EXPERIMENTAL STUDY OF THERMAL CONDUCTIVITY FOR REGOLITH USING GLASS BEADS AS ANALOGOUS MATERIAL. N. Sakatani[1], K. Ogawa[1], Y. Iijima[1], R. Honda[2], and S. Tanaka[1], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara, Chuo-ku, Kanagawa 229-8510, Japan, [2]Kochi University, 2-5-1 Akebono-cyo, Kochi 780-8520, Japan.

Introduction: The heat flow measurement on the Moon is one important technique for exploring thermal state and evolution of the lunar interior. The heat flow is given by measuring the subsurface thermal conductivity and temperature gradient. Accurate determination of the thermal conductivity is necessary to estimate the heat flow value exactly.

In Apollo 15 and 17 Heat Flow Experiments, the thermal conductivities at several depths were measured on the four sites on the Moon. As a result, Langseth *et al.* reported that the thermal conductivity of the subsurface increases with depth: 0.0141 W/mK at 35 cm and 0.0295 W/mK at 233 cm from the surface [1]. They concluded that the conductivity variation would be due to the regolith disruption during the drilling process for inserting the probes, and finally they revised the values to constants for each site, between 0.009 W/mK for Apollo 15 probe 2 and 0.013 W/mK for Apollo 17 probe 1 [2]. However, it has not been clarified whether the regolith conductivity varies with depth as a practical matter. Understanding of parameter dependencies of the thermal conductivity is not enough for powder media, such as the lunar regolith. The conductivity possibly varies with depth due to change of bulk density, particle size, and pressure applied with depth. In this study, we measured the thermal conductivity of powder media at several depths to verify degree of above-mentioned parameter dependence using glass beads as an analogous material of the lunar regolith.

Method: For the thermal conductivity measurements, glass beads samples in four diameter ranges were used: 53-63, 90-106, 355-500, and 710-1000 μm. The spherical shape and almost uniform size of beads made the same porosity ~38% in the four cases. The line heat source method [3] was used for thermal conductivity measurements. The sensor consists of a line heater providing heat into the beads and a thermocouple measuring temperature on the center of the heater line. The thermal conductivity is estimated from the temperature rising rate of the heater. In order to minimize the deviation from an ideal line heat source, a thin Nichrome wire (180 μm in diameter) was used for the heater because of its low thermal conductivity. A thin alumel-chromel wire (100 μm in diameter) was used for the thermocouple whose thermal conductivity is also sufficiently low, so that undesired heat leaks through the metal lines were considered negligible. A schematic of the sample container is shown in Figure 1. This container has four measurement points arranged in depth order, which can directly detect the conductivity variation with depth. Gas pressure was configured to less than 10^{-3} Pa during measurements, under which the heat transfer by gas is considered negligible by experimental and theoretical studies. The experimental conditions are summarized in Table 1.

Results and Discussions: Experimental results in each beads diameter and depth were plotted in Figure 2. It is summarized that the glass beads under vacuum conditions have the same order of conductivity as that of the regolith measured on the Moon. The thermal conductivity increased linearly with particle size at all depths. This trend may be attributed to the radiative heat transfer. Since the porosity is almost the same for all samples, the size of pores broadened with particle size. Past theoretical studies [4] indicated that the radiation contributes to the bulk thermal conductivity correlating proportionally with the pore size.

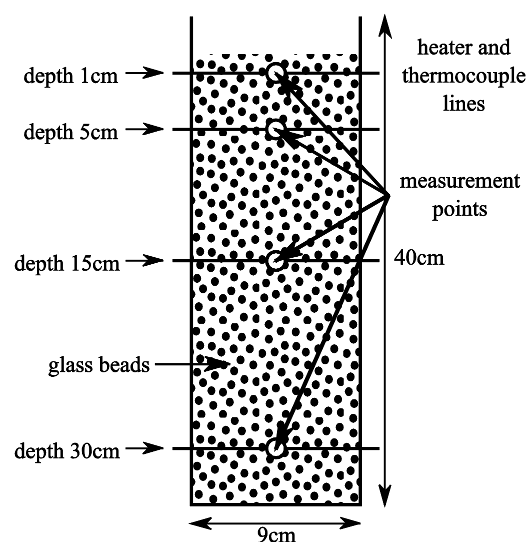
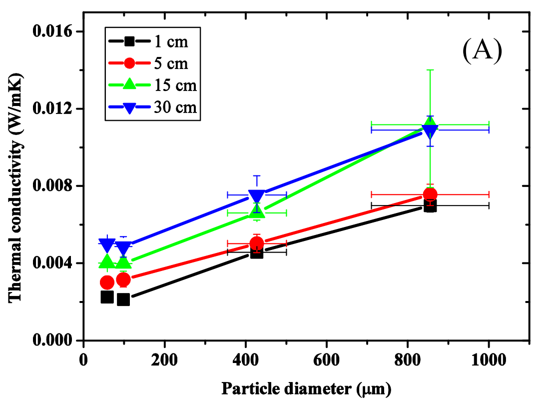


