Dust removal from surfaces in a low pressure environment

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Dust particles are ubiquitous on Mars and on the Moon and can constitute a potential hazard for space missions [1]. The microparticles can range in size from a fraction of a micron to several tens or hundreds of microns and are subjected to ionizing radiations coming from the sun and cosmic rays. Dust has the tendency to stick on surfaces thus posing several technical problems: it can hinder the proper functioning of solar panels, imaging devices, and detectors or it can block the bearings, joints and movable parts of tools or machines [2].

A couple of technical solutions for dust removal have been proposed . The first solution consists in attaching to a surface a sort of electrostatic shield [1, 3]. The shield is basically a fine metallic grid which covers the area exposed to dust. When charged dust adheres to the surface a voltage is applied on the wires of the grid and the electrostatic repulsion removes the dust particles. The mesh-grid can be printed directly on insulating surfaces or on dielectrics. It can also be coated with a dielectric material to make it usable on a metallic surface. The grid has to be dense enough at a millimeter scale in order to be effective and remove a sufficiently large number of particles. This solution can be implemented on surfaces where contamination is critical such as solar panel, view ports, etc. A second solution consists in the use of a precipitator to collect dust during the process of extracting oxygen, water or methane from Martian atmosphere [4]. A tube provided with two electrodes produces a corona discharge when a high voltage is applied. The electric field drives electrostatically the charged dust to one electrode where it is trapped. Tests in conditions similar to Martian atmosphere have shown a good collection efficiency of over 90% for sooth dust.

Here we propose a technique for removing dust from different types of surfaces in vacuum or in gases at low pressure based on pulsed plasma jet [5]. The plasma jet is produce in a coaxial plasma gun. The idea is to transfer the momentum carried by the plasma ions to the dust particles and entrain them in the direction of the plasma flow. The plasma jet is more efficient than a neutral flow of gas since its speed is orders of magnitude higher. As an example, the sound speed in argon is 323 m/s at room temperature while the speed of argon ions expelled from a coaxial gun is in the tens of km/s range, which is at least an order of magnitude higher. When comparing argon ions from a plasma jet and neutral atoms colliding with a micron size particle, the rate of momentum transfer is much higher for ions due to their higher initial speed.

In fact it has been demonstrated that carbon microparticles with hundred of microns in diameter can be accelerated to a few km/s by a relatively large coaxial gun [6] which expels a plasma jet with a speed of ≈ 60 km/s.

The coaxial plasma gun has been introduced in the late 60's by Marshall and since then it has found many applications, from tokamak fueling to surface processing. The design is simple: a center rod and an outer cylindrical metallic shell constitute the electrodes which are coupled to a high voltage source, as shown in Fig. 1. The inter-electrode gap is first pumped down to high vacuum. There are two operating scenarios: in the first one the gun is filled with gas at constant and low pressure, in the mtorr range. When the high voltage is applied the gas is ionized, typically at the connectors end of the gun, and a current flows between the electrodes. Subsequently, all the neutral gas inside the coaxial space turns into a plasma and exits the gun at high speed. In this case, the propagating ionization plasma front is impinging on the neutral gas ahead of it, hence the name "snowplow" used to describe this operation mode. In the second scenario, gas is rapidly injected inside the gun by a puff gas valve and the electrical discharge is ignited simultaneously. The formed plasma expands freely along the coaxial space and then ejected outside the gun. In both cases the Lorenz force associated with the discharge current acting on the ions ejects them with speeds of several kilometers per seconds, however the ejection speed is highly dependent on the operation regime, gas type, gas pressure, gun geometry, high voltage and energy put on the electrodes.

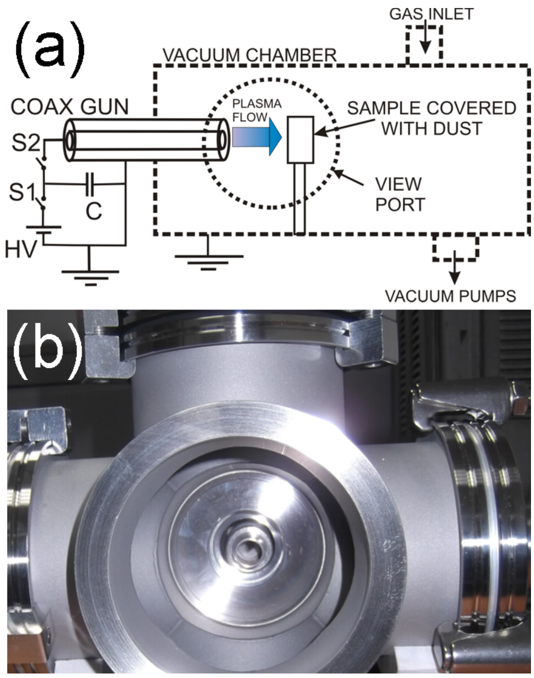

Figure 1: *(a) Setup with coaxial gun aimed at a dusty surface in low pressure gas and (b) coaxial gun used to produce a plasma jet.*

The Ampere force exerted on ions is as follows:

$$m_i n_i \frac{dv}{dt} = -\nabla p + \frac{1}{c}[\mathbf{J} \times \mathbf{B}]_z \tag{1}$$

where m_i and n_i are the mass and density of ions, respectively, z is in the axial direction of the coaxial gun, p is pressure, J is the discharge current density and B is the self-created magnetic field. Acceleration of ions is more effective at a high current density $\mathbf{J}$. In fact since $B \propto I$ the force is $\propto J^2$.

