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Technical Notes

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Charged Nanoparticle Source for High Thrust Level Colloid Thruster

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Nomenclature

A	=	wave amplitude
D_d	=	droplet diameter
d	=	distance between electrodes
E_S	=	normal electric field for surface charge emission
f	=	frequency
j	=	current density in the electrospray
m	=	particle mass
q	=	particle charge
r	=	droplet radius
V	=	voltage
ε_0	=	permittivity of vacuum
ε	=	dielectric constant
ρ	=	density
σ	=	surface tension coefficient

I. Introduction

THE use of charged/uncharged nanoparticles can be found in many areas of scientific research, as well as industrial and engineering applications [1–5]. In the field of electric propulsion, particularly, heavy charged nanoparticles are often preferable to lighter atomic ions. For a given current, a higher mass-to-charge ratio produces a larger thrust. The acceleration of heavier charged particles holds the promise of extending the useful range of electric propulsion to higher thrust power density, variable specific impulse, higher energy efficiency, and decreased space charge limitation per unit mass flux [1]. Producing sufficient uniformly charged particles with appropriate charge-to-mass ratio has been the key to developing a high-performance colloid thruster. This technical Note introduces a new method of generating a higher mass flow rate of more nearly monodisperse charged droplets using charged capillary standing waves in a thin liquid film.

II. Overview of the Basic Working Principles

In this method, liquid propellant is dispensed to the surface of a diaphragm to form a thin liquid film. A piezoelectric actuator then vibrates the diaphragm and excites capillary standing waves in the liquid film with wavelengths on the order of microns or less. The vibration amplitude is controlled such that the standing waves are at the critical stable condition, i.e., the threshold of atomization inception. An electric field is then applied to the capillary standing waves to develop electrostatic pressure near the wave crests, causing an imbalance between the surface tension and inertial forces. The introduction of electrostatic pressure leads to an instability of the capillary waves and thereby produces a fine aerosol consisting of charged droplets.

III. Theoretical Analysis

Electrospray technology based on the cone-jet mode has been extensively studied [5–13]. The method of producing charged droplets using capillary standing waves is similar to the method based on the cone-jet mode, except that the nozzle-supported, stable Taylor cones are replaced by unstable capillary standing waves. Compared with the cone-jet mode, this method has the following advantages:

1) The unstable condition of the capillary waves makes it easier for charged droplets to form and detach from the tip of the wave.

2) The unstable condition of the capillary waves also reduces the intensity of the electric field required to extract charged droplets from the waves and ion evaporation directly from the liquid meniscus is unlikely to take place; therefore, a more uniform q/m distribution in the electrospray is expected.

3) The removal of a continuous long jet from the cone's apex minimizes the space charge limit effects and makes it possible to support a higher current density carried by the electrospray.

4) The extremely large concentration of capillary waves greatly enhances the number density of charged particles in the electrospray. A typical wavelength of interest is approximately 10 μm and as many as one million capillary standing waves can exist on 1 cm^2 active area, with each standing wave being equivalent to a particle producing emitter in the regular cone-jet mode.

The influence of an electric field on a capillary standing wave at the critical unstable condition has been considered [14]. Linear static analysis predicts a neutrally stable wave when the surface tension force, inertial force due to acceleration, and the electrostatic pressure balance near the tip of the wave crest. Increasing the electrostatic pressure leads to the inception of atomization. The mean diameter of charged droplets emitted from a transient Taylor cone residing on the top of the wave crest is then given by [14]

$$D_d \sim \left(\frac{18.2\sigma}{\rho A f^2}\right)^{1/2} \tag{1}$$

The particle size and charge-to-mass ratio can be calculated from the electrospray current from experimental measurements. The calculation is valid when both of the following assumptions hold:

1) All particles released from the charged capillary waves are fully charged, i.e., in a released particle, the surface charge density reaches the limit allowed by the surface tension criterion and the ion emission criterion.

2) The current carried by the electrospray is limited by the space charge limit criterion.

