Investigation of Martian Dust Sample Capture toward Mars Aero-flyby Sample Collection Mission

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A Mars Aero-flyby Sample Collection (MASC) mission has been proposed in a Mars exploration project at Japan Aerospace Exploration Agency (JAXA). The MASC vehicle enters the Martian atmosphere, captures dust particles and atmospheric gases at sampling altitudes between 30 and 50 km, and returns back to Earth. In order to improve the feasibility of this project, the development of its sampling system during flying in the Martian dusty atmosphere is crucial. Since silica aerogel has been used as a capturing medium for micrometeoroids and space debris, it is also planned to be used for the MASC mission. However, the capture of hypervelocity micron-size dust particles during the Martian atmospheric flight using aerogel is challenging. The aerogel is exposed to significant aerodynamic heating during sampling, and thus, the effect of heated aerogel on the dust particles must be evaluated. This work attempts to evaluate the impact on aerogel and the survivability of the dust particles inside the capturing medium by carrying out light gas gun and Van de Graaff experimental tests. By comparing the cases between normal and heated aerogels, the survivability of the dust samples as well as the heating effect has been investigated.

Nomenclature

\begin{align*}
A & : \text{area} \\
C & : \text{capacitance} \\
C_p & : \text{specific heat} \\
d & : \text{diameter} \\
L & : \text{length} \\
m & : \text{mass} \\
q & : \text{heat flux} \\
r & : \text{radius} \\
t & : \text{time} \\
T & : \text{temperature} \\
v & : \text{velocity} \\
V & : \text{voltage} \\
U & : \text{acceleration voltage} \\
\rho & : \text{density}
\end{align*}

Subscripts

\begin{align*}
Ag & : \text{silver} \\
d & : \text{dust} \\
f & : \text{final} \\
p & : \text{particle} \\
\text{ref} & : \text{reference} \\
sl & : \text{slug} \\
T & : \text{target} \\
\text{tra} & : \text{track}
\end{align*}

1. Introduction

At Japan Aerospace Exploration Agency (JAXA), the Mars Exploration with Lander-Orbiter Synergy (MELOS) mission has come under review together with a lot of planetary scientific groups all over Japan. As one of the MELOS missions, a non-stop Mars sample return mission, named Mars
Aero-flyby Sample Collection (MASC),\(^1\) has been planned in our group. In order to improve the feasibility of this mission, the development of its sampling system for floating Martian dust particles is crucial. In our previous work,\(^2\) the Martian dust distributions were examined, and we found that there are a plenty of micron size dust particles between 30 and 50 km altitude depending on the weather condition, where the dust sampling is planned for the MASC mission. At 30 km, the estimated number of samples per second using 10×10 cm\(^2\) aerogel is \(3\times10^4\) for 2-\(\mu\)m sized and 30 for 10-\(\mu\)m sized particles, respectively. For the mission, a sphere-cone shape spacecraft has been proposed,\(^3\) and in Fig. 1, conceptual designs of the MASC aeroshell and sample collector are presented. The retractable sample collector will be opened for approximately 0.3 second at a sampling altitude, which is between 30 and 50 km, during the Martian atmospheric entry flight, and the sample collector will capture micron-sized dust particles. Currently, silica aerogel is planned to be used as the sample collector. In order to capture sample particles successfully, there are four main concerns that must be evaluated as shown in Fig. 2: (1) the effect of Martian dust particle heating when particles travel through a hot-temperature shock, (2) the effect of silica aerogel heating due to the hot-temperature shock, (3) the impact of heated silica aerogel on the micron-size dust particles and the effect of heating/melting when particles penetrate inside aerogel, (4) the analysis scheme of micron-size dust particles as well as the investigation on chemical compositions of Martian dust particles. This study aims to evaluate these four research tasks. For task (1), particle drag and heat transfer calculations are performed. For task (2), aerogel heating experiments are conducted in an arcjet wind tunnel at JAXA. For task (3), dust capture experiments, such as two-stage light gas gun (LGG) experiments at Institute of Space and Astronautical Science (ISAS) of JAXA or Van de Graaff (VdG) experiments at High Fluence Irradiation Facility, the University of Tokyo (HIT), are carried out. For task (4), we investigate particle tracks and the size of captured particles by a digital microscope (VHX-1000, Keyence Corp.), and after picking captured particles out of aerogel, we analyze the particle condition and its chemical composition by the scanning electron microscope (SEM) / energy dispersive X-ray spectroscopy (EDS) method.

