Electrostatic Precipitation in the Martian Environment

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Because the Martian atmosphere is mainly composed of CO₂, electrochemical reduction of oxygen from CO₂ is one of the most efficient methods of extracting the oxygen that is indispensable for astronauts to breathe and can be used as an oxidant for rocket engines. To realize a reliable oxygen production system, a large amount of CO₂ gas must be accumulated and compressed in an electrolytic conversion system. However, because dust is presented in the Martian atmosphere because of dust storms, there is a concern that it could damage the oxygen conversion system or cause it to malfunction. Thus, the presence of a dust removal system is necessary before CO₂ gas can be introduced into the system. To this end, we are developing an electrostatic precipitator suitable for use in the low-pressure Martian atmosphere. We first constructed a coaxial cylindrical precipitator consisting of a wire and cylinder electrodes. In our preliminary investigation, the efficiency was at most 60% without corona discharge, and almost no dust was collected at the corona discharge region in the low-pressure (700 Pa) atmosphere. A low pressure of 700 Pa was chosen to simulate the Martian atmosphere. In this case, dust was collected on the surface of the wire electrode, contrary to the case for a pressure of 10⁵ Pa (1 atm). The mechanism of these phenomena was investigated by the direct observation and numerical calculation of particle motion in the precipitator. It was clarified that the low charge density of particles in the low-pressure atmosphere caused a relatively large dielectrophoresis force compared to the Coulomb force, and the particles were attracted to the wire electrode. The poor performance in the low-pressure atmosphere was caused by the low charge density and low electrostatic field owing to the low limited voltage. Although the performance was degraded very rapidly in low pressure atmosphere due to the deposition of dust on the fine wire electrode, it was very easy to vibrate the wire electrode and to remove dust on the wire.

Nomenclature

C_c	=	Cunningham correction factor (-)
d	=	diameter of particle (m)
E_x	=	electrostatic field in the radial direction (V/m)
g	=	gravitational acceleration (9.8 m/s ²)
I_c	=	corona current (A)
m	=	mass of particle (kg)
P	=	pressure (Torr)
q	=	charge of particle (C)
r	=	radial coordinate from the center of the wire electrode (m)
r_i	=	radius of wire electrode (m)
r_o	=	inner radius of cylinder electrode (m)
T	=	temperature (°C)
V	=	applied voltage (V)

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V_c	=	corona onset voltage (V)
z	=	axial coordinate from the top of the system (m)
ϵ_0	=	dielectric constant in space [= 8.854×10^{-12} (F/m)]
ϵ_r	=	relative permittivity of particle
δ	=	relative air density (-)
η	=	viscosity of air (1.82×10^{-5} Pa·s)
μ	=	ion mobility (1.2×10^{-4} m ² /Vs in atmosphere pressure air, 1.7×10^{-2} m ² /Vs in 700 Pa)

I. Introduction

TO realize long-term manned exploration of Mars, in-situ resource utilization (ISRU) is necessary, both to manage the risk and reduce the cost of transporting resources from Earth. ISRU requires a number of processes, such as the drilling, collection, classification, and chemical processing of the Martian regolith, to extract and synthesize oxygen, water, and any metals.¹⁻⁷ Because the Martian atmosphere is primarily composed of carbon dioxide, electrochemical reduction of oxygen from carbon dioxide is believed to be one of the most efficient methods to extract the oxygen that is a requirement for astronauts to breathe, and can be used as an oxidant for rocket engines. To realize a reliable oxygen production system, a large amount of CO₂ gas must be accumulated and compressed in an electrolytic conversion system. However, because dust particles in the range of 2–10 μ m in diameter are present in the Martian atmosphere because of dust storms and dust devils,^{8,9} there are concerns that the dust could damage the oxygen conversion system or cause it to malfunction. Thus, the implementation of a dust removal system is necessary before CO₂ gas can be introduced in the system. To this end, we are developing an electrostatic precipitator that is suitable for the use in the low-pressure Martian atmosphere.¹⁰⁻¹³

The electrostatic precipitator consists of a wire electrode and a grounded cylinder electrode surrounding the wire.¹¹ Gas including the airborne dust is injected into the cylinder electrode. When a high voltage is applied to the wire, a corona discharge takes place near the wire and generates ions that traverse between the wire and cylinder electrodes. These particles are then charged with the same polarity as the wire electrode. The charged particles move toward the outer electrode owing to the electrostatic field between the electrodes, and the charged dust particles are deposited there. The captured particles are removed from the collecting cylinder electrode mechanically. This technology is mainly utilized in industrial applications such as the diesel engines and thermal power generation plants, to capture fine particles in the exhaust gas, and because the technology has several advantages such as low pressure drop, low power consumption, and high collection efficiency, it is suitable for the use in space applications.

