Development of a Dust Particle Analyzer for In-situ and Simultaneous Measurements of Size and Charge Distributions of Martian Dust

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***Abstract* - In this report we present our progress of the NRA 02-OSS-01 project on the development of a prototype Dust Particle Analyzer (DPA) and its performance under simulated Martian atmospheric conditions. Both theoretical analysis assuming the predicted environmental conditions of Mars and experimental data on the development of the DPA show that the instrument has an excellent potential for its application to measure the size and charge distributions of dust particles on the surface of Mars. The instrument covers a size range of 0.5 to 20.0 µm in diameter and charge-to-mass ratio of the particle in the range 0 to ± saturation charge. The measurements are made on individual particle basis at a rate in excess of 100 particles per second. The instrument is made of a Laser Doppler Velocimeter (LDV) and a relaxation cell composed of an aerosol sampling system and an electro-acoustic drive. The aerodynamic diameter and electrostatic charge spectra of the particles are determined in a non-contact manner by LDV measurements of particle motion excited by an electric/acoustic field. The performance of the prototype instrument was tested with JSC-1 Mars dust simulants under both laboratory conditions and in a vacuum chamber at 5 mb to simulate the Martian atmospheric conditions simulated at NASA KSC. Instrument design, development and test data are presented.**

I. INTRODCUTION

Martian dust characterization is important for minimizing the effects of abrasion, adhesion, corrosion, and damage to mission hardware, and also to reduce the effect on human health [1]. Martian atmosphere contains a substantial amount of suspended dust which settles on rovers, solar arrays, and spacecrafts. Mars has a significant number of localized dust storms, referred to as dust devils which can attain heights of nearly 6 km [2]. Mars has a very low atmospheric pressure (~ 5 -10 mb), and low humidity as compared to that on Earth, which makes the dust on Mars more prone to triboelectric charging and electrical discharges. Due to low Martian atmospheric pressure, the amount of UV radiation reaching the surface is high, which leads to photo-ionization of the dust particle suspended in the atmosphere. Atmospheric dust particles on Mars deposit on solar panels and obscure radiation, clogs filters, valves, and mechanical devices, may deposit on electronic components and cause malfunction. Electrostatically charged dust particles cause two major problems, (1) adhesion, between the particles and the substrate, which increases significantly under dry conditions, and (2) deposition of particles increases as the charged particles seep into the recessed areas of equipment. Also, dust sampling leads to obscuration of optical windows and lenses reducing the performance of detection equipment. During human lunar missions, astronauts have reported that dust seeps into small crevices in their EVA suits leading to obstruction of movement. Dust might be transported into Mars habitat due to leakage or accumulation on EVA suits. The inhalation of transported dust can be highly toxic to the health of the astronauts.

One of the first steps to dust mitigation is to know the particle size and charge distribution of the dust particles. Once these characteristics are thoroughly known, dust mitigation technologies can be more efficiently designed. An instrument is needed to measure the particle size and charge distributions simultaneously on dust particles in real time, which will help in designing mission hardware to withstand the effects of adhesion, abrasion, corrosion and other dust related effects.

A. Challenges in remote in-situ measurements

For any particle analyzer to function on Mars, many environmental criteria have to be considered. The atmospheric pressure on Mars is about one-two hundredth of earth's atmosphere, and its atmospheric composition is mainly CO_2. The electrical breakdown is dependent on the atmospheric composition and pressure. On Earth, the electrical breakdown occurs when the electrical field exceeds 3000 KV/m whereas on Mars it is expected to occur at approximately 20 KV/m, which leads to frequent atmospheric electrical discharges at lower voltages [3]. The analyzer to be operated has to be tested under reduced pressure levels, to ensure that electrical discharges do not occur. The weight and size of the analyzer are also of primary concern; the analyzer has to fit within the stringent specifications for incorporating it into Mars missions. A major fraction of the power generated by the solar arrays is needed for maintaining essential services; the particle analyzer should use minimal power for its operation. Another important challenge is sampling of the suspended dust particles as they are settling under the influence of Martian gravity. The sampling pump should also meet low weight and low operational power requirements.

