THERMAL CONDUCTIVITY MODEL OF POWDERS UNDER VACUUM BASED ON EXPERIMENTAL STUDIES.

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Introduction: The thermal conductivity of powdered media is characteristically very low in vacuum, and is effectively dependent on many parameters of their constituent particles and packing structure. Understanding of the heat transfer mechanism within powder layers in vacuum and theoretical modeling of their thermal conductivity are of great importance for several scientific and engineering problems. In the context of planetary sciences, thermal conductivity of regolith layers on air-less planetary bodies controls near-surface temperature. Thermal evolution of porous and dust-aggregated planetesimals depends on their thermal properties.

Thermal conductivity of powdered material layers under a vacuum environment depends on many parameters, such as grain size, porosity, compressional stress, and temperature [1]. Under vacuum, effective thermal conductivity is dominated by “solid conductivity” originating from thermal conduction through inter-particle contact, and “radiative conductivity” originating from thermal radiation through void spaces between the particles. Because both the solid and radiative conductivity vary widely depending on intricately interconnected parameters and the relationship between them has not been systematically investigated, it has been difficult to predict the effective thermal conductivity of powders under vacuum. A model that comprehensively relates the thermal conductivity of powders to their physical parameters and ambient conditions is required.

In this study, we developed a comprehensive model for the thermal conductivity of powdered materials under vacuum conditions based on systematic experimental studies using analogue materials. We report on the experimental results to reveal heat taransfer mechanism in powders under vacuum. Theoretical modeling of the effective thermal conductivity of powdered materials and comparison with our experimental data are also presented.

Experiments: Six types of glass beads with different particle size were used as analogue materials. Table 1 shows some sample properties. Five FGB glass beads were used for investigating the effect of the grain size. EMB glass beads had highly adhesive nature, so that they were used to investigate the effect of the packing porosity as well as the grain size.

Thermal conductivity of these samples was measured by the line heat source method. A nichrome wire (180 μm in diameter) was suspended in a sample container and its temperature during the heating was measured by a K-type thermocouple.

Table 1: Sample properties. $k_m(T)$ is temperature-dependent thermal conductivity of constituent glass.

ID	Grain size [μm]	Porosity	$k_m(T)$ [W/mK]
FGB-20	710-1000	0.42	8.50×10^{-4} T + 0.855
FGB-40	355-500	0.42	
FGB-80	180-250	0.40	
FGB180	90-106	0.42	
FGB-300	53-63	0.42	
EMB	< 10	0.50-0.86 (controlled)	5.10×10^{-4} T + 1.406

Vacuum level during the measurements was less than 10^{-2} Pa. A vacuum chabmer was placed in a thermostatic chamber so that we could control temperature of the whole system from 250 to 330 K. Temperature dependent thermal conductivity data were fitted by a theoretical equation of $k(T) = A\, k_m(T) + B\, T^3$, where T is temperature, $k_m(T)$ is a thermal conductivity of solid materials given in Table 1, A and B are fitting variables. The first term represents solid conductivity, and the second is radiative conductivity. This fitting procedure enabled us to evaluate solid and radiative conductivity separately for each sample, and to investigate the effect of the grain size and porosity on the solid and radiative conductivities.

Experimental data: We briefly describe the experimental results. The data were shown in Fig. 2 in terms of the grain size and porosity, together with our model estimations.

Solid conductivity of the FGB glass beads appeared to be either independent of the particle size or slightly increased with the particle size. However, EMB glass beads had higher solid conductivity than the FGB glass beads by an order of magnitude. This large discrepancy is expected to be caused by strong adhesive nature of the small EMB particles, which enhanced inter-particle contact area by the adhesive (van der Waals) force in addition to self-weighted compressional force. Moreover, we found microscopic roughness on FGB particles by SEM images, which reduces the contact area or solid conductivity.

Radiative conductivity of FGB glass beads increased with increasing the grain size. In addition, we also found that the radiative conductivity becomes higher with increasing the porosity from the data for

EMB glass beads. These results suggested that the radiative conductivity increases with the void size between the particles.

Theoretical model: We assume that the particles have spherical shape and uniform size; one-dimensional heat flow occurs within the particle bed; and conductive and radiative heat transfers take place in parallel, so that effective thermal conductivity is expressed as the sum of solid and radiative conductivity as $k = k_{solid} + k_{rad}$. Detailed formulation of the model is described in Sakatani et al. [6].

