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Magnetic Mars Dust Removal Technology

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Environmental data recorded by the Mars exploration rovers show that the martian dust is magnetic containing mostly the strong magnetic mineral magnetite (Fe_3O_4). On the other hand, it is known that dust settling onto the surface of solar arrays can affect the utility on solar power on any Mars mission, and particulary for long term operation. Dust obscuration of solar arrays can be a special issue for the case of a future 6-months Sample Fetching Rover (SFR) mission where the current baseline architecture contemplates the use of solar array and where dust storms can jeopardize the entire mission, not only affecting the supply of energy for locomotion but for the communication with the Mars Ascent Vehicle (MAV). Today, available dust-removal techniques have been classified into four categories: natural, mechanical, electromechanical, and electrostatic. However, by aforementioned, an additional category may be included in this portfolio based in the magnetic properties of the martian dust. Here a first scoping study for a magnetic Mars dust technology is outlined. Finally a specific ad hoc magnetic technology is proposed an analyzed.

Keywords. *Mars dust removal techniques, Mars dust detection, Sample Fetching Rover (MSR), Solar array*

I. INTRODUCTION

Power loss of solar array caused by settled dust for mission on Mars can be a major concern. For instance, the total obscuration of solar array for the Pathfinder (30 day) and network (2 year) mission is given in table I,[1], where for this mission losses around 77% for the baseline case and as high as 89% for the worst case during a 2 year mission were reckoned.

Although the figures in Table I can be too generic and for example never foreseen, for instance, for other missions as the Exomars mission, nevertheless unpredicted large dust storms cannot be unruled at all. Spirit's output with solar cells capable of providing more than 900 watt-hours of electricity per day has dropped to about 400 watt-hours, partly because Martian dust. Opportunity's output with around 900 watt-hours of electricity per day declined at to around 500 watt-hours -regaining partly its power because the so called cleaning events whose nature is nowadays not known). More recently, on June 2018, the Mars Reconnaissance Orbiter´s Mars Colour Imager (MARCI) camera recorded two large dust storms over its northern hemisphere during the week of May 28 to June 3, 2018 at the locations of the Opportunity rover at Meridiani Planum, and Curiosity rover in Gale Crater which are very close to the last landing site of a the InSight at Elysium Planitia (November 2018).

Dust is expected to be adhered to the array by Van der Waals adhesive forces which can be very strong for the dust particles sizes, [1]. Today, the available dust-removal techniques can be classified into four categories, [2] namely: natural, mechanical, electromechanical, and electrostatic. Natural dust removal relies in the possible capability of surface martian wind for cleaning the solar array which seems not to be applicable for horizontal arrays at locations with wind conditions similar to those find at the Viking landing site. Mechanical-removal is based in the use of mechanical wiping, blowing, or removable covers, however, the constraints in weight for, say, the SFR mission makes this a not very reasonable approach. Electromechanical-removal comprises shaking the array, or using sound to break dust adhesion, however, besides to have the wight constraint problem, also it would be necessary another supplementary system to carry the dust away after adhesion is broken. Finally, electrical-removal is based in inducing electrostatic forces. For this last method, if the array surface is charged and conductive enough, dust particles will accumulate a charge the same as the array, and then repelled from the array.

TABLE I: Total obscuration of solar array for the Pathfinder (30 day) and network (2 year) mission. From [1].

Case	Obscuration (30 day mission)	Obscuration (2 year mission)
Baseline	6.6%	77%
Best	0.5%	22%
Worst	52.2%	89%

Here, it is proposed a new approach based in the recently demonstrated magnetic properties of the martian dust. According to the recent data obtained by NASA´s Mars Exploration Rover Spirit, the martian dust is containing

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mostly the strong magnetic mineral magnetite (Fe_3O_4). If so, the magnetic properties of the martian dust can be harnessed as a new dust-removal technique.

There are several techniques in which the dipolar magnetic momentum of the dust particles can be used for cleaning the solar array. For example, it is known that under the action of an external magnetic gradient, magnetic dipoles experience a force, therefore the generation of an external magnetic gradient by, say, permanent magnets properly located, or by solenoids can generate the driving force to remove dust particles from the solar array. Another option is a kind of *dust-pump* without need of any mechanical moving part (and then avoiding issues as clogging, erosion, wear and tear of conventional pumps). Such a martian dust-pump could remove the dust by sucking dust particle from the array and ejecting far from the panel. Dust blasting or sputtering in which the solar array is bombarded by energetic dust particles accelerated by magnetic fields cannot ruled out.
Finally, another possibility is the use of a magnetic sheet and ferrofluid bubble which will be discussed in more detail next.