Based on these assumptions, the particle size and charge-to-mass ratio can be calculated by using the Rayleigh instability criteria [5],

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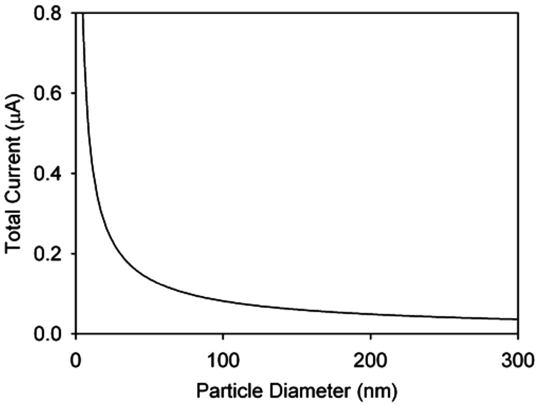

Fig. 1 Dependence of particle diameter on the total current of the electrospray. The curve is derived from Eq. (6), assuming the maximum current carried by a fully charged electrospray is determined by space charge limit criteria in Eq. (3).

which limits the charge-to-mass ratio of a charged droplet to

$$\frac{q}{m} = \frac{6(\sigma\varepsilon_0)^{1/2}}{\rho r^{3/2}} \tag{2}$$

For given voltage drop V and gap distance d, the maximum current density that can be sustained by the charged particles is given by the Child–Langmuir law.

$$j = \frac{4\varepsilon_0}{9}\left(\frac{2q}{m}\right)^{1/2}\frac{V^{3/2}}{d^2} \tag{3}$$

It is straightforward to calculate the particle charge-to-mass ratio based on the current measurements. From Eq. (3), the charge-to-mass ratio of the electrospray is

$$\frac{q}{m} = \frac{81}{32}\frac{j^2 d^4}{\varepsilon_0^2 V^3} \tag{4}$$

The particle diameter can be calculated using the Rayleigh instability criteria in Eq. (2)

$$D_d = 2\left(\frac{36\sigma\varepsilon_0}{\rho^2 (q/m)^2}\right)^{1/3} \tag{5}$$

Substituting Eq. (4) into Eq. (5) gives the particle diameter as a function of current density for a given voltage drop and gap distance

$$D_d = 3.56\left(\frac{\sigma\varepsilon_0^5 V^6}{\rho^2 j^4 d^8}\right)^{1/3} \tag{6}$$

The surface charge emission is limited by direct ion emission [5], which occurs when the applied electric field exceeds E_S, which leads to

$$\frac{q}{m} = \frac{3\varepsilon_0 E_s}{\rho r} \tag{7}$$

This surface charge emission limit is used to verify that a fully charged particle of the size given by Eq. (6) is stable, i.e., such a particle can exist without emitting ions from its charged surface. Figure 1 shows the theoretical prediction of particle size vs the total current for salt water with $V = 2$ kV and $d = 1$ cm. The active atomization surface is a circular area with a diameter of 1 mm.

IV. Experimental Setup

Figure 2 shows a diagram of the experimental setup. A diaphragm is bonded to the top of a piezoelectric actuator. A syringe pump is used to feed liquid on to the top of the diaphragm to form a thin liquid film. The liquid flow rate is adjusted such that a continuous film is maintained on the diaphragm while charged particles are extracted from the capillary wave crests. The amplitude of the capillary waves on the liquid surface is set to reach a critical value; increased amplitude leads to liquid atomization inception without an applied electric field. An electrically conducting extractor grid is installed parallel to the diaphragm. A high-voltage (HV) power supply connected to both the diaphragm and the extractor establishes an electric field across the gap between the grid and the liquid film. Salt water at 25°C with a salinity of 2% and electrical conductivity of 33 mS/cm is the working fluid in the experimental studies reported here. Experiments are carried out at atmospheric pressure.

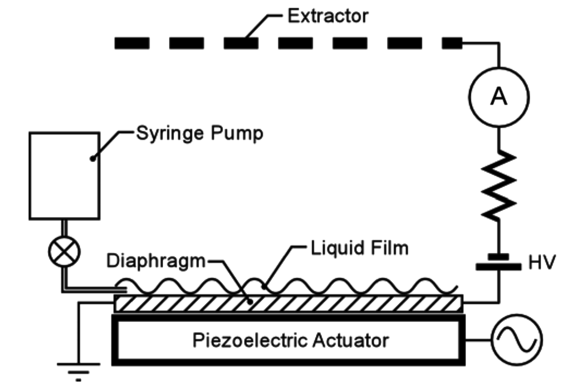

Fig. 2 Schematic overview of the experimental setup. Piezoelectric actuators are driven at resonant frequencies of 2.3 and 3 MHz to generate capillary standing waves in the liquid film. An electric field is established between the liquid film and the extractor by applying 1.5–3.0 kV. A nanoammeter measures the current carried by the electrospray. A current limiting resistor protects the HV power supply.