2. Modeling of Dust Heating

For the estimation of Martian dust heating when dust particles travel through a hot-temperature shock, particle motion, heat transfer, and thermal decomposition were simulated. First, computational fluid dynamics (CFD) and direct simulation Monte Carlo (DSMC) flow field calculations were performed for the MASC entry in the Martian atmosphere at 35 and 45 km altitudes. Three macroscopic heat transfer models, the modified Kavanau, Koshmarov and Svirsthevskii (K-S), and free-molecule (F-M) models, were then compared\(^4\) in high-temperature rarefied, low-Reynolds number conditions from subsonic to supersonic.

3. Experimental Configurations

3.1. Aerogel heating tests in arcjet wind tunnel

Aerogel heating tests were carried out in the 750kW arcjet wind tunnel at JAXA. In the tests, aerogel test pieces were exposed to a high-enthalpy air flow. The aerogel used in this study has originally been developed in the cosmic ray physics and neutrino astronomy laboratory at Chiba University,\(^5\) and a hydrophobic treatment has been applied. Three densities of aerogel, 0.02, 0.03, and 0.04 g/cm\(^3\), are used in this work. The aerogel test pieces are first trimmed with a length of 70 mm, a width of 40 mm, and a depth of 26 mm, and are put on a metal container\(^6\) without any adhesive applications. The assembly is then flush-mounted on a water-cooled wedge holder. In order to characterize the arcjet test flow at the position where the aerogel test piece is heated, the heat flux values are measured by using slag calorimeters. Three slag calorimeters are put on a copper container in a straight line so as to obtain the spatial variation of heat flux values along the centerline of the wedge holder. At the reverse side of the slag, a type-K thermocouple is embedded to measure the slag temperature. The heat flux is

![Fig. 3. Image of light gas gun experiments (top) and the picture of its aerogel holder (bottom).](image-url)
calculated from the energy balance at the slag surface as 

\[
q = \frac{mC_p}{A} \frac{\Delta T}{\Delta t} + q_{loss}.
\]  

(1)

In this work, two wedge angles, -20 and -10 degrees were tested, and the heating time was varied between 1 and 3 seconds. Further details of this experiment can be found in Ref. (6).

3.2. Light gas gun experiments

Simulations of dust particle captures with aerogel have been conducted using the two-stage LGG at ISAS of JAXA. In the experiments, particles imitating Martian dust are launched against aerogel test pieces in the LGG target chamber as a scattergun. Figure 3 shows the image of the LGG dust capture simulation using aerogel. The bottom picture in Fig. 3 is the aerogel holder. As for the target material, two aerogel test pieces are basically placed in the target chamber top to bottom: one is aerogel without heating (Type A) and the other is one after the arcjet heating test (Type B). From the point of view of thermal decomposition, the feasibility study of sampling can be improved by carrying out the capture simulation during silica aerogel heating. However, because of the difficulty to conduct the LGG experiment in such a condition, in this work, worse heating conditions (longer heating time than the estimated sampling time) were used in the arcjet heating test and the harder surface aerogel test pieces were utilized for the LGG test. Three aerogel densities, 0.02, 0.03, 0.04 g/cm³, are tested as the dust sample collector. The size of each test piece is 13×13×20 mm³.

