Determination of Thermal Effusivity of Lunar Regolith Simulant Particle Using Thermal Microscopy

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Abstract
This study aimed to measure the thermal effusivity distribution on a lunar regolith simulant (FJS-1) using a thermal microscope and to calculate the average thermal effusivity and thermal conductivity using density and specific heat. Moreover, discussions were conducted based on the results of the microstructural analysis of the sample. The FJS-1 particles were embedded in an epoxy resin and polished to a mirror finish. The samples were analyzed using scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (SEM–EDS). X-ray diffraction (XRD) was performed to identify the mineral phases in FJS-1. The results of SEM–EDS and XRD showed that a single sand particle was composed of several minerals, such as anorthite and olivine. Then, the thermal microscope was used to obtain the distribution of the thermal effusivity of a particle from the mirror-finished sample in a 1×1 mm² area with intervals of 10 μm. The measured thermal effusivity correlates with the SEM image of the sample. Anorthite has a small thermal effusivity of 1.99 ± 0.31 kJ·s⁻⁰·⁵·m⁻²·K⁻¹, while olivine has a large thermal effusivity of 2.73 ± 0.35 kJ·s⁻⁰·⁵·m⁻²·K⁻¹. In both cases, the thermal effusivity was found to be of the same order of magnitude as the reported values. The average thermal effusivity and conductivity of a single particle were determined to be 2.4 ± 0.6 kJ·s⁻⁰·⁵·m⁻²·K⁻¹ and 2.6 ± 1.3 W·m⁻¹·K⁻¹, respectively, based on the proportion of existing phases.

Keywords FJS-1 · Lunar regolith simulant · Thermal conductivity · Thermal effusivity · Thermal microscope

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1 Introduction

Landing on the surface of a planetary object, such as a moon or asteroid, can cause regolith particles to fly up and stick to the spacecraft. It is essential to consider the thermal interaction between the regolith and spacecraft and reflect it in the design of the spacecraft to ensure the success of a mission. For example, the heat emission performance of spacecraft might be changed when regolith is deposited on the spacecraft radiator. In case the heat emission performance of the spacecraft is degraded by regolith adhesion, the temperature of the spacecraft will increase, and the probability of failure of the onboard equipment becomes higher. Therefore, the effect of regolith on the heat emission performance of the radiator should be investigated analytically, and the spacecraft should be designed in consideration of the thermal effect of the regolith. For this purpose, the thermophysical properties of regolith particles (i.e., properties of particles smaller than 1 mm in diameter) are necessary, as well as the optical properties such as albedo and emissivity of the particles.

There have been many reports on the thermophysical properties of lunar regoliths and their simulants [1–10]. All of these values have been measured from a sample consisting of many particles or rocks, which can be affected by porosity, density, and mineral composition [7, 9]. However, the thermophysical properties of a single regolith particle are also required when designing the spacecraft.

Recently, techniques for measuring the thermophysical properties of small areas have been developed based on the thermoreflectance method. Thermal microscopy is one of the methods used to measure thermal effusivity in the area of 10 μm [11–15]. Hatori et al. [12] reported an example of thermal microscopy for granular materials. In their study, the sample was an alumina film electrodeposited on molybdenum sheets, and the thermal effusivity was measured over an area of 140 × 195 μm². They obtained the average thermal effusivity of a single particle to be 1220 J·s⁻⁰·⁵·m⁻²·K⁻¹. The standard deviation was estimated to be around 320 J·s⁻⁰·⁵·m⁻²·K⁻¹, which amounted to 26% of the average value. The roughness of the sample surface affected the reliability of the measurement. Therefore, mirror polishing of the specimen surface would allow the thermal microscope to be used more accurately on particles with diameters smaller than 1 mm. Furthermore, the average thermal effusivity can be understood from the distribution of the thermal effusivity and the corresponding particle microstructure. Therefore, this study aims to measure the thermal effusivity of a lunar regolith simulant with a mirror-polished surface using a thermal microscope and to discuss the validity of the measured values with the results of the microstructural analysis of the samples. The measurement technique in this study can also be applied to extra-terrestrial samples to understand the planetary evolution in the future.