We investigated the preliminary performance of the electrostatic precipitator in the low-pressure atmosphere to verify its utility for the reliable and efficient oxygen production system required for ISRU in the Martian environment.

II. Experimental

A. Experimental Setup

Figure 1 (a) shows a schematic drawing of the experimental setup. A coaxial wire-to-cylinder system was installed in a vacuum chamber. A high positive DC voltage was applied to the wire by using a high-voltage power supply (Matsusada Precision, HEOPS-10BS), and the cylinder electrode was grounded. The diameter of the tungsten wire electrode was 0.1 mm, and two aluminum cylinders with inner diameters of 30 mm and 50 mm were used for the parametric experiment. In addition to the wire-to-cylinder system, a wire-to-plate system, as shown in Figure 1 (b), was prepared to observe particle motion directly from the lateral side of the wire. The distance between the parallel plates was 50 mm and the width of the plates was 80 mm. The length of the cylinders and plates was 150 mm. Dust particles were fed to the upper part of the cylinder using a vibration feeder, i.e., a container was laterally vibrated using an unbalanced motor, and dust in the container was fed through a 124- μ m opening mesh attached to the bottom of the container. The feed rate was controlled by adjusting the applied voltage to the motor. The vacuum chamber was evacuated using a rotary pump, and pressure in the chamber was measured by a pirani gauge (ULVAC, GLD-136). The dust collection rate was determined by the weight of the dust that passed through the cylinder with the application of voltage divided by that without applying voltage. For each experiment, the weight of the dust was measured after an operational duration of one minute using an electric balance (Mettler, WMC25 -25) that is appropriate for use in a vacuum environment. Because the performance was degraded very rapidly in low pressure atmosphere due to the deposition of dust on the fine wire electrode, the dust collection rate was measured at the very beginning of the operation. Details on this feature and countermeasure are described in the section V.

Figure 1. Experimental setup. (a) Schematic drawing of electrostatic precipitator (Wire-to-cylinder electrode system is installed in the vacuum chamber), (b) wire-to-plate electrode system, (c) Photograph of setup (Wire-to-cylinder electrode system is installed in the chamber)

Table 1. Properties of test powder, actual Martian regolith, and Martian regolith simulant.

Items	Remarks	Test Powder ¹⁴	Martian regolith ¹⁵	Martian regolith simulant ¹⁶
	-	JIS test powder 1-11	Sand in Gusev crater	JSC-Mars-1
Bulk density (g/cm ³)	-	2.9-3.1	1.52	0.87-1.07
Composition (wt%)	SiO ₂	34-40	44.0	43.5
	Fe ₂ O ₃	17-23	16.5	15.6
	Al ₂ O ₃	26-32	7.5	23.2
	CaO	0-3	5.6	6.2
	MgO	0-7	6	3.4
	TiO ₂	0-4	-	-
Size distribution (wt%)	1 (μm)	15	-	-
	2	28	-	-
	4	14	-	-
	6	5	-	-
	8	3	-	-
	<5	-	-	1
	5-52	-	-	5
	53-149	-	-	19
	150-249	-	-	24
	250-449	-	-	30
	450-1,000	-	-	21
SEM image	-			

B. Dust Used for Experiment

Because it is assumed that actual airborne dust is much smaller than that on the surface of Mars, we used small test powder, the characteristics of which are listed in Table 1. It is reported that Martian particle size of dust suspended for long period of time is 1–2 μm and that raised into the atmosphere by wind and dust devil is lower than 5 μm.¹¹ It is not exact same but similar to the test sample. The chemical composition itself does not affect the motion of particles but physical and electrostatic properties of dust, such as the charge, permittivity, specific gravity, and

size of particle, determine the motion of particles in the electrostatic precipitator, nevertheless the composition of the test powder was also similar to the Martian regolith.

