Extraction of droplets in Ultrasonic Electric Propulsion system analyzed by ultra-high speed imaging

IEPC-2017-289

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: As a novel propulsion technology, ultrasonically electric propulsion (UEP) offers high specific impulse and high thrust density. The charged droplets in UEP are extracted from crests of capillary standing waves (CSWs) at the critical stable condition by applying an electrical field. The extraction process of the charged droplets is investigated by an ultra-high speed imaging technique. The solution of formamide and lithium chloride is used as the operating fluid. A long-distance microscope coupled with an ultra-high speed camera (Memrecam HX-6) is employed to research the details of the extraction process. It is found that the diameters of charged droplets decrease with the increase of vibration frequencies, the theoretical diameters are a little smaller than experimental ones because of the different environment condition. At the same time, the diameters of the charged droplets will increase as the propellant flow rate rise. The motion characteristic and velocity of charged droplets are also investigated in the extraction process, the results indicated charged droplets are not uniformly accelerated and the motion directions are also divergent.

Nomenclature

J	=	current density in the electrospray
q	=	particle charge
m	=	particle mass
V	=	voltage
d	=	distance between the emission surface and the extractor
I	=	current
ρ	=	density
Q	=	liquid volume flow rate
R	=	local radius of curvature of liquid meniscus
ε_0	=	permittivity of vacuum
λ	=	wavelength
σ	=	surface tension coefficient
f	=	vibration frequency

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I. Introduction

Electric propulsion presents an excellent alternative to conventional chemical counterparts as more efficient mass utilization and expanded space mission capabilities[1-3].Electric propulsion can decrease total mass of spacecraft, improve payload of spacecraft platform and extend spacecraft on-orbit life. Instead of using chemical fuels, the electric propulsion system separates the energy and the propellant, and uses electric energy to heat or ionize the propellant to accelerate the jet [4]. For the same aerospace mission, the electric propulsion system consumes about one tenth of propellant, or even less than chemical propulsion. Different electrostatic thrusters such as ion engine, colloid thruster and field emission electric propulsion (FEEP) thruster have been widely used in orbit transfer of a satellite, attitude control and station-keeping etc. [5]. However, the electric thrusters like the colloid thruster have difficulty in the integration of numerous emitters, which result in lower of propellant flow rate, and make it tough to achieve a larger thrust density.

There are several advantages in EP system such as low consumption of propellant， long operation time and better flexibility[6]. As an attempt to increase the thrust density of a colloid thruster, lots of emitters have been integrated on an electrospray nozzle according to certain arrays. Busek Inc. successfully tested a colloid thruster with 57 emitters and obtained a thrust of 100 mN[7]. MIT’s space propulsion lab successfully manufactured an emitter array with 1025 emitters within an area of 0.64 cm^2 using micro-fabricated electrospray emitters for space propulsion missions [8]. Needle-shaped emitters on a Si wafer were fabricated by MEMS process to measure the I-V characteristics and the frequency dependence of a bipolar pulse voltage for ionic liquid electrospray thrusters [9].Subject to the manufacturing process and level, the number of emitters integrated in a certain area is still limited.

The Ultrasonically Electric Propulsion (UEP) technology, using crests of capillary standing waves(CSWs) as emitters， provides a novel method of producing a high flux of charged particles for space propulsion applications. During the operation of UEP, the emission surface of ultrasonic nozzle is covered by a thin liquid film (micron order), which is fed to the tip of nozzle by a digital syringe pump. In order to create lots of charged droplets, the vibration state needs to be regulated to critically stable condition (ultrasonic atomization will take place immediately when an electric field is exerted to CSWs) [5]. When an electric field is applied to the CSWs, charged droplets will be extracted and accelerated to a high speed then a thrust is thus produced. Compared with other electrostatic propulsion technologies, UEP has a broad range of advantages, such as low onset voltage, more uniform particle size and charge-to-mass ratio, variable specific impulse and thrust density, etc. Therefore， it becomes one of the most promising propulsion technologies that can potentially extend the applications of electrostatic propulsion to areas where a high thrust level with a high specific impulse is required. Related researches have been conducted mainly about effects of vibration parameters on the production of charged spray and the influences of extractors on the performance of a UEP thruster[10, 11], however, the extraction process of charged droplets in UEP thruster still remain unknown. In this paper, the diameters and motion characteristics of charged droplets in the extraction process are investigated by an ultra-high speed imaging technique with respect to different vibration frequencies, applied HV voltage and propellant flow rate etc.