2 Experimental

2.1 Sample

The lunar regolith simulant FJS-1 was used as the sample to simulate the lunar regolith collected by Apollo 14. FJS-1 is recommended for use as a matrix in excavation
and flow, drilling, abrasion, and wear. Low-g tests show a high angle of repose with relatively angular particles and reasonable particle size distribution [16]. FJS-1 was mainly composed of crystalline basaltic lava, and the main minerals present in it were plagioclase, pyroxene, olivine, ilmenite, etc. The maximum particle size is 5 mm, and the median particle size is 70 μm [5]. The sample was sieved to select particles with diameters of > 150 μm, which size was considered large enough for the measurement by thermal microscope. The sieved particles were placed in a container with a diameter of approximately 10 mm and filled with epoxy resin. Then, the samples were re-filled with resin together with a fused silica standard in a container with a diameter of 25.4 mm. The specimens were polished to a mirror finish using alumina particles. The polished samples were examined using an optical microscope and scanning electron microscope equipped with an energy-dispersive spectrometer (SEM–EDS).

A pycnometer was used to measure the density of the FJS-1 sands at room temperature. Furthermore, phase identification of the samples was performed using X-ray diffraction (XRD) by employing Cu-Kα radiation.

### 2.2 Experimental Apparatus

The thermal microscope measures the thermal effusivity on a micrometer scale using the cyclic heating method and the thermoreflectance technique [11–15]. Figures 1(a) and (b) show the schematic of the principle of thermal microscopy. A thin Mo film is formed on a smooth surface of the sample via DC sputtering. An intensity-modulated heating laser periodically heated the sample surface, causing periodic temperature changes on the sample surface. The temperature change at the sample surface has the same frequency as that of the heating laser but with a phase difference. The phase difference depends on the thermophysical properties of the sample. The reflectivity of Mo changes depending on the temperature. Thus, the temperature change of the sample surface is detected from the intensity change of the reflected light of a detection laser irradiated at a constant intensity on the sample surface, and the phase difference is determined.

The thermal effusivity of the sample was calculated based on the two-layer model for the Mo film and sample from the measured phase difference. The model assumes that the sample is of semi-infinite thickness and that heat diffuses only in the thickness direction. In the steady-state, the AC component of the temperature response of a sample surface due to cyclic heating (angular frequency ω) is expressed as follows:

\[
T(t) = A \sin(\omega t - \delta)
\]

where \(T(t)\) is the temperature response, \(t\) is time, \(A\) is a constant, and \(\delta\) is the phase difference between the period of temperature change of the Mo thin film and the intensity of the modulated heating laser. The value of \(\delta\) provides the thermal effusivity of the sample using the following equation:
$$\delta = 3\pi/4 + \arctan\left[ \frac{\cosh^2 \sqrt{\frac{\omega \tau_f}{2}} \left( \tanh \sqrt{\frac{\omega \tau_f}{2}} + \beta \right) \left( \tanh \sqrt{\frac{\omega \tau_f}{2}} + \beta^{-1} \right)}{\cosh^2 \sqrt{\frac{\omega \tau_f}{2}} \left( \beta - \beta^{-1} \right) \tan \sqrt{\frac{\omega \tau_f}{2}}} \right]$$  \tag{2}

Here

$$\tau_f = \frac{d_f^2}{\alpha_f}.$$  \tag{3}
where \(d_f, \alpha_f, b_s, \) and \(b_f\) are the thickness of the Mo film, thermal diffusivity of the Mo film, and thermal effusivity of sample and Mo film, respectively. Equation 2 determines the value of \(\beta\) to obtain \(b_s\) through Eq. 4. The previous study measured the thermal effusivity of Si, Ge, Al_2O_3, yttria-stabilized zirconia, and pyrex [14]. The thermal effusivity of these materials ranges from 15,321 to 1417 J·s\(^{-0.5}\)·m\(^{-2}\)·K\(^{-1}\), which values were determined from separate measurements of density, specific heat, and thermal diffusivity. The thermal microscopy reproduced the thermal effusivity of these standard samples within 4% [4].

The small spot size of the detection laser (ca. 10 \(\mu\)m) enables measurements with high-spatial resolution. In addition, the XY motorized sample stage provides an in-plane distribution of the thermal effusivity of the sample, as shown in Fig. 1(b).

