Numerical and Experimental Studies of the Electrohydrodynamic Pump for Sampling System on Mars

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***Abstract*—In this paper an electrohydrodynamic (EHD) pump, which is designed to sample suspended dust for a particle analyzer on Mars, has been studied numerically and experimentally. The proposed EHD pump utilizes the secondary EHD flow generated by the electric corona discharge. From a series of experimental measurements it was found that an air flow velocity of 350 feet/minute (or 6.4 km/h) can be achieved on earth if a voltage equal to approximately twice of the corona onset voltage level is supplied. A numerical model of the pump performance is also proposed to simulate the electrical field and the fluid flow involved in the sampling process on Mars. This numerical model considered unique conditions on Mars including the low atmospheric pressure (100 times lower than that on earth), the low ambient temperature (recorded average of 210.15K) and different gas type (mainly carbon dioxide). A calculated flow rate of 3.44l/minute can be obtained with the proposed EHD pump system at a much lower voltage level. The simulation results suggest that the flow rate and pressure drop requirements of the sampling system should be able to be met by using the proposed device. However, the final conclusion cannot be drawn without the actual tests under simulated Mars conditions.**

I. INTRODUCTION

Mars is known to be a dry and dusty planet: there are "regional dust storms" which persist for a few days or weeks and world-wide dust storms which encircle the entire plane. Dust particles are lifted and carried around by the storm wind. Because the Martian atmosphere is thin--about 1% of Earth's at sea level--only the smallest dust grains hang in the air. "Airborne dust on Mars is about as fine as cigarette smoke" [1] and these fine dust particles with a typical radius from 0.1 to 10 μm can remain suspended for months

[2]. It was found that the suspended dust has an important effect on the efficiency of photovoltaic power systems providing the energy for modules landed on the Mars surface. For example, a dust layer deposited on horizontal solar panels degraded the performance of the photovoltaic cells about 0.3% per day [2]. A few authors have studied the possibility of using either the technique of electrostatic precipitation [2] or electric curtains [3][4] to keep the solar panel surface clean. Knowing the accurate properties of the dust is a crucial part of this research. Mazumder and his team at University of Arkansas at Little Rock hold a NASA grant to build a particle analyzer just for this purpose. Design a reliable, easy maintained, light and Mars environment suitable sampling system for this analyzer is one of the problems the team would like to achieve.

In this paper a unique EHD dust sampling system, which will be connected directly to the bottom of the particle analyzer, has been proposed. It utilizes the EHD phenomenon, so it works silently, uses only electrical energy and generates gas flow without any mechanical moving parts. A prototype has been tested under earth atmospheric conditions, providing very promising result. A numerical model has been proposed in the second part of this paper to simulate the performance of the pump under Mars atmospheric conditions.

II. PROTOTYPE DESIGN AND TESTS UNDER EARTH CONDITIONS

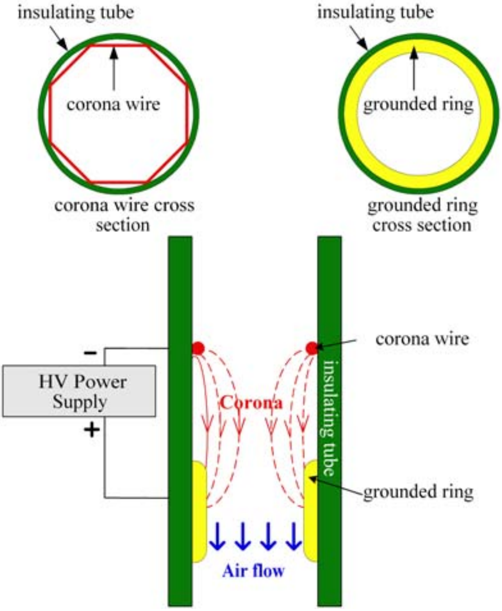

Fig. 1. The structure of the EHD pump prototype.

The EHD pump was designed to be in a shape of a cylinder, as shown in Figure 1, with a pair of corona electrodes being mounted on the inner wall of the insulating tube. A thin tungsten corona wire with a radius of 0.05mm is formed in a shape of an octagon facing a much thinker copper grounded ring. Figure 2 shows a picture of the fabricated prototype. The pump is 10cm high and 3cm in diameter. The distance between the corona wire and the ground electrode is 2.5cm. The design of the EHD pump configuration was derived from the electrostatic lifter which has been studied numerically and verified experimentally [5-7].