V. Results and Discussion

Two important observations are made. The first observation is that the spray is accelerated and attracted to the positively charged

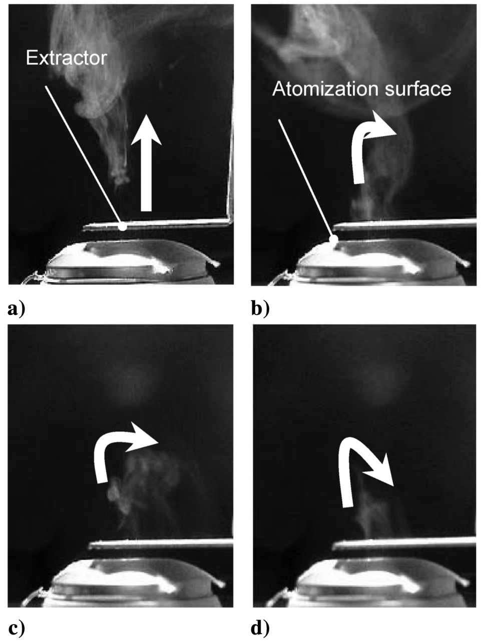

Fig. 3 A time sequence of images of electrospray emitting from the vibrating diaphragm at four consecutive times. Arrows in the pictures indicate the flow direction of the spray. a) At $t = 0.0$ s, neutral spray passes the extractor grid at low velocity when no electric field is applied; b) At $t = 0.2$ s, a voltage of 2500 V is applied. Charged high velocity electrospray passes the grid and is pulled back to the extractor; c) At $t = 0.4$ s, electrospray continues moving toward the extractor; d) At $t = 0.6$ s, electrospray reaches a stable operating condition. For scale, the extractor is 2 cm.

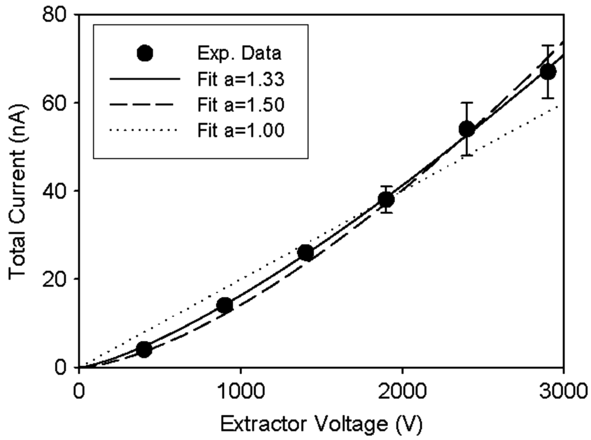

Fig. 4 Dependence of total electrospray current on the applied voltage. Measurement errors are shown when larger than the experimental data symbols. Power law fits to the data are also shown. A regression fit produces a scaling exponent of $a = 1.33$. However, $a = 1.5$ provides a close fit.

extractor. This indicates that charged droplets are indeed produced using this new technique. Figure 3 shows photographs of the electrospray at four consecutive times 0.2 s apart. The piezoelectric actuator, diaphragm, and the extractor are visible in the photographs. A hole is bored in the extractor over the atomization area on the diaphragm so that the charged droplets can pass the extractor for observation purpose. The arrows in Fig. 3 show the moving direction of the charged droplets. Without being neutralized in this experimental study, the charged particles return to the extractor in steady-state operation, as shown in Fig. 3d, indicating visually that charged particles are produced using the proposed method. In space propulsion applications, steady-state operation produces a neutralized colloid beam emitted from the thruster. Figure 4 shows the dependency of the measured electrospray current on the applied voltage for a fixed liquid flow rate. Data points fit closely to a power law fit with a scaling exponent of $a = 1.5$, which is the current limited by the Child–Langmuir law, indicating that the electrospray current is nearly space charge limited. Space charge limited current demonstrates that the capillary waves on the vibrating diaphragm are able to release sufficient charged droplets to support the maximum current allowed by the Child–Langmuir law.

The second observation is that the size of the droplets in the electrospray decreases when the electric field is applied. This observation is obvious visually. The size reduction indicates that when the capillary standing waves are properly charged, the electrostatic pressure caused by charge accumulation near the wave crest emits smaller droplets from the unstable wave. This observation agrees with the theoretical predictions in [14]. The fact that both the droplet size and charge-to-mass ratio can be controlled is important for electric space propulsion because it offers more flexibility to vary the I_{sp} and thrust density. These findings suggest that the described charged nanoparticle source could be useful for energy efficient colloid thrusters with high thrust levels and variable I_{sp}.

VI. Concluding Remarks and Future Work

A method of producing charged nanoparticles using charged capillary standing waves is developed. Preliminary experimental results indicate that the concept of using charged capillary standing waves at the critical stable condition to produce charged particles is feasible. Results show that the particle size and charge-to-mass ratio can be controlled by adjusting the magnitude of the applied electric field, suggesting that such a charged nanoparticle source could be useful for developing high-performance space thrusters and other applications, such as nanoparticle coating.

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