III. Fundamental Characteristics

Before conducting the dust removal experiment, the voltage-current characteristics of the wire-to-cylinder system were measured as shown in Figure 2. The current was measured by dividing the voltage drop in a shunt resistor inserted between the power supply and the wire electrode by the resistance. The parameters in consideration were; the inner diameter of the outer cylindrical electrode and pressure of the air. At voltages lower than the threshold (4.7–5.1 kV for normal atmospheric pressure and 0.68–0.75 kV at 700 Pa), no substantial current flowed in the air gap. However, at voltages higher than the threshold voltage, a discharge current of the order of several microamperes was measured, and a weak luminescence was observed at the wire electrode at the same time. That happened because of the occurrence of corona discharge. The associated current and luminescence were stable, and the discharge was silent. When the applied voltage was increased, the magnitude of corona current increased, and the discharge mode shifted to a spark discharge. These characteristics are typical in a wire-to-cylinder system.¹⁷

The corona onset voltage V_c (V) is calculated by the following equation.

$$V_c = 7200\delta \left(1 + \frac{0.0301}{\sqrt{r_i\delta}} \right) r_i \log_{10} \frac{r_o}{r_i}, \quad \delta = \frac{P}{760} \frac{298}{T+273} \text{ (relative air density)} \quad (1)$$

where r_i is the radius of the wire electrode (m), r_o is the inner radius of the cylinder electrode (m), P is the pressure (Torr), and T is the temperature (°C). The calculated corona onset voltage at 10^5 Pa (1 atm, 760 Torr) was 4.68 kV for the case of the 30-mm inner diameter cylinder and 5.10 kV for the case of the 50-mm inner diameter cylinder. The onset voltage at 700 Pa was 0.68 kV for the case of the 30-mm inner diameter cylinder and 0.75 kV for the case of the 50-mm inner diameter cylinder. These values were consistent with the measured values shown in Figure 2. The corona onset voltage in a low-pressure atmosphere was lower compared to that at a pressure of 10^5 Pa.

The corona current I_c (A) is calculated by the following equation.

$$I_c = \frac{4\pi\epsilon_0\mu}{r_o \ln(r_o/r_i)} V(V - V_c) \quad (2)$$

where ϵ_0 is the dielectric constant in space (8.854×10^{-12} F/m), μ is the ion mobility (1.2×10^{-4} m²/Vs at an air pressure of 10^5 Pa, 1.7×10^{-2} m²/Vs at 700 Pa), and V is the applied voltage (V). As shown in Figure 2, the calculated values coincided fairly well to the measured values.

Figure 2. Measured and calculated V–I curves in the wire-to-cylinder system (parameter: inner diameter of cylinder electrode).

Figure 3 shows the measured dust collection rate in the wire-to-cylinder system. The rate increased with an increase of the applied voltage, and was around 70–80% at the atmosphere pressure when the applied voltage was just below the corona onset voltage, as shown in Figure 3 (a). The rate was a little high when the inner diameter of the cylinder electrode was small. A very high rate, approximately 100%, was realized by the application of a high volt-

age to the wire electrode that generated the corona discharge. Dust was collected on the inner surface of the cylinder electrode.

On the other hand, at a lower pressure (700 Pa), which was selected to simulate the Martian atmosphere, the efficiency was at most 50–60% without corona discharge and almost no dust was collected in the corona discharge region, as shown in Figure 3 (b). The applied voltage at 700 Pa was very low compared to that at earth's atmospheric pressure, owing to the low corona onset voltage. Dust was collected on the surface of the wire electrode contrary to the case for 10^5 Pa.

Figure 3. Measured dust collection rate in the wire-to-cylinder system.

The wire-to-parallel plate electrode system was prepared to investigate the different characteristics of the particle motion between the dust collection at atmosphere pressure and that in the low-pressure atmosphere. This is because the motion of particles could be observed directly from the lateral side of this system using a high-speed video camera. Figure 4 shows the measured V-I curves in the wire-to-plate system at 10^5 Pa and at 700 Pa. The characteristics were common to those for the wire-to-cylinder system shown in Figure 2.

Figure 4. Measured V-I curves in the parallel wire-to-plate system.

Figure 5 shows the measured dust collection rate in the wire-to-plate system. The fundamental characteristics are common to those in the wire-to-cylinder system shown in Figure 3. The rate increased with an increase in the applied voltage, and was around 80% at 10^5 Pa at the applied voltage just below the corona onset voltage. A very high rate, of approximately 90–100%, was realized by applying a higher voltage to the wire electrode that generated the corona discharge. Dust was collected on the inner surface of the plate electrodes. However, in the low-pressure (700 Pa) atmosphere, although the efficiency was 80% without a corona discharge, almost no dust was collected in corona discharge region. Dust was collected on the surface of the wire electrode unlike the case for 10^5 Pa.

Figure 5. Measured dust collection rate in the parallel wire-to-plate system.

IV. Particle Trajectories

A. Measured Trajectories and Motion of Particles

Figure 6 summarizes particle motions observed from the lateral side of the wire electrode in the wire-to-plate system. Typical particle trajectories are illustrated in the figure.