When a sufficiently high voltage is applied between the corona wire and the ground ring, corona discharge takes place. The ions with the same polarity as that of the corona wire travel towards the ground electrode in the electric field. On their way, the fast moving ions frequently collide with the surrounding neutral gas molecules and transfer momentum to them. As a result, gas flow is generated and the electrical energy is converted directly to mechanical energy.

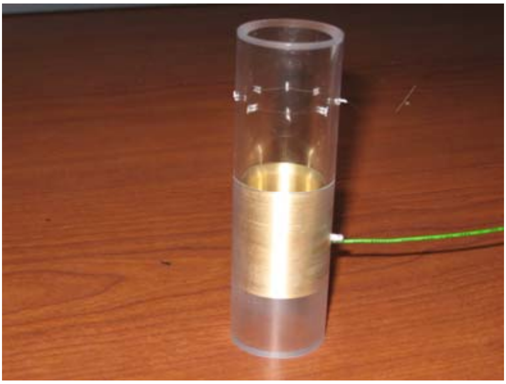

Fig. 2. The EHD pump prototype.

The preliminary experiments with the EHD pump were conducted in air at room temperature and atmospheric pressure. Figure 3 and 4 display the measured I-V curve and the velocity voltage relationship, respectively. The measured onset voltage for the pump is around 17kV. At 32kV, about double the value of the onset voltage level, an air flow velocity of 350 feet/minute, around 6.4 km/h, can be achieved.

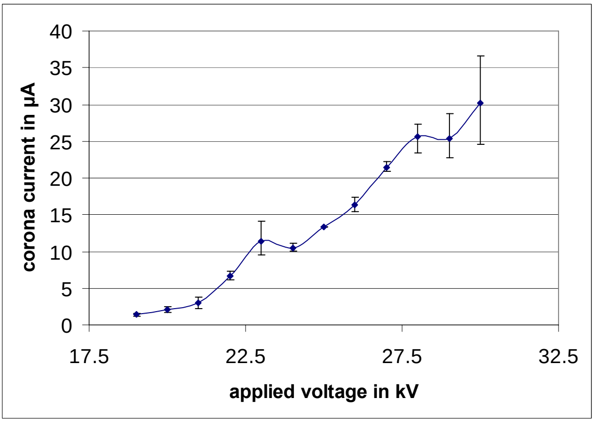

Fig. 3 I-V curve of the EHD pump under Earth atmospheric conditions

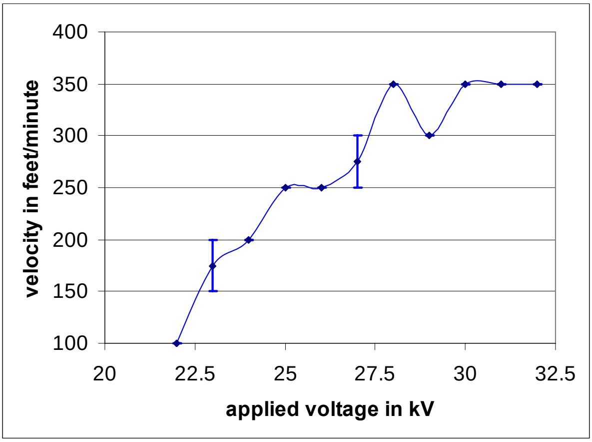

Fig. 4 Average velocity versus the applied voltage of the EHD pump under earth atmospheric conditions

III. MATHEMATICAL MODEL AND NUMERICAL ALGORITHM OF THE EHD PUMP UNDER MARTIAN CONDITIONS

The numerical simulation of the pump performance under the Mars atmospheric conditions was based on a 2-D model in cylindrical coordinates (r, z), as shown in Figure 5, where all the detailed dimensions are indicated. The computational domain is defined as $0<=r<=0.015$ and $-0.01<=z<=0.085$.