2.3 Measurement Procedure

A thin Mo film with a thickness of approximately 100 nm was deposited on the polished surface of the sample via DC sputtering. A stylus profilometer measured the thickness of the Mo film. The thickness was determined by a wavelength of 830 nm intensity-modulated laser heated the sample with a frequency of 1 MHz at an intensity of 9.55 mW. A He–Ne laser was used to detect the temperature response of the Mo film at a wavelength of 633 nm and an irradiation intensity of 0.55 mW. The spot diameters of the heating and detection lasers were 27 and 8 \(\mu\)m, respectively. Ten measurements were taken at each position for 500 ms, and the average value was considered as the thermal effusivity at that position. The measurements were carried out at intervals of 10 \(\mu\)m around a 1 \times 1 mm\(^2\) area. The measurements were carried out at room temperature.

The reference sample of the fused silica was measured to obtain \(\alpha_f\) as follows [15]. The value of \(\delta\) for the measurement of fused silica can determine \(b_f\) by substituting Eq. 5 into Eq. 3 to reproduce the thermal effusivity of fused silica (1.57 kJ·s\(^{-0.5}\)·m\(^{-2}\)·K\(^{-1}\) [17]).

\[
\frac{\beta}{\rho_f C_f} = \frac{b_s}{b_f},
\]

(4)

\[
\alpha_f = \left(\frac{b_f}{\rho_f C_f}\right)^2
\]

(5)

where \(\rho_f\) and \(C_f\) are the density and specific heat of the Mo film, respectively, the value used for \(\rho_f C_f\) was \(2.29 \times 10^6\) J·m\(^{-3}\)·K\(^{-1}\) [14]. Finally, \(\alpha_f\) can be determined from Eq. 5.
3 Results and Discussion

3.1 SEM–EDS and XRD Analysis Results

Figure 2(a) and (b) show the backscattering electron images (BEIs) of the specimens after mirror polishing. In Fig. 2(a), all sand particles are composed of several phases. Figure 2(b) is the magnified image for the particle suggested by an allow in Fig. 2(a). The upper right part of the particle is a single-phase colored with dark grey, and the other part is composed of several phases with several 10 µm or less in size. SEM–EDS analyzed the red frame area in Fig. 2(b), and also the particle was measured by thermal microscopy. Figure 3 shows the results of EDS mapping, and Table 1 shows the chemical compositions obtained qualitatively by point analysis of SEM–EDS for regions A-D, which were suggested in Fig. 3. Region A (the darkest grey phase) in the BEI shows high Al, Si, and Ca content. On the other hand, region B in the BEI (light grey phase) contained more Mg, Fe, and Si. In addition, the bright region C in the BEI is rich in Fe and Ti. The region with high Si content (region D) seems to have a large amount of K in elemental mapping; however, the chemical composition by SEM–EDS showed that region D contains a small amount of K but a large amount of Fe. Region D does not clearly contrast with region A in the BEI.

Figure 4 shows the XRD profile of FJS-1. Existing phases in FJS-1 were reported as plagioclase, pyroxene, olivine, ilmenite, Spinel, etc. [16]. According to the
The XRD reference profile in Fig. 4 showed the closest shape to the present sample, and the chemical composition determined by EDS was also taken into account to find the reference. The phases identified in Fig. 4 were anorthite (calcium-rich endmember of the plagioclase), olivine, clinopyroxene, and ilmenite; however, it was difficult to

**Table 1** Chemical compositions obtained qualitatively by point analysis of SEM–EDS (in mass %)

| Position | O      | Na     | Mg     | Al     | Si     | P      | K      | Ca     | Ti     | Cr     | Mn     | Fe     | Total |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| A        | 46.73  | 2.42   | 0.51   | 15.86  | 24.04  | 0.29   | 9.32   | 0.07   | 0.05   | 0.72   | 100    |        |
|          | 46.82  | 2.31   | 0.59   | 16.05  | 24.06  | 0.23   | 9.22   | 0.04   | 0.05   | 0.69   | 100    |        |
|          | 46.84  | 2.38   | 0.51   | 15.72  | 24.35  | 0.27   | 9.23   | 0.05   |        | 0.64   | 100    |        |
| B        | 42.78  | 0.49   | 12.3   | 1.05   | 23.98  | 0.03   | 4.99   | 0.34   | 0.04   | 0.22   | 13.77  | 100    |
|          | 42.75  | 0.45   | 9.56   | 1.58   | 23.85  | 0.04   | 11.74  | 0.39   | 0.06   | 0.14   | 9.44   | 100    |
| C        | 25.85  | 0.75   | 1.48   | 0.13   |        | 0.01   | 0.11   | 8.68   | 0.03   |        | 62.98  | 100    |
|          | 26.58  | 0.64   | 1.24   | 0.75   | 0.07   | 0.16   | 0.16   | 10.21  | 0.09   |        | 60.17  | 100    |
| D        | 38.99  | 0.46   | 2.2    | 1.92   | 18.73  | 1.36   | 0.67   | 6.78   | 3.77   | 0.05   | 0.34   | 24.72  | 100    |
|          | 40.34  | 0.41   | 4.02   | 2.23   | 21.88  | 0.24   | 10.9   | 1.34   | 0.08   | 0.34   | 18.24  | 100    |
|          | 39.51  | 0.45   | 1.97   | 2.64   | 19.55  | 1.24   | 0.61   | 6.85   | 3.1    | 0.06   | 0.34   | 23.68  | 100    |