II. ESPART ANALYZER

There are many instruments which can measure particle size and electrostatic charge distributions [4]. The most common methods of non-contact measurement of particle size are: (1) Optical Particle Counter (2) laser diffraction analyzer, and (3) Laser or Phase Doppler Velocimetry. Electrostatic Classifiers, Differential Mobility analyzers (DMA), Electrical Low Pressure Impactors (ELPI), are based on charging the aerosol particles first, to measure particle size distribution. Faraday Cup is used to measure the bulk charge-to-mass ratio of powders. Charge separators separate the powders based on the polarity of their charge, giving information relating to positive and negative charge-to-mass ratio fractions. None of these instruments meet the criteria listed in the previous section for measuring both size and charge distribution in real time.

To measure simultaneously both particle size and charge distribution in real time, the Electrical Single Particle Aerodynamic Relaxation Time (ESPART) Analyzer [5] was developed at University of Arkansas at Little Rock over a number of years. The basic underlying principle of the ESPART analyzer is to measure the phase difference (Fig. 1) between the oscillating particle motion and the acoustic or the electric field. The frequency of oscillation of a particle and an external sinusoidal field moving the suspended particle are same but the phase lag depends only upon the equivalent aerodynamic diameter of the particles. By calculating the relaxation time from the measured phase lag, the aerodynamic diameter of the particle is determined.

The measured phase difference is same whether the drive is electric or acoustic with the size computations made in real time. The range of size measured by the ESPART analyzer depends on the applied excitation frequency. When the excitation is an AC field $E_0 \sin\omega t$, the amplitude of particle motion depends upon the electrostatic charge of the particles. ESPART has been used extensively in copying and laser printer industries for measuring the particle size and the charge-to-mass ratio of toners. Other applications include characterization of drug particles used for respiratory drug delivery.

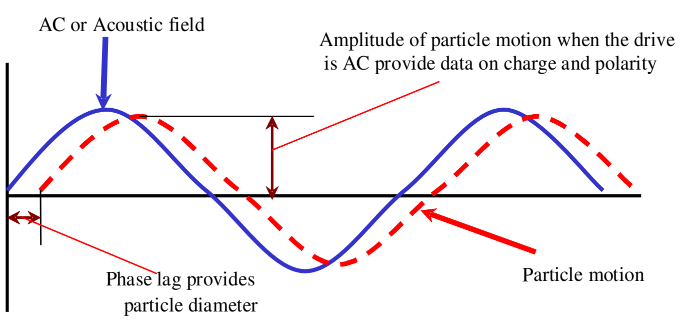


Figure 1: Motion of a suspended particle driven by an external sinusoidal electric/acoustic field.

The operation of the ESPART analyzer is based on the response of a suspended particle in gaseous medium when excited by (1) acoustic field, (2) electric field, or (3) simultaneous electric and acoustic fields, using the principle of Stokes' Law and Laser Doppler Velocimetry in determining the particle size and charge. As a particle travels through air it experiences a drag force which is proportional to the aerodynamic diameter of the particle. From Stokes' Law [6], the drag force is $F_D=3\pi\eta dV$, for a spherical particle if the particle Reynolds number is less than one. In the equation, η is the viscosity of the gaseous medium and V is the relative velocity of the particle with respect to that of the medium suspending the particles.

When a particle is subjected to an external force, the time required for it to attain its steady state is called the relaxation time of the particle (τ_p). For sinusoidal external forces the relaxation time is related to the phase lag between the oscillation of the particle and that of the excitation force. The phase lag (ϕ) is related to τ_p by

$$\phi = \tan^{-1} \omega\tau_p \tag{1}$$

The aerodynamic diameter (d_a) and the electrostatic charge (q) of the particle can be derived when an external AC field ($E_0 \sin\omega t$) is applied,

$$d_a = \left(\frac{18\eta\tau_P}{\rho_0 C_C} \right)^{1/2} \tag{2}$$

$$q = \frac{V_p}{E_0} \frac{3\pi\eta d_a}{C_c} \sqrt{(1+\omega^2\tau_p^2)} \tag{3}$$