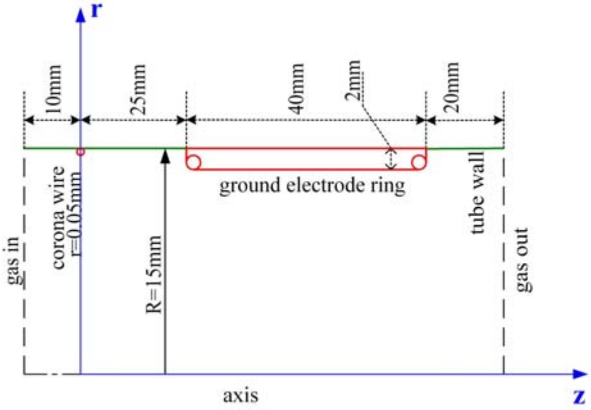

Fig. 5 Calculation model of EHD pump in 2-D cylindrical coordinates

The Martian atmosphere is mainly composed of carbon dioxide (content: 95%), the average recorded temperature on Mars is 210.15K, and the Mars atmosphere pressure varies from 5 to 10 mbar with an average of 7 mbar [8]. These atmospheric conditions make the corona discharge characteristics quite different than that on Earth. Some researchers have reported their work on experimental investigation of the corona discharge under simulated Mars conditions [2][9]. Pang and Atten investigated the corona discharge in CO_2 under low pressure with three popular configurations. Their experiments revealed that the corona onset voltage decreases and the unipolar corona discharge is limited to a relatively small voltage range [2].

The Mars atmospheric conditions will be considered in the proposed numerical model. Based on the assumption that the ionization layer of the corona discharge can be neglected and the unipolar electric charges are assumed to be injected from the corona electrode, the governing equations are the Poisson and charge conservation equations [10]:

$$\nabla^2 \Phi = -\frac{q}{\varepsilon_0} \qquad (1)$$

$$\nabla q (k_i \nabla \Phi + \mathbf{u}) = k_i \frac{q^2}{\varepsilon_0} \qquad (2)$$

where Φ (V) is the scalar electric potential, q (C/m^3)- the space charge density, ε_0 (F/m) - the permittivity of the gas, $\mathbf{u}$ (m/s) – gas velocity, and k_i (m^2/Vs) - the ion mobility

$$k_i = p_{atm} \times k_{i0} \qquad (3)$$

where p_{atm} is the actual pressure in atm and k_{i0} is the ion mobility at atmospheric pressure (760mmHg).

Under the assumption that the gas is incompressible, has constant density and viscosity, the gas flow has to satisfy the continuity and conservation of momentum equations [10]:

$$\nabla \cdot \mathbf{u} = 0 \qquad (4)$$

$$\rho_f [\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}] = -\nabla P + \eta \nabla^2 \mathbf{u} + \mathbf{F} \qquad (5)$$

where ρ_f =18.01(g/m^3) is the gas density at 7mbar and 210.15K, P (Pa) - the static pressure, η - the gas viscosity which, at 7mbar and 210.15K, is $\eta = \eta_0 \frac{T_0 + C}{T + C}\left(\frac{T}{T_0}\right)^{3/2} = 10.64 * 10^{-6}$ (kg/ms), and F (N/m^3) - the body force, in this case equal to the Coulomb force $q\nabla\Phi$.

The numerical model governed by (1), (2), (4) and (5) is the fully coupled model where the gas flow velocity vector appears in the corona discharge governing equation (2) and the space charge density and electric field are included in the flow governing equation (4). Therefore, both electric and flow fields are mutually coupled with each other.

The boundary conditions for the electric potential are straightforward: a constant DC potential is applied on the corona electrode and zero on the ground electrode. An indirect boundary condition for space charge density is obtained by adopting the Kaptzov hypothesis, which suggests that the electric field increases proportionally to the applied voltage below the corona onset, but it remains at the same level after the corona is initiated [11]. This critical electric field on the surface of corona electrode is given by the experimental Peek's value [12],

$$E_0 = 2.62 \cdot 10^6 \cdot \delta\left(1+\frac{0.525}{\sqrt{r_c\delta}}\right) \qquad (6)$$

where r_c is the radius of the corona wire in cm and $\delta = \frac{T_0 P}{T P_0} = 8.98 * 10^{-3}$ at 7mbar and 210.15K.

In the flow field, shown in Figure 5, surfaces of both electrodes and dielectric cylinder are defined as the stationary walls, where the gas velocity vector vanishes, and both ends of the pumping channel are defined as gas inlet and gas outlet.