Fig. 3 BEI and elemental mapping for the area shown in Fig. 2(b) as a red frame. Regions A, B, and C were identified as anorthite, olivine, and ilmenite, respectively, with the XRD results, shown in Fig. 4 (Color figure online)
investigate whether clinopyroxene really existed. Finally, based on the above information, the BEI was reviewed again to determine the phases present: regions A–C were anorthite, olivine, and ilmenite, respectively; however, region D could not be identified.

### 3.2 Measurement Results by Thermal Microscopy

Figure 5(a) and (c) show the results of the first and second measurements by thermal microscope on corresponding BEI. These BEIs are shown in Fig. 5(b) and (d), respectively. The white frames in Fig. 5(a) and (b) indicate the areas measured by the thermal microscope. The second measurement was performed by re-polishing after the first measurement. After conducting the measurements using a thermal microscope, the BEIs were obtained with the Mo thin film. In the areas measured by the thermal microscope shown in Fig. 5(a) and (c), the transparent regions of the measured area showed abnormally large values. To show the thermal effusivity distribution clearly on the sample particle, Fig. 5(a) and (c) showed such abnormally large values as transparent. This result is mainly observed in the resin part and is considered to be due to the lifting of the Mo film caused by heating because the epoxy resin has a much smaller thermal conductivity of 0.2 W m\(^{-1}\)K\(^{-1}\) [18] than that of the sample particle (2.6 W m\(^{-1}\)K\(^{-1}\), which is calculated later). The applied
power of the heating laser was adjusted for the sample particle, and the power would be too large for the resin, resulting in the lifting of the Mo film.

In the first measurement shown in Fig. 5(a), some areas were expressed as transparent even though there were grains to be measured. Figure 5(e) shows the BEI for a wider area after the second measurement. The squares inside the image indicate the areas measured for the first and second measurements. Based on the figure, some particle parts measured first disappeared after polishing. In this area, abnormally large values were obtained in the first measurement. Therefore, the thermal effusivity can be obtained for the sufficiently thick portion in the resin (i.e., larger than the heat diffusion distance, as shown in Fig. 1(a)). In Fig. 5(c), the values were obtained for almost all sand particles in the measurement area, indicating that the thickness was sufficient. A comparison of the BEI with the results in Fig. 5(c) shows that the blue-green area with relatively
low thermal effusivity \((b=2\ \text{kJ} \cdot \text{s}^{-0.5} \cdot \text{m}^{-2} \cdot \text{K}^{-1})\) is dark grey (anorthite) in the BEI. In Fig. 5(c), yellow has a relatively high thermal effusivity area \((b=3\ \text{kJ} \cdot \text{s}^{-0.5} \cdot \text{m}^{-2} \cdot \text{K}^{-1})\) and shows a lighter grey color than anorthite in the BEI, corresponding to the value for olivine. In addition, in Fig. 5(c), larger thermal effusivity showed as red can be seen inside the sample particle, both around the transparent area and on the particle. The larger value means two possibilities: the resin in the crack caused the lifting of the Mo film, resulting in the apparently large value or phases having high thermal effusivity. It was difficult to identify the phase below such part, and the contribution of the crack seemed larger. Thus, this part was treated as a crack part from now on.