where η is the coefficient of viscosity of medium is computed for the atmospheric conditions (temperature and pressure), V_p is the relative velocity of the particle with respect to the fluid is measured by using the laser doppler velocimeter of the ESPART analyzer, and C_c is the Cunningham Slip correction factor which takes into account that the motion of small particles may not be a continuous flow, ω is the frequency of excitation, and ρ_0 represents unit density 1000 Kg/m^3. To find the charge (q) on a particle from the particle velocity amplitude V_p, the ratio of V_p to the amplitude of the electric field E_0 is determined in real time. For acoustic drive, the phase lag and the amplitude ratio both provide the same size information.

However, the acoustic drive allows size distribution to be determined irrespective of the charge q of the particle where an AC drive provides both size and charge information only when the particles are charged. Operating the ESPART analyzer by alternating the acoustic and AC drive it is possible to measure the fraction of the particles that are charged.

III. DUST PARTICLE ANALYZER DESIGN

A. Optics

The ESPART analyzer currently used in copier/printer industries is a large size unit. One of the primary challenges in building an ESPART analyzer for Mars (Dust Particle Analyzer (DPA)) is to substantially reduce its physical dimensions, weight, and power requirements. The conventional ESPART analyzer utilizes a He-Ne gas Laser, a standard optical system for the LDV with two Bragg cells to generate the frequency shifted laser beams and a photomultiplier. For the DPA, the He-Ne gas laser was replaced by a laser diode incorporated in a commercially available "MiniLDV" manufactured by Measurement Science Enterprise Inc, CA. There are two methods for frequency shifting of the laser beams, (1) Bragg Cell (Acousto-optic modulators), and a (2) Rotating diffraction grating. The Bragg cell needs a high frequency generator to drive the modulators typically operating at a frequency higher than 35 MHz. The MiniLDV employs a rotating diffraction grating to generate frequency shifts that can vary over the desired range, 200 KHz to 5 MHz for the DPA. The grating is rotated by a motor therefore the frequency shift is proportional to the rotational speed of the motor allowing the DPA operation at a desired frequency shift. The Bragg cells require much more power compared to the power requirement for a micromotor. To incorporate these features a MiniLDV was used (Fig. 2).

The MiniLDV is composed of a laser diode, a rotating diffraction grating, transmitting and receiving optics, and an avalanche photo diode (APD). Its compact size and weight (0.5 lbs) met our requirements in the development of the DPA for Mars. The motor speed of the MiniLDV is set to provide a frequency shift between the two beams of 300 KHz. The probe also includes the transmitting and receiving optics, which is useful for analyzing the particles in back-scattered mode. The two frequency shifted laser beams in the DPA intersect at a distance approximately 50 mm from the MiniLDV probe, and the intersection creates a fringe pattern with fringe spacing of 1.65 μm.

The MiniLDV was mounted within a relaxation chamber, constructed for detecting Doppler signal bursts as shown in Fig. 3. The relaxation chamber incorporates both acoustic and electric drives, so as to measure both uncharged and charged particles respectively. The relaxation chamber houses the sensing probe of the Dust Particle Analyzer (DPA). It is designed to sample the particles to flow through the intersection of the two laser beams generated by the MiniLDV. The acoustic and the electric drives are designed to operate either alternatively or simultaneously. The chamber is constructed to operate either in back scattering or in forward scattering detection mode to analyze particle oscillations under the applied driving field(s).

Fig. 4 shows the schematic for particle analysis using the MiniLDV and the relaxation chamber operating in a forward scattering mode. A Doppler signal bust generated by each particle transiting the LDV sensing volume is a frequency modulated signal detected by the Avalanche Photo Detector (APD).The signal is processed using a bandpass filter and an amplifier, and is analyzed by the data acquisition card (National Instruments PCI-5112) on the PC. The Doppler bursts are demodulated and compared with the driving signals (acoustic or electric) by the data acquisition card.