Figure 1: The sample container for the thermal conductivity measurements of the glass beads.

Table 1: Summary of the experimental conditions.

Gas pressure	Temperature	Particle size	Porosity	Measurement depth
$< 10^{-3}$ Pa	~20 degC	53-63 μm	~0.38	1 cm
		90-106 μm		5 cm
		355-500 μm		15 cm
		710-1000 μm		30 cm

The significant conductivity increase was found in deeper layers to 30 cm, although the bulk density of the beads samples is almost the same at all depths. In the powder media, physical contact points between the bead particles perform as thermal resistances. The contact area would become large in the deeper layers because of the higher stress at the points. The broadened contacts perform wide heat paths through which heat can effectively flow to next particles, and then the bulk thermal conductivity becomes high.



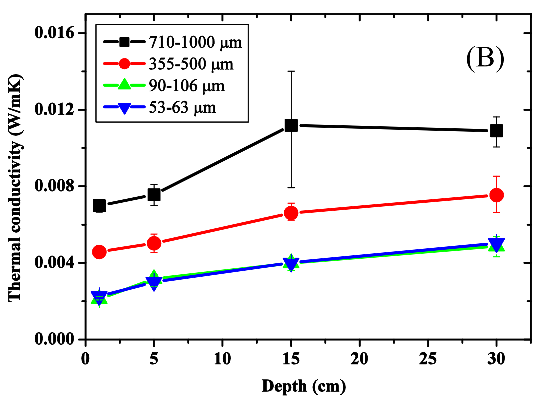


Figure 2: Relations between the thermal conductivity and the particle size (A) and the measurement depth (B) are shown. The horizontal error bars in (A) represent the bead diameter ranges of each sample and the vertical error bars in both plots represent fluctuations in three measurements, respectively.

Halajian and Reichman [5] modeled the thermal conductivity considering the mechanical strain of elastic spherical materials by the applied stress. It was found that their theoretical expression agreed with the measured conductivity as a function of the depth. This agreement supports our understanding that the measured conductivity increase with depth is due to the change of contact area by stress.

In this study, the conductivity variations with the particle size and load were verified. Considering the gravity difference between the Earth (~9.8 m^2/s) and the Moon (~1.6 m^2/s), an upper load at 30 cm in depth on the Earth corresponds to that at 180 cm in depth on the Moon for example. The average particle size of the lunar regolith is estimated to be ~70 μm [6]. Our experimental results indicate that the thermal conductivity of glass beads under lunar environment is lower than the results in Apollo missions. This disagreement would be caused by the difference of other parameters (such as particle shape, size distribution, bulk density, etc.). However, it was obviously revealed that there are the effects that increase the thermal conductivity with depth on the Moon.

References: [1] M.G. Langseth *et al.* (1973) *Apollo 17 Pre. Sci. Rep.*, NASA SP-330, 9. [2] M.G. Langseth *et al.* (1976) *Proc. Lunar Sci. Conf.*, 7, 3143. [3] M.A. Presley and P.R. Christensen (1997) *J. Geophys. Res.*, 102, 6535. [4] R.B. Merill (1969) *NASA Tech. Note*, D-5063. [5] J.D. Halajian and J. Reichman (1969) *Icarus*, 10, 179. [6] W.D. Carrier *et al.* (1991) in *Lunar Sourcebook*, Cambridge Univ. Press.