### 3.3 Analysis of the Thermal Effusivity of Each Phase

This section determines the thermal effusivity of each phase in the particle. For this purpose, a Gaussian mixture distribution was analyzed. The distribution of the probability density of the measured thermal effusivity is shown in the histogram in Fig. 6. The distribution was examined under the following conditions. There are three phases: anorthite, olivine, and others, and the measured value is mixed with high thermal effusivity due to the effect of the crack. In other words, the four Gaussian distributions of thermal effusivity are combined to form a histogram, as shown in Fig. 6. Therefore, the analysis was performed assuming the existence of four mixed normal distributions. A Gaussian mixture in scikit-learn and a machine-learning library in Python [19] were adopted to estimate the parameters for normal distributions. The curves in Fig. 6 show the results, and Table 2 lists the parameters obtained from the analysis. In this analysis,

![Fig. 6 Analysis result for the four Gaussian models: histogram shows the probability density of measured thermal effusivity with 100 J·s−0.5·m−2·K−1 intervals, curves of Gaussian 1–4 were calculated based on the parameters listed in Table 1, and curve for G1+G2+G3+G4 is the sum of Gaussian 1–4](image)
the normal distribution parameters were obtained simply without any restrictions on the parameters. The histogram shape is almost the same as the curve of G1 + G2 + G3 + G4; however, the peak intensity is larger for the histogram because the peak positions agree well. Furthermore, the curve of G1 + G2 + G3 + G4 and histogram appear to match well to the right side of the peak. The analysis was considered sufficient to calculate the thermal effusivity of each phase present in the particle. “Weight” indicates the proportion of the mixture of each normal distribution. This weight result would correspond to the fraction of the phases present. The phase ratio was calculated to confirm the relation between weight and the phase ratio. Figure 7(a) is the original BEI image, and Fig. 7(b)–(e) show the binarized image for each phase found in Fig. 7(a). ImageJ [20] was used for the analysis. The region D found in Fig. 3 was included in Fig. 7(b) because no contrast was found in the BEI image for regions A and D in Fig. 3. The weight in Table 2 and the percentage of each phase presented in Table 3 are in good agreement. Therefore, the thermal effusivity measured in the present study reflects the dispersion state and proportions of the phases: Gaussians 1–4 correspond to the anorthite, olivine, others, and crack effects.

Table 4 lists the thermal effusivity calculated from the specific heat, density, and thermal diffusivity of literature values [21–25] to examine the validity. Horai [22, 23] reported the thermal conductivity of rocks without voids at room temperature. The applied technique was the needle-probe method, and the sample used was powdered rocks immersed in water. The effect of water on the measured thermal conductivity was analytically eliminated, and the thermal conductivity of the rock was calculated. For both anorthite and olivine, the results obtained in this study listed in Table 2 agree with the values obtained from the literature. The size of the grains in the particles measured in this study was very small, less than a few 10 μm, and the thermal effusivity of each phase obtained is likely to be affected by the surrounding grains and grain boundaries. In particular, grain boundaries are expected to reduce the measured value of thermal effusivity. However, the values obtained in this study were in good agreement with literature values, as listed in Table 4. This suggests that the measured values were not affected by the thermal resistance between the grains because the grains were well contacted. On the other hand, in the case of cracks, the thermal resistance is not negligible and may exhibit unusually large values for thermal effusivity due to the lifting of the Mo film. Further work will require criteria to determine whether a large thermal effusivity is an abnormally large value due to the lifting of the Mo film or a correct large value. In conclusion, the values obtained in this study were reasonable. From the results

| Weight | Gaussian 1 | Gaussian 2 | Gaussian 3 | Gaussian 4 |
|--------|------------|------------|------------|------------|
| Mean value for thermal effusivity [kJ·s\(^{-0.5}\)·m\(^{-2}\)·K\(^{-1}\)] | 0.61677 | 0.22021 | 0.12037 | 0.04266 |
| Standard deviation [kJ·s\(^{-0.5}\)·m\(^{-2}\)·K\(^{-1}\)] | 1.99 | 2.73 | 3.55 | 5.00 |
| Corresponding phase | 0.35 | 0.31 | 0.45 | 0.56 |
| Anorthite | Olivine | Others | Crack |
Fig. 7 BEI for measured particle by thermal microscope (a), binary images for dark grey region (anorthite) (b), light grey region (olivine) (c), white region (ilmenite) (d) and others (e)