Figure 2: Photograph of the MiniLDV probe (Measurement Science, CA)

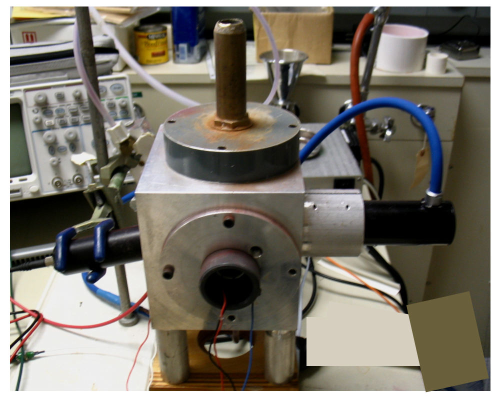


Figure 3: DPA relaxation chamber for Mars simulant dust sampling.

To calculate the particle size and charge from the acquired signals, LabVIEW is used incorporating the signal processing technique of quadrature demodulation for demodulating the FM Doppler burst signal [7].

B. Development of a Sampling system

The conventional ESPART employs a vacuum pump to draw the aerosol particles through the sensing volume at a rate of 1 liter per minute. Since vacuum pumps are bulky and require considerable power to operate and not easily applicable to Mars atmosphere, an electrohydrodynamic (EHD) pump [8] is used for sampling dust particles through the DPA relaxation cell. Two different versions of electrohydrodynamic (EHD) pumps were used: (1) ionic pump with a large number of corona electrodes (Fig. 5a), or (2) a pair or ring electrodes (Fig. 5b). The vacuum pump is substituted by the EHD pump to sample at the desired flow of gas. The EHD pump operation is based on ion wind produced by the flow of ions in a point-to-plane corona discharge. During corona discharge, ions travel from a HV point electrode to ground electrode forming an ion wind.

IV. Results and Discussion

To test the performance of the Dust Particle Analyzer (DPA), a comparative analysis of the test aerosols was done using a conventional ESPART analyzer and by the new DPA. Typically testing of the ESPART analyzer is done using toners, drug powders, Polystyrene Latex (PSL) spheres, oil droplets, and other aerosols [9, 10].

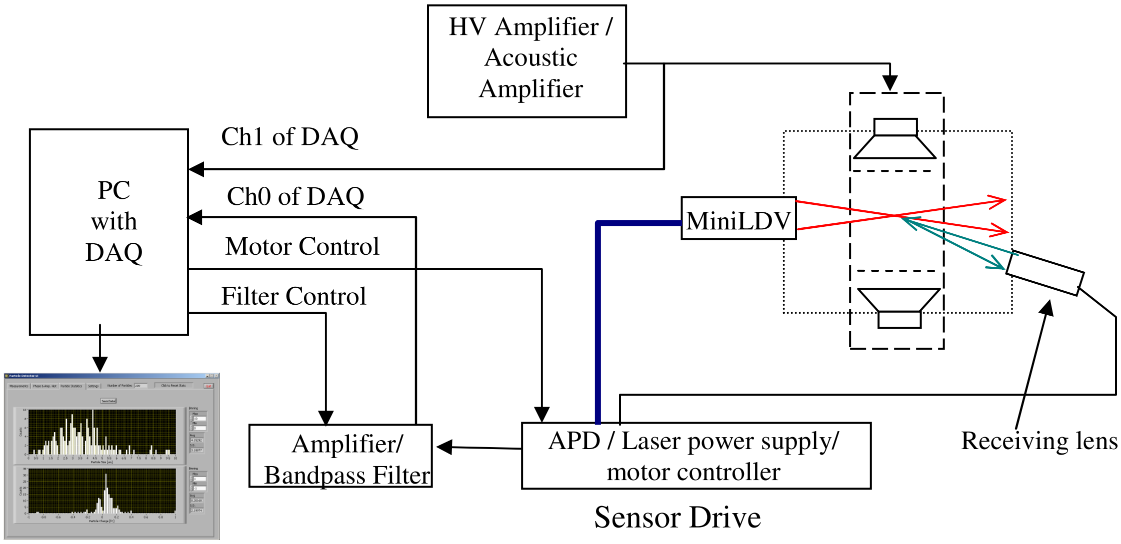
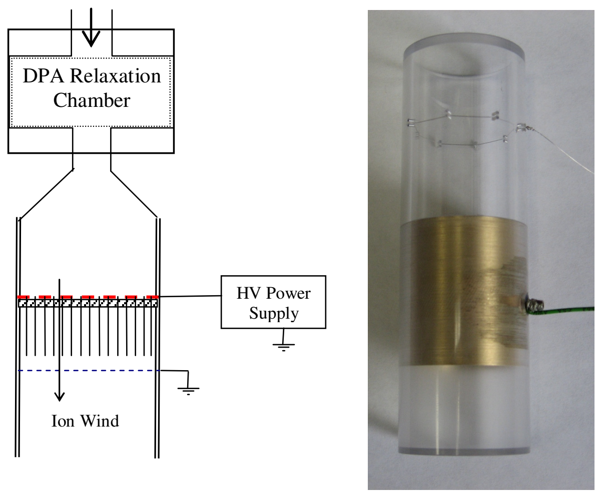