(1) At atmospheric pressure (10^5 Pa), applied voltage lower than corona onset (0.6–4.5 kV)

Particles introduced near the wire electrode moved to the wire electrode owing to the Coulomb force and dielectrophoresis force applied to particles, and then touched the wire. The particle was charged positively at contact, and repelled from the positive wire electrode to the negative plate electrode. The repelling speed of charged particle was high when the applied voltage was high, owing to the high electrostatic field, and the particles were attracted to the plate electrode. On the other hand, particles introduced near the plate electrodes moved to the plate electrodes owing to the Coulomb force (if the particle was charged positively), and then attracted to the plate. In both cases, particles were deposited on the surface of the plate electrodes as observed. Because some particles were charged negatively, the dust collection rate was not 100%.

Figure 7 shows the accelerations of randomly selected particles in the system. The accelerations were deduced from the video images by using the motion analyzing software TEMA (Image Systems). It was confirmed that particles near the wire electrode were attracted to the wire electrode. Figure 7 (a) shows that particles located at approximately 8 mm from the wire were attracted to the wire electrode when the applied voltage was lower than corona onset at 10^5 Pa.

Figure 6. Summary of particle trajectories in the wire-to-plate system.

(2) At atmospheric pressure (10^5 Pa), applied voltage higher than corona onset (7 kV)

Almost all particles were attracted to the plate electrode, because both positive and negative particles were charged positively when they came in contact with the positive ions generated by the corona discharge. This was consistent to the experimental results wherein almost 100% particles were deposited on the surface of the grounded electrode at the corona discharge region at 10^5 Pa.

(3) At low pressure (700 Pa), applied voltage lower than corona onset (0.6 kV)

Particles introduced near the wire electrode moved to the wire electrode owing to the Coulomb force and dielectrophoresis force applied to particles, and then touched the wire. The characteristics of particles' motion were similar to those at 10^5 Pa so far. However, the contacted particles were not repelled but rather deposited on the wire electrode. This caused the low dust collection rate.

Figure 7 (b), the trajectories of particles at 700 Pa analyzed by TEMA, showed that particles located at approximately 2 mm from the wire electrode were attracted to the wire electrode at 700 Pa. The influential area at 700 Pa was much smaller than that at 10^5 Pa. The mechanism of these features is discussed in the subsequent section.

(4) At low pressure (700 Pa), applied voltage higher than corona onset (0.8 kV)

Almost all particles dropped without contact with the wire or plate electrodes, and therefore, the dust collection rate was almost 0%.

Figure 7. Measured acceleration to the wire of randomly selected particles in the wire-to-plate system.

B. Numerical Calculation of Particle Motion

Particle dynamics was simulated to investigate the difference between the particle motion at 10^5 Pa and that at 700 Pa. Particle motion was calculated based on a simple motion equation.

$$m\ddot{x} = qE_x + 2\pi\epsilon_0\epsilon_r \frac{1-\epsilon_r}{1+2\epsilon_r} \left(\frac{d}{2}\right) grad E_x^2 - \frac{3\pi\eta d}{C_c} \dot{x} \quad (3)$$

$$m\ddot{y} = mg - \frac{3\pi\eta d}{C_c} \dot{y} \quad (4)$$

where x is the lateral coordinate from the center of the wire electrode, m is mass of the particle, q is the charge of particle, E_x is the electrostatic field in the lateral direction, ϵ_r is the relative permittivity of the particle, d is the diameter of the particle, η is the viscosity of air (1.82×10^{-5} Pa·s), C_c is the Cunningham correction factor,¹⁸ y is the axial coordinate from the top of the system, and g is the gravitational acceleration. The electrostatic field was calculated by the finite difference method, by reproducing the geometry and boundary conditions of the actual system. The first, second, and third terms in the right-hand side of Equation (3) are the Coulomb force, dielectrophoresis force,¹⁹ and air drag, respectively. The first and second terms in the right-hand side of Equation (4) are the gravitational force and the air drag, respectively. Equations (3) and (4) are numerically calculated using the Runge-Kutta method.