Table 3 Phase ratio and corresponding phase after analyzing BEI image in Fig. 7 by ImageJ

| Color in BEI | (b) Dark grey | (c) Light grey | (d) White | (e) Others |
|--------------|---------------|---------------|-----------|------------|
| Phase ratio  | 0.64          | 0.24          | 0.04      | 0.08       |
| Corresponding phase | Anorthite | Olivine | Ilmenite | Others |
Table 4 Literature values for density, heat capacity thermal conductivity and calculated thermal effusivity for anorthite and olivine, where Fo is Mg$_2$SiO$_4$ and Fa is Fe$_2$SiO$_4$

|                | Density [kg·m$^{-3}$] | Specific heat [J·kg$^{-1}$·K$^{-1}$] | Thermal conductivity [W·m$^{-1}$·K$^{-1}$] | Thermal effusivity (calculated) [kJ·s$^{-0.5}$·m$^{-2}$·K$^{-1}$] |
|----------------|-----------------------|--------------------------------------|--------------------------------------------|--------------------------------------------------|
| Anorthite      | 2750 [21]             | 700–709 [22]                         | 1.68–2.31 [22, 23]                         | 1.80–2.12                                         |
| Olivine        | 3320 [24]             | 843 (Fo$_{100}$) [25]                | 5.06 [22, 23] (Fo$_2$Fa$_{98}$)            | 3.76–2.40                                         |
|                |                       | 550 (Fo$_4$Fa$_{96}$) [22]           | 3.16 [22, 23] (Fo$_4$Fa$_{96}$)            |                                                  |
listed in Table 2, the average thermal effusivity of the simulant particle was obtained as $2.4 \pm 0.6 \text{kJ}\cdot\text{s}^{-0.5}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. This value does not include the effect of the crack or void. Although some mineral phases in FJS-1 were not identified in this study, the effect on the average thermal effusivity of a single particle was considered to be small because the proportion of these phases was as small as 8% (Table 3).

The temperature increase of the sample also affected the measurement result. The average temperature increase of the sample during the one cycle measurement was estimated as follows. Assuming that the power of the heating laser ($P$) is absorbed in the volume ($V$), which is expressed by the multiplication of heating area ($S$) and thermal diffusion distance ($l$), the following equation holds for the temperature rise ($\Delta T$).

$$P = \rho_s C_s V \Delta T = \rho_s C_s S l \Delta T$$  \hspace{1cm} (6)

where $\rho_s$ and $C_s$ are the density and specific heat of the sample, respectively. The heat diffusion distance is expressed as follows.

$$l = 2\sqrt{\alpha_s t}$$  \hspace{1cm} (7)

Thus, from the above two equations, the temperature increase ($\Delta T$) is expressed as follows.

$$\Delta T = \frac{P}{\rho_s C_s S l} = \frac{P}{2\rho_s C_s S \sqrt{\alpha_s t}} = \frac{P}{2b_s S \sqrt{t}}$$  \hspace{1cm} (8)

By substituting $P=9.55 \times 10^{-9} \text{J}$, $b_s=1.99 \text{kJ}\cdot\text{s}^{-0.5}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, the smallest value in the existing phase, $S=573 \times 10^{-12} \text{m}^2$, and $t=1 \times 10^{-6} \text{s}$, the temperature increase was estimated as 4.2 K. The temperature increase is considered to be small. The heat diffusion distance was calculated using Eq. 7 by substituting the following relation,

$$\sqrt{\alpha_s} = \frac{\lambda_s}{b_s}$$  \hspace{1cm} (9)

The values used in this calculation were thermal effusivity listed in Table 2 and thermal conductivity listed in Table 4. The heat diffusion distance calculated was 1.0–1.7 $\mu$m and 2.3–3.7 $\mu$m for anorthite and olivine, respectively. These heat diffusion distances are much smaller than the size of sand particles in this study.

### 3.4 Average Thermal Conductivity of a Simulant Particle

Thermal effusivity for the individual phases and then an average thermal effusivity were calculated for the entire particle in this study. The average thermal conductivity of a single sand particle can be calculated based on the measured thermal effusivity using the following equation:
\[ \lambda = \frac{b^2}{\rho C} \]  