Figure 4: Schematic showing the basic setup of the Dust Particle Analyzer (DPA)



(a) (b)

Figure 5: Schematics of the two types of EHD pump for sampling Mars atmospheric dust particles through the DPA relaxation chamber.

The effect of electric field on the measurement of particle size was analyzed, since the breakdown voltage on the surface of Mars is much lower than that of earth. The DPA was tested to measure whether it would give reliable data with variation in electric field. For testing, red color toner was tribocharged with stainless steel beads and dispersed using a blow-off cup for sampling by the DPA and the conventional ESPART. The electric field was varied with the applied voltage between the two electrodes at 3000, 2000, 1000, and 500 V with an electrode spacing of 2.5 cm spacing between the two electrodes. About 1000 particles were counted for each run. Experimental data showed that the DPA can be operated over a wide range of electric field intensities (Fig.6). Similarly, the effect of variations in acoustic excitation field was studied to see whether the DPA would provide the same size distribution regardless of the amplitude of the acoustic field. The acoustic excitation voltage was varied by applying drive signal from a signal generator over a wide range. The experimental data showed that the particle size distribution with the change in the acoustic drive voltage remained same (Fig. 7). This would be essential for testing the DPA under Martian atmosphere where larger acoustic voltages might have to be applied. The frequency of acoustic excitation was 2 KHz.

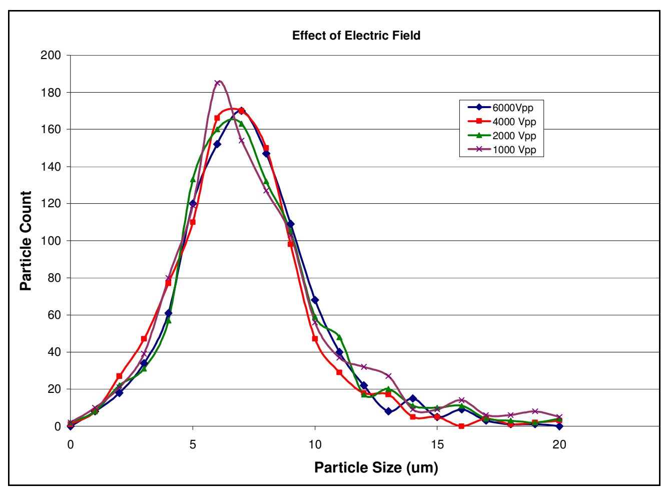


Figure 6: Particle Size distribution with change in electric field

A. DPA test results with Mars Dust Simulant

Ideally, the testing of the DPA is to be performed with actual Martian dust under Martian atmospheric conditions, since no returned dust samples are available, JSC-1 Mars simulant was used. The Mars Dust Simulant is a powdered and sieved dust material obtained from volcanic ash approximating the various physical and chemical properties of the oxidized soil of Mars [11]. The chemical composition of

JSC-1 Mars dust simulant contains predominantly (>82 wt %.) SiO_2, Al_2O_3, and Fe_2O_3.