Bacis concept for the solid conductivity model is parallel and serial connections of the thermal conductance at the inter-particle contacts and inside the particles, packed in a cube of unit volume. Network of the contacts was characterized by coordination number as a function of the porosity. We used a model by Suzuki et al. [2]. Thermal conductance at the contact was modeled by a theory of Cooper et al. [3], and radius of the contact area was given by JKR theory [4], which includes the effects of both external compressional force and adhesive force. Microscopic roughenss on particle surface affects the contact thermal conductance. We introduce a factor ξ representing the restriction of the contact area due to the surface roughness. For perfectly smooth particles, ξ equals to unity.

Radiative heat transfer through the void spaces in powdered media was modeled by one-dimensional thermal radiation between multiple infinitely-thin parallel planes. In this case, the radiative conductivity is proportional to the cubic temperature and the distance between adjacent planes, or effective radiative heat transfer distance. This distance can be scaled by geometrical void size between the particles, which was modeled based on Piqueux and Christensen [5] in terms of the grain size and porosity. The scaling factor, ζ, was introduced.

Comparison with experimental data: Figure 1 shows comparison of solid and radiative conductivity models with the experimental data in terms of the particle diameter and porosity. For FGB glass beads, we found that the modeled solid conductivity with $\xi = 1$ is higher than all of the experimental data. Preferred values of ξ for the FGB glass beads range from 0.29 to 0.83, which would be affected by the surface roughness on FGB beads. On the other hand, the model with $\xi = 1$ is agreed with the experimental data for EMB glass beads, contributed from the smooth surface nature of the EMB beads.

Radiative conductivity model with $\zeta = 1$ is lower than the experimental data for FGB and EMB glass beads. For FGB glass beads, the value of ζ, which is a measure of the deviation in the mean free path of photons from the geometrical void size, increases with decreasing particle size. This would be caused by radiative scattering (transmission) for the smaller particles. For EMB glass beads, $\zeta = 15$ is fitted well to the experimental data. This high value of ζ would reflect aggregation of the small particles, which yields large void spaces between the aggregates.

Conclusions: We constructed a new thermal conductivity model for powders under vacuum. Comparison with the experimental data suggested that careful determinations of ξ and ζ parameters is important. We are experimentally investigating the probable range of these parameters for natural samples.

Our model can be used to determine the thermal conductivity of powdered materials using a given set of physical parameters. Conversely, we can constrain the parameters from the thermal conductivity or related thermal properties of a specific sample, or planetary surface regolith. Hayabusa2 mission is planning to observe an asteroid 162173 Ryugu by a thermal infrared imager, TIR [7]. Estimated thermal inertia relates to the physical properties, such as grain size, of surface regolith. Applying our model, the effects of the grain size and other parameters on thermal inertia and their detectability by TIR measurements are being examined in preparation for the rendezvous with the asteroid Ryugu.

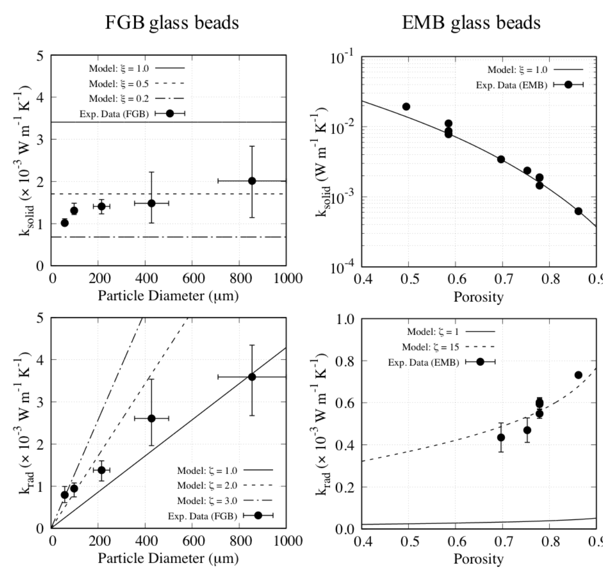

Figure 1: Modeled solid conductivity (top) and radiative conductivity (bottom) at 300 K, compared with the experimental data for FGB and EMB glass beads. Effects of ξ and ζ are shown. Surface energy γ is set at zero for FGB glass beads and 0.02 J/m^{-2} for EMB glass beads.

References: [1] Wechsler et al. (1972), in *Thermal Characteristics of the Moon*. [2] Suzuki et al. (1980), *Kagaku Kogaku Ronbunshu*, 6, 59-64. [3] Cooper et al. (1969), *Int. J. Heat Mass Transfer*, 12, 279-300. [4] Johnson et al. (1971), *Proc. R. Soc. Lond. A. Meth. Phys. Sci.* 324, 301–313. [5] Piqueux and Christensen (2009), *JGR*, 114. [6] Sakatani et al. (submitted), *AIP Adv.*. [7] Okada et al. (2016), *SSR*.