where \( \lambda \) is the thermal conductivity, \( \rho \) is the density, and \( C \) is the specific heat. The density of the simulant used in this study was determined as \( 2.92 \pm 0.02 \text{ g\cdotcm}^{-3} \) using a pycnometer at room temperature. The specific heat of the simulant was reported to be \( 741.6 \text{ J\cdotkg}^{-1}\cdot\text{K}^{-1} \) \cite{6, 7}. Thus, the calculated thermal conductivity was \( 2.6 \pm 1.3 \text{ W\cdotm}^{-1}\cdot\text{K}^{-1} \). FJS-1 was manufactured mainly from basalt rocks. The thermal conductivity of basalt rocks was reported in ranges \( 1.6–2.6 \text{ W\cdotm}^{-1}\cdot\text{K}^{-1} \) \cite{26}, suggesting that the value obtained in this study was reasonable. However, the present measurement was conducted for only one particle. Representative values for FJS-1 can be obtained by measuring the thermal effusivity of a large number of particles.

Kanamori et al. reported the thermal conductivity of FJS-1 in the range \( (2–3.5) \times 10^{-4} \text{ W\cdotm}^{-1}\cdot\text{K}^{-1} \) with a sample density of \( 1.55–1.80 \text{ g\cdotcm}^{-3} \)\cite{5}. The measurement by Kanamori et al. was conducted in a vacuum and would use the granular sample. The reported thermal conductivity is much smaller than obtained in this study because of the \( 47\% \) to \( 62\% \) porosity. For further use of thermal conductivity in the simulation of the thermal management of the spacecraft, the thermophysical properties need to be selected according to the expected situation, that is, considering the porosity. The thermal conductivity model can be applied to calculate the thermal conductivity of granular material \cite{27}.

### 3.5 Future Determination of the Thermal Effusivity of a Lunar Regolith Particle as a Function of Temperature

Thermal effusivity measurements using thermal microscopy in this study were successfully carried out on a single sand particle, but measurements were limited to room temperature only. However, for the thermal design of the spacecraft, the thermophysical properties of sand particles, including their temperature dependence, are required. In this section, the method is proposed for estimating the temperature dependence of the thermal properties of a single sand particle.

The results of the thermal microscopy showed that the thermal effusivity of the single FJS-1 particle could be described by the thermal effusivities and proportions of the constituent phases when grains are contacted well. Furthermore, the effect of porosity, cracks, and voids needs to be considered for deriving average thermal conductivity. Thus, first, the thermophysical properties of the sand particle without crack or void are measured by preparing single-phase samples of the constituent phases (anorthite, olivine, ilmenite, etc.) as a function of temperature. Conventional methods can be used to measure the thermophysical properties of a single mineral phase. The sample for the single mineral phase should have a chemical composition and thermophysical property close to that of the phases in the sand particles. It should be checked to be consistent with the results of thermophysical microscopy at room temperature.

Previously reported thermophysical properties of lunar regoliths and their simulants have been measured from a sample consisting of many particles or rocks.
[1–10], i.e., granular samples were used. In contrast, this study determined the thermal effusivity of individual particles of sand from the distribution. This approach will provide new insights into spacecraft design, and the production and use of simulants. The thermal microscope would also be applicable for extra-terrestrial samples to understand the planetary evolution in the future.

4 Conclusions

Thermal microscopy was adopted to measure the thermal effusivity of a single particle of lunar regolith simulant FJS-1. The mirror-finished sample in resin was successfully measured, and the thermal effusivity distribution was obtained. Comparing the measured value with the SEM analysis provides an understanding of the thermal effusivity distribution from the mineral phase distribution. Based on the Gaussian mixture model, the thermal effusivity for anorthite and olivine in the particle was determined as $1.99 \pm 0.31$ and $2.73 \pm 0.35$ kJ·s$^{-0.5}$·m$^{-2}$·K$^{-1}$, respectively. The effect of grain boundary on the thermal effusivity would be negligibly small where the grains contact close. Furthermore, the average thermal effusivity was determined as $2.4 \pm 0.6$ kJ·s$^{-0.5}$·m$^{-2}$·K$^{-1}$, leading the thermal conductivity of $2.6 \pm 1.3$ W·m$^{-1}$·K$^{-1}$, which is reasonable compared with the previous studies. The value is for a single particle without cracks or voids. The measurement in this study has been limited to only a single sand particle and at room temperature. Thermophysical properties of the lunar regolith particle can be predicted from those values for single-phase samples of the constituent minerals, i.e., anorthite, olivine, and ilmenite, including the temperature dependence. Moreover, thermophysical property models can be applied for granular samples or samples with cracks or voids [27, 28].

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