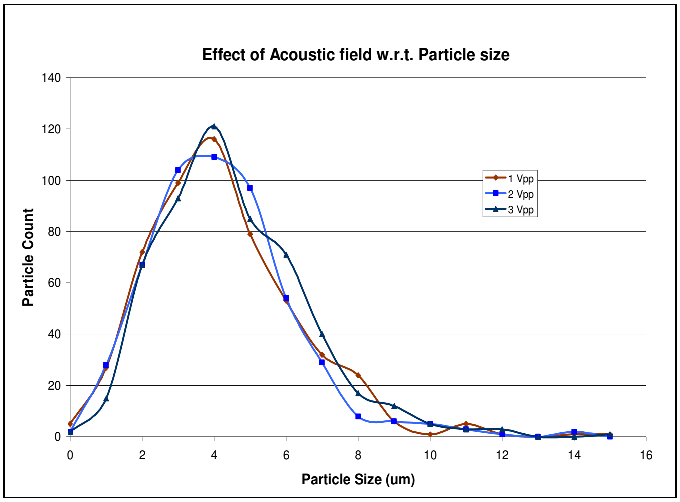
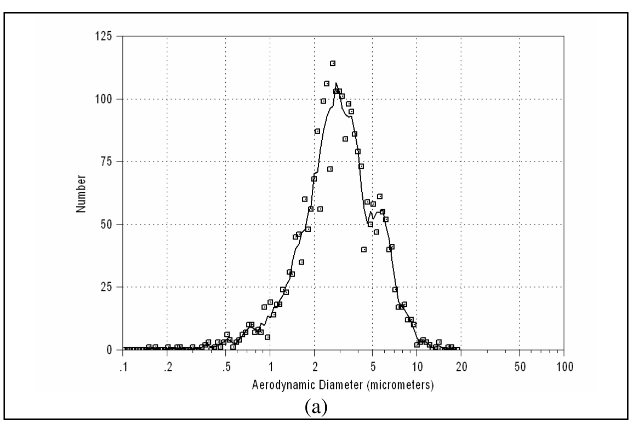


Figure 7: Particle size distribution with change in acoustic field

To analyze the PSD and (Q/M)D distributions of the Mars simulant dust, experiments were carried out by generating a dust cloud within a chamber from where the DPA can draw samples of dust particles for measuring the size and charge distributions. Tribocharging of the Mars dust resulting from particle-to-particle collisions and contacts against different materials shows the dust gets charged with materials such as stainless steel, Teflon, and glass (Fig. 8). Fig. 8a shows the particle size distribution of size classified Mars simulant dust as measured by the DPA analyzer.

The aerodynamic median diameter was approximately 3.0µm, indirect size distribution measurements on Mars dust show that the count median diameter (CMD) of the dust is 1.6 µm. Inter-particle charging takes place when the surface dust layer becomes re-suspended in the atmosphere by high velocity (> 30m/s) or in dust devils. Mars dust will be tribocharged against different materials likely to be used in human and robotic exploration of Mars. The particles will become negatively or positively charged based on the work function difference between contacting materials.