<table>
<thead>
<tr>
<th>Run</th>
<th>Projectile</th>
<th>Target</th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>Name</td>
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<td>(d_p, \mu m)</td>
<td>(v_p, \text{km/s})</td>
<td>(\rho, \text{g/cm}^3)</td>
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</table>

The LGG experimental conditions are summarized in Table 1. First, alumina sphere particles are used, which are well sorted out with the average diameter of 30 μm. Second, since aeronomers and meteorologist pointed out that the primary constituent of dust particles floating in the Martian atmosphere might be clay mineral such as montmorillonite or palagonite, montmorillonite particles are also used as the projectiles. In this work, a product, named “kunibond,” was utilized for the LGG tests. “Kunibond” is collected as bentnite whose main chemical constituent is montmorillonite with quartz, cristobalite, mica, feldspar, zeolite and so forth. The montmorillonite in the “kunibond” is Ca-rich montmorillonite (70.9% SiO₂, 14.9% Al₂O₃, 3.9% MgO, 2.2% CaO, 1.8% Fe₂O₃, etc.). The particles are sorted out with the average diameter of either 30 or 10 μm. The gun accelerates projectiles up to approximately 4.2 km/s, which is the predicted relative velocity of the Martian dust particles to the sample collector in the MASC mission. A specified amount of the test particles are crammed into a sabot, and the sabot is fired and breaks up as a scattergun at a sabot breaking spot. It should be noted that the diameter of particles used in this experiment is much larger than the representative diameter of dust particles considered in the MASC mission (\(d_r ~ 1-2 \mu m\)). Nevertheless, we believe that this size of particle would be suitable for projectiles as a beginning of this investigation because of easy handling and quick analysis of aerogel carved by the launched projectiles. Furthermore, since it is difficult to operate the LGG experiment using particles smaller than 10 μm, micron-size dust capture simulations are planned using a VdG generator integrated with a particle accelerator instead of the LGG experiment.

3.3. Van de Graaff experiments

In order to operate Martian dust capture simulations for...
micron-size particles, VdG experiments at the HIT facility have been carried out. In Fig. 4, the image of the VdG experiment and the picture of the VdG target chamber are presented. The VdG aerogel holder can hold 10 aerogel test pieces at once, and the HIT automatic xyz stage controls the target position. In this work, a normal aerogel is classified as Type A, and Types B1 and B2 are aerogels that are heated with $q=160$ kW/m$^2$ and 80 kW/m$^2$, respectively. In total, seven types of aerogel test pieces [0.02 g/cm$^3$(A, B1, B2), 0.03 g/cm$^3$(A, B2), 0.04 g/cm$^3$(A, B2)] were prepared. The size of the test pieces is the same as the LGG case. At HIT, a dust analyzer with time of flight (TOF) mass spectrometry is used to obtain the particle velocity. Two cylindrical electrodes are placed on a beam line, and when a charged particle passes through the electrodes, the change of voltage is measured. The particle velocity is amplified using a charge sensitive amplifier. The induced voltage is amplified using a charge sensitive amplifier. The capacitance is 1 pF. In order to target the particle speed to 4.2 km/s, the acceleration voltage, $U$, is set to 1 or 2 MV in this work. The particle diameter is calculated as $d=\left[6m_p/(\pi\rho_p)\right]^{1/3}$. In addition, by putting metal meshes in front of each aerogel gate, the mesh is used as a particle detector getting the induced voltage change when a charged particle passes through the mesh or hit the mesh. For the metal mesh, either aluminum or copper is used. Furthermore, a vacuum photomultiplier tube module (PMT; R7400-03ASSY, Hamamatsu Photonics Corp.) is placed inside the test chamber, and the PMT faces the direction toward an aerogel surface so as to detect the particle impact emission (See Fig. 4). The VdG experimental conditions are summarized in Table 2. The particle used in this experiment is silver ion (3050HD), the experimental conditions are summarized in Table 2. The velocity perturbation is within 0.3 km/s. Additionally, so as not to damage the aerogel sample collector, the vacuuming and leaking speed of the test chamber must be controlled carefully.