A hybrid numerical technique based on the combination of Boundary Element Method (BEM), Finite Element Method (FEM) and the Method of Characteristics (MoC) has been used to simulate the corona problem. The whole algorithm is arranged into two iterative loops. In the inner loop, for assumed space charge density on the corona electrode surface, governing equations for the electric field and space charge density are solved iteratively until convergence is reached in the whole calculation domain. In the outer loop, the charge density on the corona wire surface is continuously updated using equation

$$q_{0new} = q_{0old} + \alpha(E - E_0) \qquad (7)$$

where α is an experimentally found coefficient, q_{0old} is the old value used in the previous iteration and q_{0new} is the new estimate at the present iteration, until convergence is reached for the electric currents calculated on both electrodes.

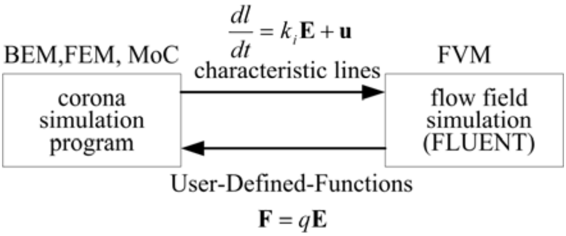

Fig. 6 Schematic calculation procedure for the fully coupled model.

Meanwhile, the commercial fluid mechanics software FLUENT was employed for the calculation of the gas flow. The corona simulation program was coded as a User-Defined-Function (UDF) of FLUENT and the Coulomb force was inserted into FLUENT as the gas body force. The gas flow governed by (4) and (5), which has been modified by EHD, is simulated using the finite volume method (FVM). After the residuals of both components of the velocity, the turbulence kinetic energy (k), and its rate of dissipation (ε) satisfy the specific tolerance, the flow simulation process terminates. The gas flow velocity is then entered back into the corona simulation program, which makes the whole simulation algorithm a triple iterative loop. The above-mentioned process is repeated, as shown in Fig. 6, until convergence is reached for all essential electrical and flow parameters. This stage of calculation can provide detailed information on the airflow, such as stream functions, path lines, velocity and pressure distributions, etc.

IV. SIMULATION RESULTS

Some preliminary simulation results for the designed pump prototype at a voltage level of 1.4kV (which is a little bit higher than the onset voltage at 1.05kV) under the Mars atmospheric conditions are presented in this Section.

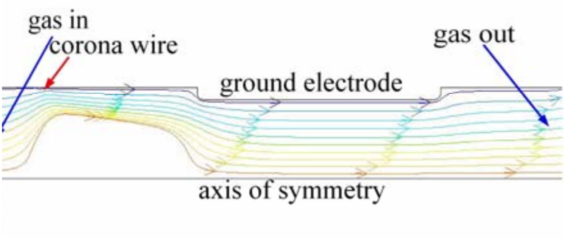

Fig. 7 Gas flow pathlines

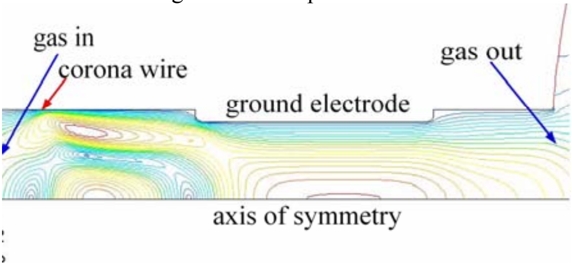

Fig. 8 Gas flow velocity contours

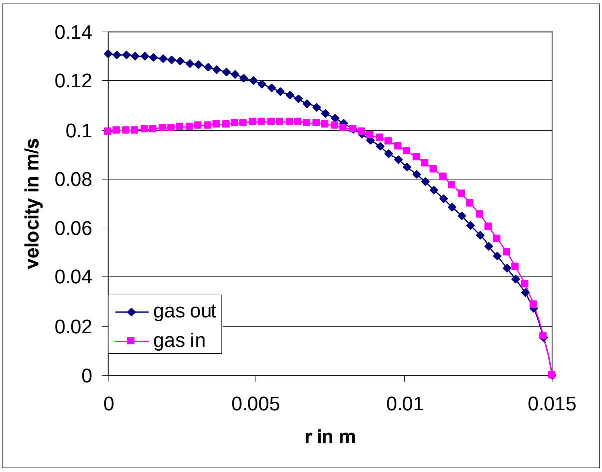

Fig. 9 Gas flow velocity profiles along both ends of the pump (gas inlet and gas outlet)

Figure 7 displays the gas flow pathlines with the arrows indicating the flow direction from the gas inlet end to the gas outlet. Figure 8 shows the gas flow velocity contours in the pump.

