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# 月面製鉄模擬実験のための月面環境再現装置の製作

# Construction of a lunar environment reproduction device for lunar ironmaking simulation experiments

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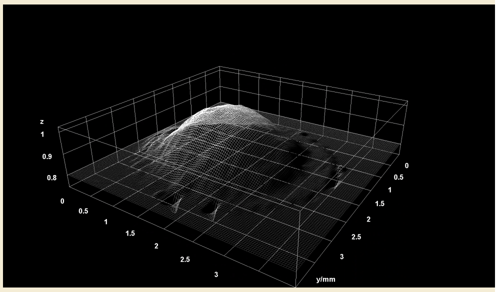
**Abstract:** In vacuum heating experiments of lunar regolith simulants aimed at realizing in-situ resource utilization (ISRU), it is important to evaluate bulk density (packing ratio), which affects thermal conductivity, and to understand the tilt of the irradiated surface during laser heating. In recent years, research into extracting and utilizing resources from regolith on celestial bodies' surfaces has been progressing around the world. Our laboratory is also conducting experiments to extract iron (Fe) from lunar regolith simulants using electromagnetic radiation (e.g., laser). Previous studies have shown that pellets with fewer voids absorb laser energy more efficiently and melt more easily than powders heated in vacuum with lasers, compared to pellets compressed and molded from the powder. Previous research on powder thermal conductivity has reported that as bulk density increases, solid-state thermal conduction between particles increases and radiative thermal conduction decreases. However, samples are often packed in the atmosphere, which leaves air spaces remaining in the powder. Even when a vacuum is applied after packing, the air in the voids is not completely expelled, which can result in changes to the measured thermal conductivity.To address this issue, this study developed a new device capable of packing lunar regolith simulant in a high-vacuum environment equivalent to that of outer space, making it possible to measure bulk density and angle of repose in a high vacuum. This will enable a quantitative evaluation of the packing state of the sample, with the aim of understanding the thermal conduction characteristics and improving energy efficiency in the laser heating process in a vacuum.



**Keywords:** ISRU, Lunar resource, angle of repose, bulk density

## 1. Introduction

In vacuum heating experiments of lunar regolith simulants aimed at realizing in-situ resource utilization (ISRU), it is important to evaluate bulk density (packing ratio), which affects thermal conductivity, and to understand the tilt of the irradiated surface during laser heating. In recent years, research into extracting and utilizing resources from regolith on celestial bodies' surfaces has been progressing around the world. Our laboratory is also conducting experiments to extract iron (Fe) from lunar regolith simulants using electromagnetic radiation (e.g., laser). Previous studies have shown that pellets with fewer voids absorb laser energy more efficiently and melt more easily than powders heated in vacuum with lasers, compared to pellets compressed and molded from the powder. Sakatani et al.(2018)1), reported that increasing bulk density in lunar regolith simulant (JSC-1A) increases interparticle solid-state thermal conduction and decreases radiative thermal conduction. However, in that study, the sample was packed in the atmosphere, which meant that air layers remained in the powder, and even when a vacuum was applied after packing, the air in the voids was not completely expelled, which could result in changes to the measured thermal conductivity. To solve this issue, this study created a new device that can pack lunar regolith simulant in a high-vacuum environment equivalent to that of outer space, making it possible to measure bulk density and angle of repose in a high vacuum. This will enable a quantitative evaluation of the packing state of the sample, with the aim of understanding the thermal conductivity characteristics and improving energy efficiency in the laser heating process in a vacuum.

## 2. Experiment

### 2.1. Experimental Apparatus and Methods

A schematic diagram of the experimental equipment used in this study is shown in **Fig.1**.To calculate bulk density, it is necessary to measure both the mass and pile shape of the powder. Mass was measured using a load cell installed below the powder filling section. For the pile shape, height was measured using a photoelectric ranging sensor placed above the powder, and the powder's outline was obtained through image analysis, allowing shape evaluation using the angle of repose. This allows comparison and verification with the measurement results from the photoelectric ranging sensor. The height data obtained by the photoelectric ranging sensor was input as an analog signal into a digital voltmeter and sent to a PC via serial communication, after which calibration was performed and volume and shape information was calculated. Mass data was also obtained from the load cell output via the A4988 module and Arduino Uno, and similarly sent to the PC via serial communication for recording.