The charge of the particle is one of the critical parameters in the numerical calculation. Although substantial efforts have been devoted on the charging of particulates, it is still unclear. It depends on many parameters, such as particle size, composition, atmosphere, and collision. The charge is not identical but distributes in wide range, from positive to negative.⁷ Therefore, we adopted the typical values measured by the free-fall method.^{7,20} In this method, the particles were supplied at the center of the parallel plate electrodes, to which high DC voltage was applied. The

particles fell down, moving right or left from the center depending on the polarity and charge of the particle. A picture of all fallen particles that settled on an adhesive sheet on the grounded lower plate was taken using a high-precision scanner (CanoScan 9000F, Canon), and the charge of the particle was deduced implicitly using their distance from the centerline. The measured result at 10^5 Pa indicated that although the charge densities were distributed in a wide range both positively and negatively, the averaged values of positively and negatively charged small particles were approximately $+0.03 \mu\text{C/g}$ and $-0.13 \mu\text{C/g}$. On the other hand, at 700 Pa, the respective values were $+0.02 \mu\text{C/g}$ and $-0.02 \mu\text{C/g}$. Therefore, the charge density of the particle at 10^5 Pa was assumed to be $-0.1 \mu\text{C/g}$, and at the other two cases, $+0.001 \mu\text{C/g}$ and $-0.01 \mu\text{C/g}$, as calculated at 700 Pa.

Figure 8 shows the calculated trajectories of the particles. It was predicted that particles fed at 9.5 mm from the wire were attracted to the wire electrode at 10^5 Pa. On the other hand, the effective region at 700 Pa was 1.7 mm from the wire for the negatively charged particle and only 0.5 mm for the positively charged particle, values which were much smaller than that at 10^5 Pa. These calculated results coincided with the experimental results described above. Considering all the experimental and numerical results, it was assumed that the low charge density of particles resulted in the low Coulomb force, and because the dielectrophoresis force was dominant, the particles were deposited on the wire at 700 Pa. It was assumed that the low charge density was caused by the discharge between particles during the evacuation process, because the threshold voltage of the spark discharge was low at low pressure, based on Paschen's law.¹⁷

Calculated particle motions in the Martian gravity are added in Fig. 8 (b) and (c), designated in broken blue curves. Particles are attracted on the upper side of the wire electrode owing to the relatively low gravity on Mars, but fundamental characteristics in the Mars gravity is similar to that in the Earth gravity.

Figure 8. Calculated trajectories of particles. Solid black curves are trajectories in the Earth gravity and broken blue curves are those in the Mars gravity. (parameter: initial position of particle, $d = 20 \mu\text{m}$)

V. Cleaning of Trapped Dust

Figure 9 shows time dependent characteristics of dust collection performance in 700 Pa air. Figure 9 (a) is weight of slipped dust from the precipitator versus the operation time. The feed rate was deduced from the derivative of the weight of slipped dust without application of voltage, designated in red. The dust collection rate shown in Figure 9 (b) was determined by the rate of the slipped dust with the application of voltage divided by the feed rate. It is clearly seen that the performance was degraded very rapidly, because dust is collected on the fine wire electrode in the low-pressure air (700 Pa). Actually, cleaning of collected dust is one of the most serious issues in industrial electrostatic precipitators. However, fortunately, it is very easy to vibrate the wire electrode and to remove dust on the wire. We have successfully demonstrated the cleaning of dust by vibrating the wire. It was realized by a small unbalance motor attached at the top end of the wire.

Figure 9. Time dependent characteristics of dust collection performance in the parallel wire-to-plate system. (0.6 kV, in 700 Pa air)

VI. Conclusion

An electrostatic precipitator was developed to remove dust from the CO₂ gas to be used in ISRU for the production of oxygen in the Martian environment. The electrostatic precipitator is expected to make the atmospheric gas clean and usable for the oxygen extraction system. The technology has several advantages, such as low-pressure drop, low power consumption, and high collection efficiency. The setups that consist of the wire-to-cylinder electrode and wire-to-plate electrode were constructed to investigate the fundamental characteristics of the system. A preliminary experiment was conducted and it was found that performance at low pressure (700 Pa), which was selected to simulate the Martian environment was different from that at atmosphere pressure (10⁵ Pa), i.e., (1) the applied voltage must be low because the values of corona onset and spark discharge voltage are low compared to those at 10⁵ Pa, (2) the dust deposited on the wire electrode at 700 Pa while it deposited on the cylinder or plate electrodes in atmosphere pressure, (3) at corona discharge region no dust was collected in 700 Pa while the dust collection rate was almost 100% at 10⁵ Pa. The mechanism of these phenomena was investigated by direct observation and numerical calculation of the particle motion, and it was clarified that lower applied voltages and lower charge density of the particles caused these characteristics. Although the performance was degraded very rapidly in low pressure atmosphere due to the deposition of dust on the fine wire electrode, it was demonstrated that it was very easy to vibrate the wire electrode and to remove dust on the wire. Countermeasures to realize high deposition performance of the system in the Martian atmosphere are under investigation.

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