An alternate description of the discharge can be provided based on the parameters of the circuit realized with a capacitor bank C charged at a high voltage U and connected to the coaxial electrodes trough wires with resistance R and inductance L_0. The inductance L of the coaxial system is considered as a linear varying function with distance. In the snowplow regime we consider the formation of a thin ionized layer with density D which propagates along the gun axis. Numerical simulations have been carried out by solving a set of differential equations in order to find the optimum working parameters for the given conditions of the circuit and gas density.

For $L = 500$ nH, $R = 50$ mΩ, $U = 2$ kV, $D = 2 \times 10^{-4}$ kg/m^3 and the ratio between the outer and inner coaxial radii $r_o/r_i = 2$ we obtain by integrating numerically using a 4-th order Runge-Kutta method the speed of the ionization front as a function of the distance traveled inside the coaxial gap, and the discharge current. The model predicts (Fig. 2) a peak plasma flow speed of 1.7 km/s at about 1 cm from its origin, which then decreases rapidly with distance to about 500 m/s after a distance of 6 cm. This is due by the compression of the gas lying ahead of the formed plasma, opposed to the plasma flow. The predicted peak current reaches about 7 kA, in agreement with measurements.

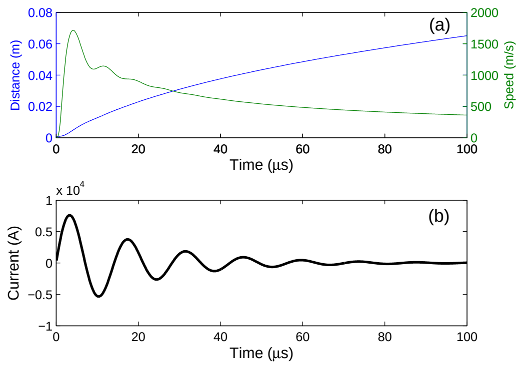

Figure 2: *Simulation of the discharge parameters: (a) traveled distance and speed of the ionization front and (b) current variation in time.*

An example of a measured I-V characteristic of the coaxial plasma gun is shown in Fig. 3. A positive high voltage is applied on the center rod while the outer coaxial cylinder is grounded. The current is measured with a Rogowski coil while the instantaneous high voltage with a Tektronix probe. The gun is operated at 5.3 torr in CO_2 and a charging voltage of 1.6 kV. Due to the circuit inductance the discharge current lags behind the voltage, as expected.

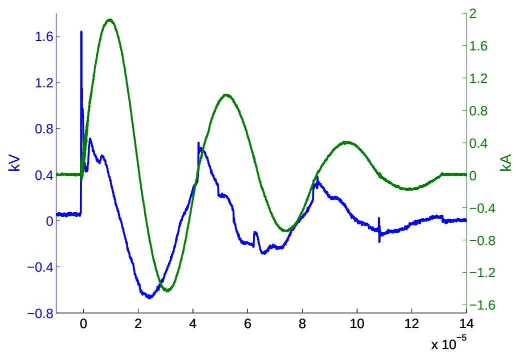

Figure 3: *Measured I-V characteristic of the coaxial gun.*

The force exerted by the plasma flow on the dust particles can be estimated using a simple dust drag model [5]. Since electrons have a negligible mass compared to ions, the plasma drag force is mainly established by the ion flow. We consider the idealized situation in which a stream of ions with density n_i and flow speed v_{plasma} is colliding with a spherical dust grain. We also consider that the charging of the dust grain is negligible and therefore the Coulomb interaction between ions and the dust particle does not contribute to the net drag force F_{plasma}. The direct impact force of ions relative to the mass of a dust grain is $\propto (n_i r_d^2)$ and depends on the ratio between the ion flow speed and the ion thermal speed. We consider a dust particle with radius 1 μm and estimate the drag force as a function of the ion flow speed, for several values of the ion density (from 10^{15} to 10^{20} m^{-3}), as presented in Fig. 4. In order to lift off a dust particle from a surface we expect to have a plasma drag force larger than the gravity force: $F_{plasma} > m_d g$. Here we consider a particle made of JSC-Mars 1 Martian regolith simulant with a density 1910 kg/m^3. The equilibrium of these two forces depends drastically on the ion flow speed and ion density. In the low range $n_i = 10^{16}$ m^{-3} the minimum ion flow speed is about 6 km/s while for $n_i = 10^{18}$ m^{-3}, a flow of a few hundred m/s is required to levitate the dust particle.

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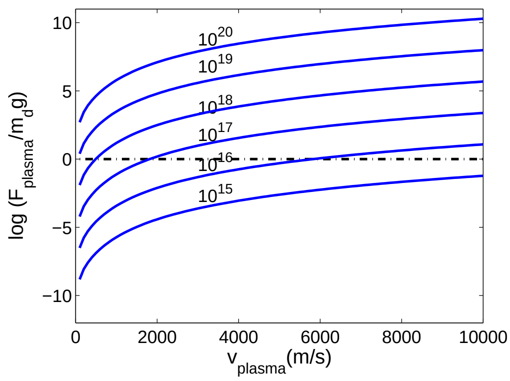

Figure 4: *Plasma drag force relative to the gravity force acting on a dust with* 1 μ*m radius, at different plasma densities (in* m^{-3}).

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