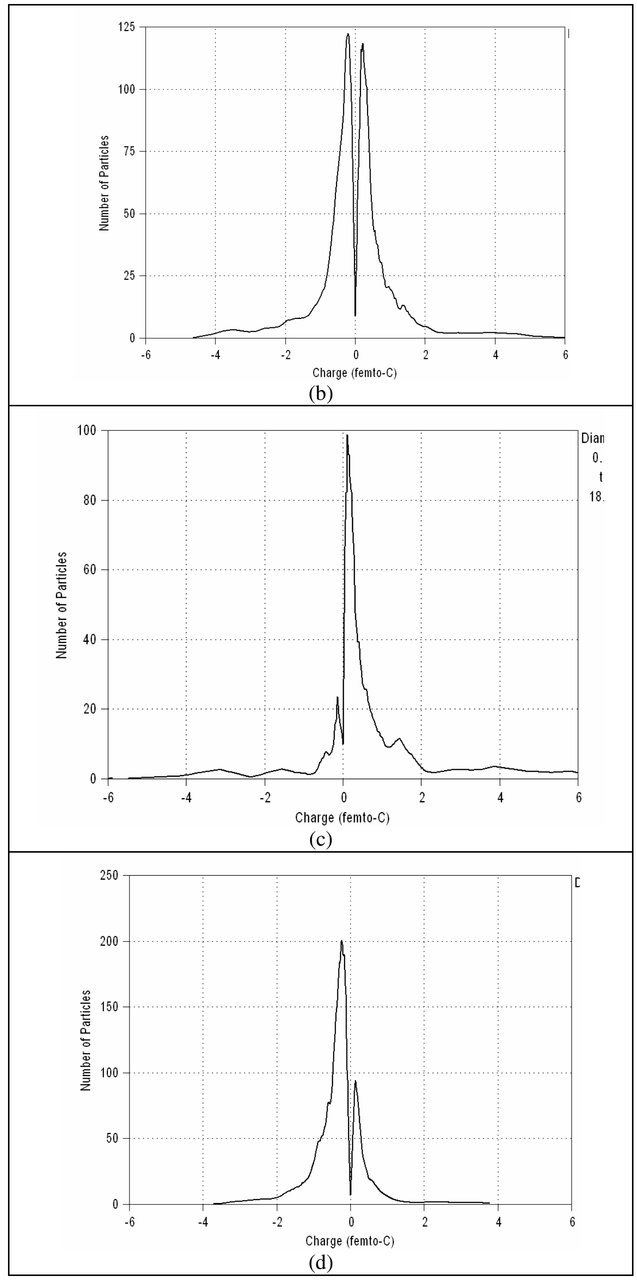


Figure 8: Characteristics of tribocharging Mars Simulant Dust JSC Mars-1 showing Particle Size Distribution (a), Charge distribution of dust (b), dust tribocharged against Teflon (c), and against stainless steel (d).

B. Testing the DPA under Martian conditions

The DPA was tested in a vacuum chamber designed to simulate Martian atmospheric conditions at the NASA Kennedy Space Center using the test setup designed by Mantovani et al. [12]. The relaxation cell was placed inside the low pressure test chamber. The chamber was operated at 5-7 mb using CO_2 in the chamber. In earth atmospheric pressure, the DPA can be operated at electrode voltages up to 3000V across the electrodes. The operating voltage was reduced to 900 V for DPA to function under Martian conditions to prevent electrical breakdown. Fig. 9 shows the particle size distribution for classified Mars simulant dust. No electrical breakdown was observed.

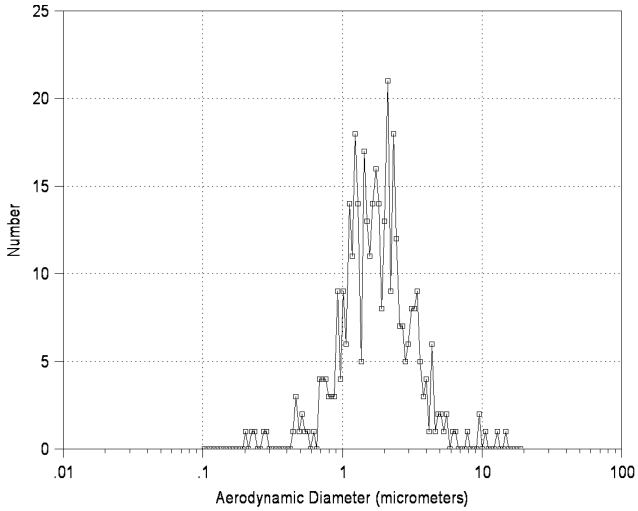


Figure 9: Particle Size distribution of Mars simulant dust measured under Mars atmospheric conditions using the DPA.

V. Conclusions

The Dust Particle Analyzer (DPA) developed under the NASA NRA grant 02-OSS-01 and tested on the simulated conditions shows that DPA is suitable to measure both particle size and charge distributions on Mars. Real-time particle size and charge distribution measurements on Mars are possible in-situ using a light-weight low power instrument under different dust concentrations. The DPA is being tested with optimized design for developing a flight-worthy analyzer for its application in future Mars missions.

Acknowledgment

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