Combining Figures 7 and 8, we can see that the gas flow is initialized from the locations close to the corona wire and pushed towards the ground electrode. However, there are some vortices close to the center-line of the pumping channel indicating the gas recirculation within the pump. Since the inside circulation won't contribute to the average flow rate of the pump, better design should be attempted to avoid this type of energy loss.

Figure 9 further displays the gas flow velocity profile at both pump ends, the gas inlet and gas outlet. It can be seen that at the inlet the maximum velocity is located at the center of the pump, it then decreases when going close to the inner wall of the tube, and reaches zero on the wall. At the gas outlet the velocity distribution shows a local maximum at about 6 mm radius. The flow rate obtained in this case is about 3.44l/minute, which meets the requirement of 0.5-1l/minute flow rate for the particle analyzer.

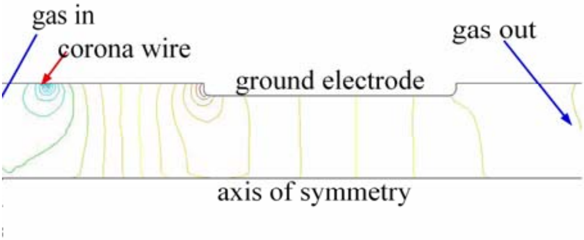

Fig. 10 Static pressure contours inside the pump channel

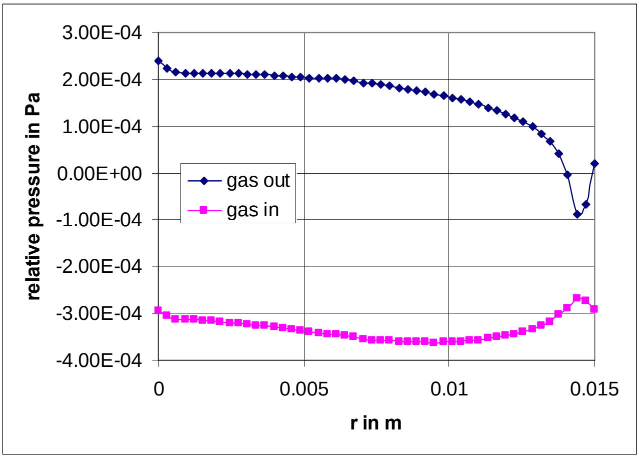

Fig. 11 Static pressure profiles along both ends of the pump

Figure 10 shows the static pressure contours in the pump with a standard [8] pressure of 7mbar. The lowest pressure is located in the region close to the wire where the gas is forced to flow away. The maximum pressure takes place in the region close to the ground electrode, where the gas flow is forced to change direction by the solid wall. Figure 11 further displays the pressure profiles along both ends of the pump, the gas inlet and gas outlet. It can be seen that the pressure difference between both pump ends is in the rage of 1 mPa.

V. CONCLUSION

A proposed EHD pump system for particle analyzer on Mars has been investigated experimentally and numerically. The experimental results with the pump prototype under the Earth conditions reveal that using the EHD pump to replace a traditional vacuum pump is realistic, if the required flow rate is low. Under Earth conditions the proposed corona system can effectively generate a gas flow of 6.4 km/h in the direction parallel to the pump channel.

A numerical model for simulating the EHD pump under the Mars atmosphere conditions was proposed as well. The simulation results seem to indicate that is quite possible to design a pump for the particle analyzer on Mars producing a required flow rate of 0.5-1l/m. It also should be pointed out that the presented research work is only at the preliminary stage.

More cases of numerical simulations should be conducted to provide the guidelines for an optimum design, such as the distance between both electrodes, shape of the ground electrode, shape and position of the corona electrode, etc. A better pump design should be attempted to meet the flow rate and the pressure drop requirements at a lower applied voltage and with a much lighter pump weight. The present numerical model should be further modified further to reflect the real condition on Mars.Experiments should be carried out under the simulated Mars environment to provide indirect experimental data for the optimum design.

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