$$v_p = \frac{L_1}{t_1}, \ m_p = \frac{2CAUV}{v_p^2}, \ (2)$$

where $L_1$ is the distance between the two electrodes and 1.3 m, and $t_1$ is the time between the two signals. The induced voltage is amplified using a charge sensitive amplifier. The capacitance is 1 pF. In order to target the particle speed to 4.2 km/s, the acceleration voltage, $U$, is set to 1 or 2 MV in this work. The particle diameter is calculated as $d=\left[6m_p/(\pi\rho_p)\right]^{1/3}$. In addition, by putting metal meshes in front of each aerogel gate, the mesh is used as a particle detector getting the induced voltage change when a charged particle passes through the mesh or hit the mesh. For the metal mesh, either aluminum or copper is used. Furthermore, a vacuum photomultiplier tube module (PMT; R7400-03ASSY, Hamamatsu Photonics Corp.) is placed inside the test chamber, and the PMT faces the direction toward an aerogel surface so as to detect the particle impact emission (See Fig. 4). The VdG experimental conditions are summarized in Table 2. The particle used in this experiment is silver ion (3050HD), the average diameter of which is 1.8 μm. Additionally, so as not to damage the aerogel sample collector, the vacuuming and leaking speed of the test chamber must be controlled carefully.

#### Table 2. Van de Graaf test cases

<table>
<thead>
<tr>
<th>Run</th>
<th>VdG condition</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>$v_p$ km/s</td>
<td>$U$ MV</td>
</tr>
<tr>
<td>D01</td>
<td>2.31</td>
<td>1</td>
</tr>
<tr>
<td>D02</td>
<td>2.21</td>
<td>1</td>
</tr>
<tr>
<td>D03</td>
<td>2.83</td>
<td>2</td>
</tr>
</tbody>
</table>

4. Results and Discussions

4.1. Particle heating by a hot-temperature shock

The influence of Martian dust heating when dust particles travel through the hot-temperature shock was evaluated by performing particle motion, heat transfer, and thermal decomposition simulations for Martian dust particles ($v_p=1$, 2 and 10 μm). Three macroscopic heat transfer models were compared, and it was found that the difference between K-S and F-M models is small in the dust sample conditions, and these models predict higher particle temperature in the stagnation region than the modified Kavanau model. However, in the downstream region, the modified Kavanau model predicts higher particle temperature than the other two models. Although the maximum particle temperature for 1 μm particle in the stagnation region is approximately 740 K and 525 K at 35 and 45 km, respectively, using the K-S or F-M model, it is lower than 540 K and 400 K at 35 and 45 km, respectively, in the downstream region. Therefore, the sample collector is equipped in the downstream region for the MASC mission (see Fig. 1). Note that in order to investigate the accuracy of the macroscopic models, the drag coefficient $C_D$ and the heat transfer coefficient $C_h$ of macroscopic models in the dust particle simulations have been compared with the microscopic DSMC results, $^4$ and the superiority of K-S and F-M models has been verified for the MASC condition.

4.2. Aerogel heating experiments

Heating tests of silica aerogel were carried out in the arcjet wind tunnel to see whether the material is suitable for the MASC sample collector. First, the heat flux was measured, and we found that with the wedge angle of -20 degree, the average heat flux is nearly 160 kW/m$^2$, and with -10 degree, it is approximately 80 kW/m$^2$, which is similar to the estimated heat flux on the sampling condition of the MASC mission. In the arcjet tests, the flow field near the aerogel surface glazed strongly because the surface of aerogel melted and vaporized due to the aerodynamic heating. Using a digital microscope, we have inspected the aerogel surfaces, and three-dimensional structures of the heated aerogel surfaces were revealed (see Figs. 9 through 12 in Ref. (6)). Apparently, considerable alterations were observed on the aerogel surface after the heating tests. The surface of aerogel has become black, and many crevices have developed along the aerogel surface. The higher the density of aerogel becomes, the darker the aerogel surface becomes and the shallower the depth of crevices becomes. These observations lead to our presumption that a structural strength against deformation and shrinkage due to heat decreases for lower-density aerogel. Besides, the surface layer of about 20 μm thickness becomes glassy and looks hard. This melted layer becomes thicker when the exposure time becomes longer. These heated aerogel test pieces are utilized for the LGG and VdG dust capture simulations.