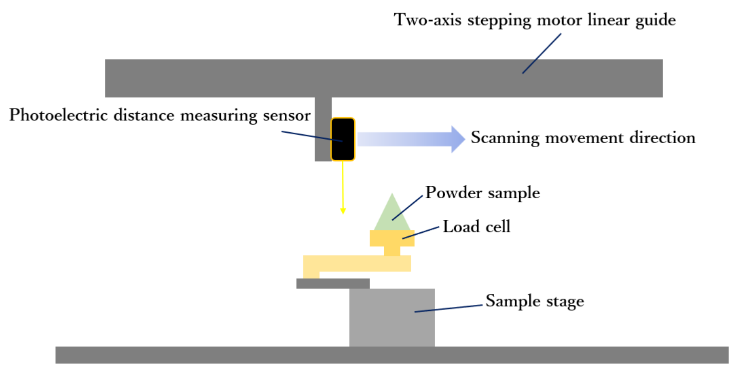



**Figure 1.** Schematic diagram of the equipment used in the experiment.

### 2.2. Sample

The sample used in the experiment was a mineral composed mainly of magnetite collected from the Sanpou Mine in Okayama Prefecture. This mineral was ground into powder and dried at 120°C for one day before use in the experiment.

## 3. Experimental results and analysis-proofreading methods

The data obtained in the air experiment was saved in CSV format and converted into a calibrated text image using Fiji (ImageJ).The text image was then input into the "Interactive 3D Surface Plot v2.4" module of Fiji to reconstruct the powder's three-dimensional shape **(Fig.2)** .

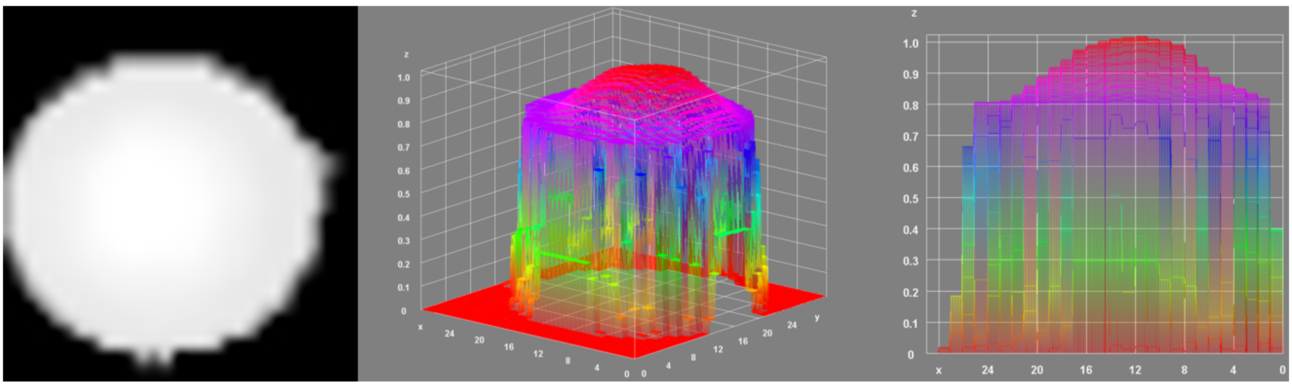


**Figure 2.** Left figure: Text image / Center and right figure: Powder outline.

Next, we constructed a system that captures the general shape of the powder with a USB camera and analyzes it using Python's OpenCV library. Specifically, we captured video from the camera in real time and used binarization processing to clarify the shape of the powder. Furthermore, we extracted the black and white boundary lines from the binarized image, allowing us to calculate the inclination angle of the powder from the boundary shape.

## 4. Conclusion

In this study, we developed a new device capable of precisely measuring bulk density and angle of repose in a high-vacuum environment, which are important parameters for the lunar regolith simulant heating experiment in a vacuum for ISRU. The device combines mass measurement using a load cell and height measurement using a photoelectric ranging sensor, as well as image analysis using a USB camera and Python's OpenCV, enabling quantitative evaluation of the powder's three-dimensional shape and tilt angle. The obtained measurement data was reconstructed in three dimensions using Fiji (ImageJ) and compared with the sensor measurements. This system allows accurate understanding of the sample packing state in a vacuum, enabling the acquisition of basic data useful for evaluating thermal conductivity characteristics during laser heating and improving energy efficiency.

## Conflicts of Interest

The authors state no conflict of interest.

## References

1) Sakatani et al. "Thermal conductivity of lunar regolith simulant JSC-1A under vacuum." *Icarus* **2018**, *309*, 13-24.