A. Magnetic Mars Dust Removal

It is known that particles provided with a magnetic dipole -as is the case of magnetite Fe_3O_4, and under the action of a non-uniform magnetic field, undergo a force which is given by

$$\mathbf{F}_m = \mu_o M \nabla \mathbf{H} V \tag{1}$$

where μ_o is permeability of free-space and has value $\mu_o = 4\pi \times 10^{-7}$Hm; M is the magnetization of the particle; $\nabla\mathbf{H}$ the gradient of the external magnetic field; and V the volume of the particle.
Therefore, by applying an external non-uniform magnetic field, e.g., using a permanent magnet or solenoid, this translates into a force which can be used for removal of the particle from the solar array. In order to accomplish this, there are two chief forces which the magnetic force must overcomes. Firstly, the strong adhesive *Van er Waals* force, and secondly, it must be able to carry the dust away after adhesion is broken, i.e., overcoming gravitational force.
To begin with, it is useful to consider expressions for various energy terms.
From Eq.(1), the magnetic energy is given by

$$E_m = \mu_o M \mathbf{H} V \tag{2}$$

The Van der Waals energy between a sphere and surface is given by, [3]

$$E_w = \frac{A}{6}\frac{R}{D} \tag{3}$$

where A is the *Hamaker constant*; R is the radius of the particle, and D is the distance between the particle and the surface which is around $1\mathring{A}$, i.e, the typical distance between atomic planes in a crystal and inter-atomic distances. On the other hand, the gravitational energy is given by

$$E_g = \rho \mathbf{g} L V \tag{4}$$

where ρ is the density of the particle - neglecting the atmospheric density of Mars in comparison with than the particle; $\mathbf{g}$ is the gravitational acceleration; and L is the characteristic length of the system, or in our case the vertical clearance distance to jettison the dust away from the array.

It is easy to see that, magnetic energy is available to broken adhesive *Van der Waals* force, with the effectiveness of the disruption governed by

$$\frac{E_m}{E_w} = \frac{8\mu_o M \mathbf{H} R^2 D}{A} \tag{5}$$

where the volume of particle was given by $V = \frac{4\pi}{3}R^3$.

Likewise, the relative influence of magnetic to gravity is described by the ratio

$$\frac{E_m}{E_g} = \frac{\mu_o M \mathbf{H}}{\rho \mathbf{g} L} \tag{6}$$

- **Discussion**

To obtain some idea of the potential of magnetic dust-removal, predicted by the Eq.(5), Eq.(6), we assume some typical values of the parameters: For magnetite Fe_3O_4: $M = 4.46 \times 10^5$ Am^{-1} and $A = 10^{-19}$ Nm, [4]; a mean density $\rho \approx 2.0 \times 10^3$ kg/m^3; $g = 3.71$ m/s^2, a clearance distance $L = 0.1$ m, and the distance between the particle and the surface for the calculation of the Van der Waals energy as $D = 1\mathring{A}$, i.e., the typical distance between atomic planes in a crystal and inter-atomic distances.
The resulting curves are shown in Fig. 1 as function of the magnetic field. For the case $\frac{E_m}{E_w}$ several radius of the dust particles were considered. Referring to Fig. 1, it is easy to see that if one considers that a hand-held permanent magnet can be as high as $H = 8 \times 10^4$ Am^{-1}, [4], then, the proposed magnetic technique for dust-removal can be an attractive method, even considering very mild magnetic fields.

B. A ferrofluid bubble design

Though there may be many possible designs in which magnetic fields can be used to remove dust from the solar