4.3. Aerogel dust capture LGG experiments

Using the two-stage light gas gun, we have simulated capturing dust particles. In total, 11 shots were executed. In the experiments, a projectile sabot is fired into aerogel test pieces at a speed similar to that of the MASC mission. As can be seen in Table 1, the velocity perturbation is within 0.3 km/s. After the LGG experiments, the aerogel test pieces were observed by using a microscope. Figure 5 shows the impact surface and side view pictures of aerogels shot by 30-μm alumina particles. The pictures present comparisons between Type A and B, and for both cases, the aerogel test pieces have approximately 50 tracks carved by the particles. The shape and length for each track were investigated. We found that most of the tracks have a carrot shape, and the particles are captured at the very tips of the tracks. Only a few of the tracks...
are a bulbous-shape. Figure 6 shows a comparison of distributions for 30-μm alumina particle track length between Types A and B. The average track length is about 11.2 mm for Type A, and is approximately 2 mm shorter for Type B. We consider that this feature is attributed to the glassy surface of the heated aerogel (Type B), which may be harder than the normal aerogel surface. The track length is modeled using the modified Horz model \(^1\) as

\[
L_{\text{tra}} = L_{\text{ref}} d \left( \frac{\rho_a}{\rho_p} \right)^{0.860}.
\]

Figure 7 shows a comparison of the track length of 30-μm alumina particles between the LGG results and the model. Although the magnitude of track lengths are adjusted by setting a parameter, \(L_{\text{ref}}\), to 4.0 in the model, the LGG dependency of aerogel density agrees well with the model.

30 and 10 µm montmorillonite particles were also used in the LGG experiment. Figure 8 shows a comparison of track length of 30 and 10 µm montmorillonite particles between the LGG results and model as well as the prediction of 2 and 1 µm montmorillonite. For montmorillonite, using a value of \(L_{\text{ref}} = 2.071\), good agreement is obtained between the LGG and the calculated results. Compared to the alumina cases, the montmorillonite track length becomes significantly shorter. This characteristic change originates from the lower density than alumina, the irregular layered shape, and the thermal decomposition effect. The densities of alumina and montmorillonite are approximately 4.0 and 2.4 g/cm³, respectively. The chemical composition of montmorillonite is (Na,Ca)(OH)\(_2\)(Al,Mg)\(_2\)Si\(_4\)O\(_{10}\)(OH)\(_2\)·nH\(_2\)O, and this material is thermally and mechanically more friable than alumina. Note that for particles greater than 10 μm, the melting silica aerogel layer is so thin compared to the track length that the effect of heated surface is smaller than the overall heating during the penetration into the silica aerogel. For 2 or 1 μm montmorillonite particles, the track length is estimated to be shorter than 0.5 mm.

The launched particles were successfully picked out from the aerogel by manual manipulation. The observation of the particles leads to the fact that although the survival rate of the captured alumina particles is higher than 90 %, that of the montmorillonite particles is estimated to be 60-70 %. Thus, the heating effect is more essential for montmorillonite particles than alumina. The SEM/EDS analysis has been performed for these picked particles at the University of Tokyo. The SEM/EDS analysis was conducted for the particles before the LGG shots. 10 to 20 samples were randomly selected, and the elemental constituents were first investigated. Then, the EDS patterns for the captured particles were investigated at approximately five points for each particle.

In Fig. 9, SEM/EDS results of 30-μm alumina particles are compared between the cases of Type A and Type B. The particle surface of Type A is rarely damaged, and the EDS result shows only alumina compositions. In contrast, the Si composition from aerogel is detected from the surface of Type
B, and the melted aerogel adheres to the particle surface. Nevertheless, the particle chemical composition is not damaged inside the particle.

