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# Development and evaluation of heat flow probe for the precise measurement of lunar and planetary heat flow

HORIKAWA, Yamato[1*] ; TANAKA, Satoshi[2] ; SAKATANI, Naoya[1] ; TAKITA, Jun[3]

[1]The Graduate University for Advanced Studies, [2]Japan Aerospace Exploration Agency, [3]The University of Tokyo

The precise measurement of lunar and planetary heat flow contributes to a better understanding of bulk composition and thermal history of the solid bodies. In order to conduct the in situ measurement, a high speed penetration probe, penetrator, which can be buried into a depth of 1 to several meters, has been developed. Since the shock durability at the penetration and the weight saving are required prior to scientific measurements, the heat flow sensors are installed on the surface of the penetrator. However, the sensors must have an uncertainty by disturbances of temperature distribution around the penetrator due to a large difference of thermal conductivities between the penetrator and the surrounding regolith.

In this study, we propose to develop an extension mechanism of needle probes from the buried penetrator which can avoid the thermal disturbance and measure heat flux with an uncertainty better than 10%. The temperature sensing part is required to be placed at a distance as far as possible from the penetrator body. Although the theoretical solution has been obtained to estimate thermal conductivity of the particulate material at the tip part of the probe, no research has yet been carried out to measure thermal conductivity of regolith by the needle probes whose temperature sensing parts are at the tip part. We developed a prototype model of the probe and evaluated the measurement uncertainty of thermal conductivity of glass beads as the regolith simulant material under vacuum condition.

The prototype of the needle probe consists of a wire heater, a K-type thermocouple, a stainless pipe as the needle probe's sheath, and epoxy resin fixing the heater and the thermocouple in the pipe. The length of the probe is 10cm which is the equivalent size of inner diameter of the penetrator body. Thermal conductivity of the glass beads under 200Pa can be controlled to be about 0.02W/m/K, which is almost the same thermal conductivity of the lunar environment at a depth of 1 to several meters. The needle probe was placed at the center of the sample container and surrounded by three sets of line heat source conductivity sensors for reference calibration.

Under 200Pa, we obtained 0.0165W/m/K by the theoretical solution of the probe, and 0.0207W/m/K by the average values of three line heat source sensors. The measurement uncertainty of thermal conductivity by the probe was calculated to be about 31%. However, the thermal conductivity by the probe can't be estimated directly from the theoretical solution because the conditions of the solution differ from the properties of the actual probe, such as the diameter of the probe, the thermal contact between the probe and the glass beads, and the axial heat flow of the probe. Therefore, we conducted the heat-transfer simulation whose numerical model included the properties of the actual probe, and estimated the thermal conductivity by the probe from increases in temperature after heating of the simulation. In addition, we confirmed an agreement with the temperature profiles of the theory and the simulation whose model condition was the same as the condition of the theory.

As a result, the thermal conductivity by the probe was estimated to be 0.0212W/m/K, and the measurement uncertainty of thermal conductivity was calculated to be about 3%, which was well satisfied with the requirement uncertainty of better than about 5%. In future, in order to estimate thermal conductivity of the regolith in lunar and planetary surface layer by using our probe, the measurement uncertainties are required to determine for the probable thermal conductivities by using the heat-transfer simulation.

Keywords: heat flow, thermal conductivity, moon, planet, penetrator, needle probe