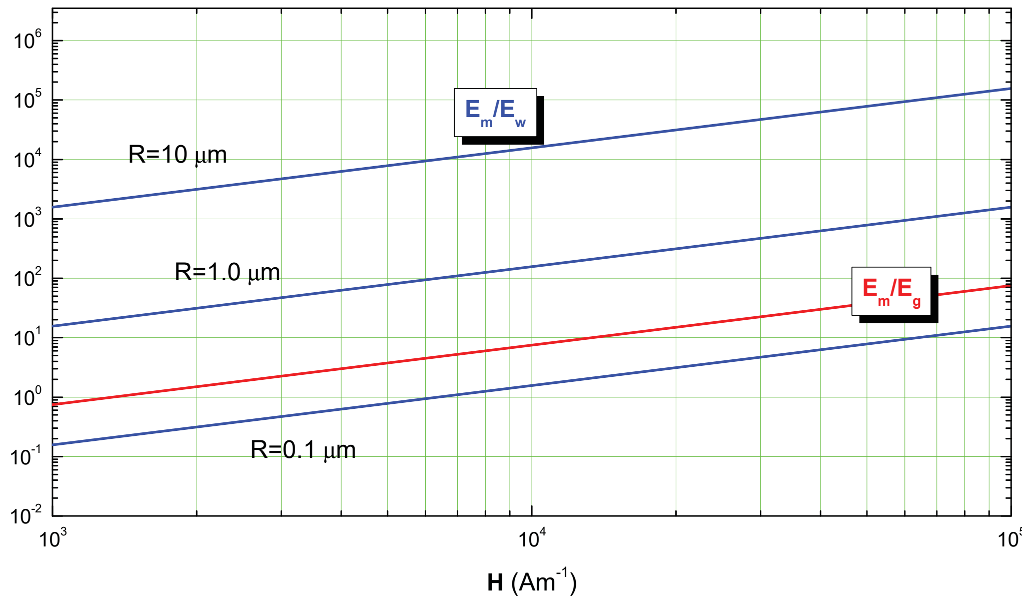

FIG. 1: Energy ratios: magnetic-to-adhesive; and magnetic-to-gravitational as function of the magnetic field applied.

array, it is interesting to assess at least one of them in terms of power/mass/volume requirements. In this section an ad hoc magnetic technology for dust removal is proposed and analyzed.

To begin with, let us assume a solar array with a certain area in which the sunlight side -with the photocells, is receiving the sunlight. Now let us put in the back area -located in the shadow side, a very thin flexible magnetic sheet (similar to those we find in the market) and covering the area of the array. Simple commercial magnetic sheets can be found with typical thickness around 0.5 mm and densities around 36000 kg/m^3; and can generate weak magnetic fields around $\approx$ 10-to-50 Gauss which translates into a pull force of 40 g/cm^2 or thereabouts. This magnetic sheet will create a very soft uniform magnetic field on the sunlight side which can be felt by the particles of dust adhered onto the solar array. Therefore, we have a magnetic field background without any expenditure of energy (where electrical power for solenoids were not required). However, it is clear that in order to move the dust particles, it is necessary a non uniform magnetic field. This can be made as follows:

Let us put in the middle of the solar array and the flexible magnetic sheet a third layer in between composed by a labyrinth closed system where a working fluid (for example a gas like CO_2) is pumped with a very slow circulation. Now, if in this system a bubble of ferrofluid is introduced, then, with the pass of the bubble there will be a local increase of the magnetic field due to the added magnetic field of ferrofluid bubble (given by the magnetization), and then the total local magnetic field at the position of the bubble H_t will be $H_t = M + H$ and a net attractive force acting on the surrounding dust particles and towards the location of the bubble will be present. In other words, the particles of dust onto the solar array will follow the bubble moving in the beneath layer. The method will be very similar as moving ferromagnetic objets on a table by the motion of a magnet beneath the table.

Fig. 2 shows a summarized sketch of this hypothetical system.

The energy required for dust removal for this system can be easily calculated by calculating the pumping power required to move the bubble through the circuit as follows. On one hand the the pumping power W for the circulation of the bubble is given by.

$$W = \Delta p s u \tag{7}$$

where Δp is the drop pressure, s is the cross section area of the circuit which calculated with its equivalent hydraulic diameter is equal to $s = \frac{\pi D_h^2}{4}$; and u is the velocity of the bubble.