The SEM/EDS analysis was also carried out for 30 and 10-µm montmorillonite particles. Approximately 15 samples for 30µm-sized and 10µm-sized montmorillonite were picked and the EDS patterns were investigated at approximately five points for each particle. It was found that montmorillonite grains have irregular-shaped, and the surface condition is various. In Fig. 10, SEM/EDS results of 10-µm montmorillonite particles are compared between the virgin particle and the captured one. For virgin montmorillonite particles, Si, Al, O, Mg, and Ca were primarily detected. This result basically agrees with the montmorillonite chemical compositions. Since the main chemical constituent of particles is montmorillonite, we regard the left EDS pattern in Fig. 10 as the Martian dust test particle. The right EDS pattern shows an example of chemical compositions on captured montmorillonite particle surfaces. As shown in the figure, similar EDS patterns were basically obtained between the particles before and after the LGG shot. It should be pointed out that similar to 30µm-sized cases, the melted aerogel (Si and O) was identified from several points on the captured montmorillonite surfaces. Some of them were Ca-rich, and some showed the same chemical compositions as the virgin montmorillonite. In addition to Si, Al, O, Mg, and Ca, Na and Cl were also detected from some samples. The Ca-rich montmorillonite contains a small amount of Na while Cl is considered to be impurity in the “kunibond.” Note that carbon was also detected from some parts of particles captured in the hydrophobic silica aerogel. This may be from the hydrophobic treatment of silica aerogel, and the difference cannot be seen evidently between Types A and B. Consequently, we deduce that dust particles can be captured by the heated aerogel without mechanical destruction or thermal metamorphism if the particle has a diameter of the order of 10 µm.

4.4. Aerogel dust capture VdG experiments

Based on the LGG experimental results, we found that 10 µm-class particles can be successfully captured in the MASC mission. However, most of dust particles at the sampling altitude are estimated to be micron-class. Thus, micron-size dust capture simulations were carried out using a VdG generator integrated with a particle accelerator at HIT. In total, three cases, D01 through D03, were operated. For D01 and D02, U was set to 1 MV, and for D03, it was set to 2 MV. Whereas more than 100 particles were sampled for D01 and

Fig. 9. SEM/EDS analysis: Comparison of the captured 30 µm alumina particle between Type A (left) and Type B (right).

Fig. 10. SEM/EDS analysis: Comparison of the montmorillonite particle between the virgin one (left) and the captured one (right).

Fig. 11. TOF signals of a particle with $v_p=2.9$ km/s and $d_p=1.7$ µm in the VdG experiment.

Fig. 12. Comparison of the observation of aerogel between the virgin particles (top) and the captured ones (D03, bottom) using the VHX-1000 digital microscope.
D02, only 32 particles were sampled for D03 due to the operational limitation. From the TOF signals, the average particle velocity, \( v_p \), and diameter, \( d_p \), were calculated, and the results are listed in Table 2. In Fig. 11, TOF signals of a particle with \( v_p = 2.9 \) km/s and \( d_p = 1.7 \mu m \) are shown. With \( U = 1 \) MV, the average speed is approximately 2.3 km/s, and the speed increases by 0.5 km/s with 2 MV. The average particle diameter is roughly 1.4 \( \mu m \). Unfortunately, the signals of the metal mesh or the PMT were not detected due to the low sensitivity.

The observation of aerogel test pieces was carried out using the VHX-1000 digital microscope. In Fig. 12, the observation results of aerogel between the virgin particles and the captured ones (D03) using the VHX-1000 digital microscope are shown. The maximum magnification ratio is set to 1,000. By carrying out careful observations, we could identify micron-sized particles near the aerogel surface as shown in the figure. Furthermore, the SEM or the electron probe micro-analyzer (EPMA) method is planned to investigate the survivability of micron-size particles in the future.

5. Conclusions

In the MASC mission, the development of the sampling system during flying in the Martian dusty atmosphere is crucial. In order to improve the feasibility of this mission, four research points: (1) the effect of a hot-temperature shock to micron-size dust particles, (2) the aerogel heating effect, (3) the dust capture possibility using silica aerogel, (4) the analysis technique of micron-size dust particles, have been investigated. First, we found that despite the heating due to the interaction with the shock, dust particles can survive and reach the dust collector. Second, by carrying out the aerogel heating experiment in the arcjet wind tunnel, the LGG dust capture simulation, and the SEM/EDS analysis, we have concluded that dust particles can be captured by the heated aerogel without mechanical destruction or thermal metamorphism if the particle diameter is larger than 10 \( \mu m \). For micron-size dust particles, the VdG dust capture experiments have been performed, and we found that the particles are successfully trapped inside the aerogel. The captured particles have been analyzed, and the survivability of the particles will be evaluated.

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