar rapid density gradient is suggested from the results of Diviner lunar radiometer experiments onboard the Lunar Reconnaissance Orbiter (Vasavada et al., 2012). In addition, ground-based thermal observations of asteroids show a systematic change of the thermal inertia ($I = \sqrt{k\rho c}$, where k is the thermal conductivity, ρ is the density, and c is the specific heat) with the size of the body (Delbo' et al., 2007). Gundlach and Blum (2013) attempted to estimate the grain size of surface regolith on 23 asteroids (including Ceres, Vesta, and Itokawa), Moon, Phobos, and Mercury, from the thermal inertia data using their thermal conductivity model (Gundlach and Blum, 2012). They found that the surface grain size is inversely related to the size of the body, or gravitational acceleration. Like this,

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infrared observation can give information about the physical condition of surface materials, which cannot be resolved by ground-based or orbital optical observation.

The Japanese asteroid sample return mission Hayabusa2 will arrive at C-type asteroid (162173) Ryugu in mid-2018 (Watanabe et al., 2017). The National Aeronautics and Space Administration (NASA) OSIRIS-REx probe will approach B-type asteroid (101955) Bennu just after the arrival of Hayabusa2 (Lauretta et al., 2015). Both missions carry thermal infrared observation instruments. Hayabusa2 has a thermal infrared imager TIR (Okada et al., 2017; Takita et al., 2017) and OSIRIS-REx has a thermal emission spectrometer OTES (Christensen et al., 2017). From these missions, the detailed surface distribution of the thermal inertia of the asteroids will become known. To estimate the physical properties of surface regolith from the thermal inertia, a thermal conductivity model applicable to the regolith-like materials on planetary surfaces is required. We have proposed a thermal conductivity model for mono-sized granular materials under vacuum (Sakatani et al., 2017). We tested its validity using the experimental results for glass beads. We also suggested that the microscopic surface roughness of grains and radiative scattering in granular media have important effects on the estimate of the thermal conductivity. To apply this model to planetary regolith, calibration with the experimental data of natural samples is essential.

In this study, we investigate the thermal conductivity of JSC-1A, which is a simulant for lunar mare regolith, under vacuum conditions. The dependences of the thermal conductivity on temperature, density, and compressional stress are considered. We also discuss the effect of the grain size distribution on the thermal conductivity. Finally, the applicability of our thermal conductivity model (Sakatani et al., 2017) to JSC-1A is investigated.

2. Samples

In 1994, The NASA Johnson Space Center produced lunar mare regolith simulant JSC-1 from a basaltic pyroclastic deposit located in the San Francisco volcanic field (McKay et al., 1994). JSC-1A was subsequently produced in the same manner as JSC-1 but with particle sizes less than 1 mm. The physical and geotechnical properties of JSC-1A, such as the grain size distribution, density, shear strength, and compressibility, have been investigated (Alshibli and Hasan, 2009; Arslan et al., 2010; Zeng et al., 2010), and they are similar to those of lunar regolith samples. Therefore, JSC-1A is a potential material to simulate the mechanical properties of the lunar surface. Parzinger et al. (2012) measured the thermal conductivity of JSC-1A under vacuum (10^{-3} Pa) from 150 to 650 °C, which are higher temperatures than those of the lunar surface. They reported that the thermal conductivity ranges from 0.008 to 0.033 W m^{-1} K^{-1}, which is higher than laboratory measurements of lunar regolith samples (e.g., Cremers et al., 1970). Hütter (2011) measured the thermal conductivity of JSC-1A under various ambient pressures, and obtained a thermal conductivity of about 0.0037 W m^{-1} K^{-1} at bulk density of 1700 kg m^{-1} under vacuum (10^{-2} Pa). However, the temperature dependence of the conductivity within lunar and planetary temperature ranges, and the effect of compressional stress were not reported.

We used JSC-1A for the thermal conductivity measurements and demonstration of the applicability of the thermal conductivity model (Sakatani et al., 2017). Fig. 1 shows the cumulative weighted fraction of the grain size of JSC-1A measured by the sieving technique. The probability density function of the grain size is well represented by a log-normal distribution:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}x} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right] \quad (1)$$

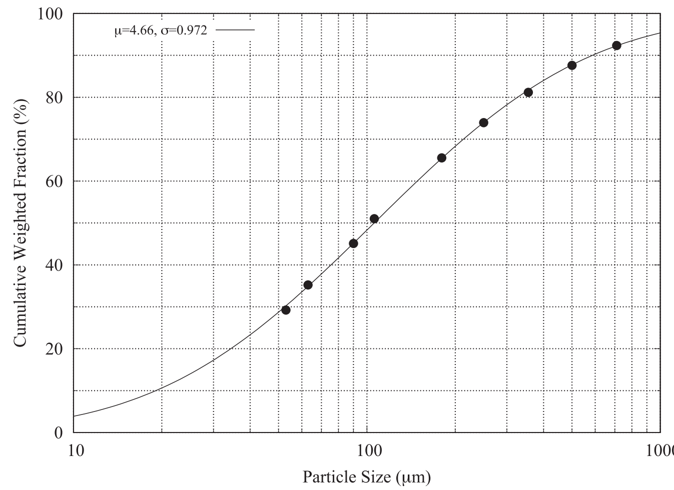

Fig. 1. Cumulative weighted fraction of JSC-1A. The solid curve represents fitting of Eq. (2) to the experimental data.

where x is the grain size, and σ and μ are parameters that describe the shape of the distribution with median and variance of $\exp(\mu)$ and $[\exp(\sigma^2) - 1]\exp(2\mu + \sigma^2)$, respectively. The cumulative distribution function is determined by integrating Eq. (1):

$$F(x) = \frac{1}{2}\left(1 + \mathrm{erf}\frac{\ln x - \mu}{\sqrt{2\sigma^2}}\right) \quad (2)$$

Least-squares fitting of Eq. (2) gives $\mu = 4.66 \pm 0.01$ and $\sigma = 0.972 \pm 0.006$, where x, e^{μ}, and e^{σ} have units of μm. Therefore, the median grain size of JSC-1A is estimated to be $\exp(\mu) = 106$ μm, which is consistent with the report of Arslan et al. (2010), who found that the median is about 100 μm.

We also measured the thermal conductivities of the prepared sieved samples. Comparison with the thermal conductivity of original JSC-1A has an important role for evaluating the effect of the wide grain size distribution, and comparison with the thermal conductivity of spherical beads aids in determining the effect of the grain shape on the thermal conductivity.

3. Thermal conductivity of JSC-1A

In this section, we report the thermal conductivities of two JSC-1A samples with different packing densities as a function of temperature. In Section 4, the effect of the external compressional stress on the thermal conductivity of JSC-1A will be discussed.

3.1. Measurement method

The thermal conductivity of JSC-1A was measured by the line heat source method (Carslaw and Jaeger, 1959). This method has frequently been used for powdered materials (e.g., Cremers et al., 1970; Fountain and West, 1970; Hütter and Kömle, 2012; Presley and Christensen, 1997b; Sakatani et al., 2012, 2016). In this method, the thermal conductivity of a sample can be estimated from the non-steady temperature change of a line heat source within the sample. After a sufficiently long heating time, analytical solution predicts that there is a linear relationship between the temperature and the natural logarithm of time:

$$T = s \ \ln t + b \quad (3)$$

where T is the temperature of the heater at heating time t, s is the slope, and b is a constant. The slope s is related to the thermal conductivity of the surrounding material k by

$$k = \frac{q}{4\pi s} \quad (4)$$