On the other hand the drop pressure c can be calculated with the Darcy-Weisbach equation

$$\Delta p = \frac{fl}{D_h} \frac{\rho_f u^2}{2} \tag{8}$$

where f is the friction factor, l is the total length of the circuit; ρ_f the density of the working fluid. Now, the velocity required can be calculated by fixing the number of cycles pr day, i.e., the number of times that the bubble must travel along the panel during the day. Therefore, if the total length of the circuit is L, and it is desired n cycles per day every day with a duration t_d, then the velocity is given just by

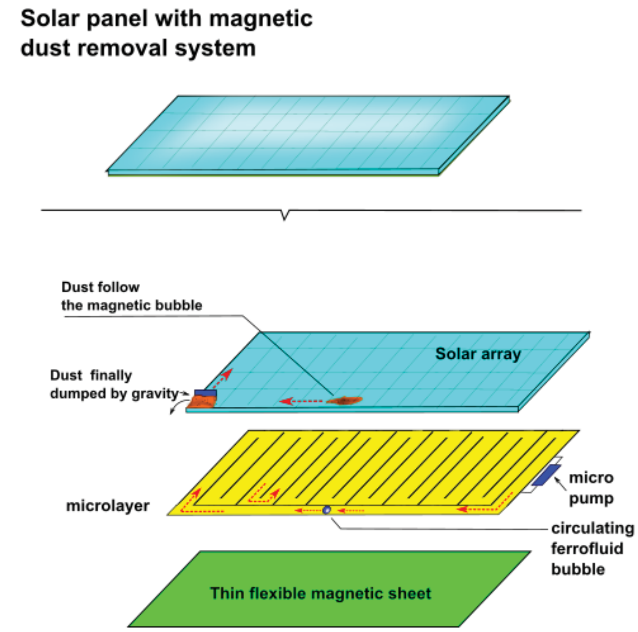

FIG. 2: Hypothetical magnetic Mars dust removal system based by the use of a magnetic sheet and a ferrofluid bubble.

$$u = \frac{l}{t_d} n \tag{9}$$

Therefore taking into account Eq.(7), Eq.(8) and Eq(9), one obtains

$$W = \frac{\pi f \rho_f l^4 D_h n^2}{8 t_d^3} \tag{10}$$

and the energy required per day as

$$E = W t_d$$

$$E = \frac{\pi f \rho_f l^4 D_h n^2}{8 t_d^2} \tag{11}$$

- **Discussion**

To obtain some idea of the energetic requirements predicted by Eq.(11) we assume some values of the parameters: Let us say that the pumping fluid is actually CO_2 with a certain pressurization making its density $\rho_f = 1$ kg/m^3. Typical friction factor can be as high as $f = 0.005$. Because it is desired a very thing layer, the hydraulic diameter through which the fluid (and ten the bubble) circulates be around 0.5 cm. Let us analyze the case for a square solar array with 1 m$\times$1 m area (1 m^2) and thus the total length of the circuit should be around $l = 200$ m; the martian day is around $t_d = 8.82 \times 10^4$ s. Therefore, if it is desired that every day the magnetic bubble clean the panel say, $n = 10$ times, we obtain from Eq.(11) a requirement around 20 Joules per day. Although in the preceding calculation we don't consider the stopping force exerted by the magnetic dust on the bubble, nevertheless even considering this and other several uncertainties, and assuming a figure 100-fold, , this amount of energy can be easily provided by the own solar array if one considers that irradiation on Mars could be averaged around 100- 200 W/m^2.

Finally the weight required by the the system, is given by the weight of the magnetic sheet, the weight of the microlayer and the micro pump.

As aforementioned, typical magnetic sheets can be around 0.5 mm thickness and with density 3600 kg/m^3, therefore, for an area of 1 m^2 it will weight around 1.8 kg. The microliter with the micro circulating systems -which can be just a furrowed matrix worked by laser, and can be with a very light material, so a figure around 5 kg seems reasonable. Finally a micro-pump (for example a peristaltic) could be around 0.1 kg. Therefore, the total weight of the system could be 6.9 kilograms per m^2 of solar array.

Finally, it is interesting to note, that the microlayer circuit can be used as heat exchanger if it is desired, i.e., the magnetic dust removal system could be integrated with the heat removal system.

NOMENCLATURE

A = Hamaker constant
c_d = drag coefficient
D = distance between the particle and the surface
D_h = hydraulic diameter
E = energy

f = friction factor
F = force
$\mathbf{g}$ = gravitational acceleration
H = magnetic field
l = length of the pipeline
L = clearance vertical distance
M = magnetization
n = number of time the bubble travel the solar panel per day
R = radius of the particle
t_d = time of a Martian day
u = velocity of the working fluid
V = volume of the particle

Greek symbols
μ_o = permeability of free-space
ρ = density of the dust particle
ρ_f = density of the working fluid

subscripts symbols
g = gravitational
k = kinetic
m = magnetic
w = adhesive

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