II. Basic Principles of the Ultrasonic Electric Propulsion Technology

The UEP technology employs crests of capillary standing waves as emitters to create charged droplets. As figure 1(a) shows, the emission surface of ultrasonic nozzle is covered with a thin liquid film, which is fed to the tip of nozzle by a digital syringe pump. In figure 1 (b), in order to create lots of uniformly charged droplets, the vibration state needs to be regulated to critically stable condition, which ultrasonic atomization will take place immediately when an electric field is exerted to CSWs [5].As figure 1(c) shows, when an electric field is applied to the CSWs, charged droplets will be extracted and accelerated to a high speed.

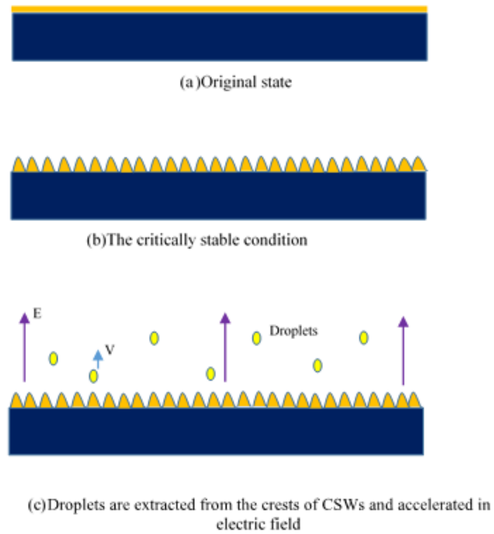


Figure .1 Formation process of charged droplets in UEP system

The critically stable condition of CSWs is affected by several factors such as propellant properties, operating parameters and intensity of electric field etc. If the dynamic viscosity of propellant is too high, it is hard to stimulate liquid propellant to critically stable condition. This is because a high dynamic viscosity of propellant means the force between the liquid molecules is bigger and a high vibration power is needed to stimulate them to a critically stable condition. At the same time, a suitable vibration power is also of great importance to achieve critically stable condition, when vibration power is too strong, the CSWs will atomize directly which is driven mainly by mechanical vibration instead of by electric field. Therefore， the intensity of electric field needs to be able to extract droplets from crests of CSWs and accelerate them to extractor and beyond.

During the operation of the UEP thruster, charged droplets will undergoes the process of formation, extraction, separation and acceleration, as figure 2 shows. In the electrostatic field, the internal charge of the liquid moves toward the crest of CSWs by electric force and causes local charge accumulation (as shown in Figure 2 (b)). When electrostatic pressure exceeds the sum of the surface tension and inertial forces, the liquid near the wave crests will detach, and then a charged droplet will be formed, as shown in Figure.2 (d).

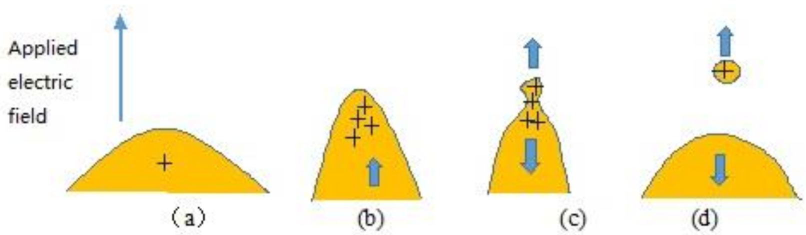


Fig.2 Evolution of a charged droplet from crest of CSWs

The current carried by the UEP is determined by Child-Langmuir Law [12]：

$$J = \frac{4\varepsilon_0}{9}(\frac{2q}{m})^{1/2}\frac{V^{3/2}}{d^2} \qquad (1)$$

If the total current and propellant flow rate are known, the average charge-to-mass ratio of the spray particles is given by:

$$\left\langle \frac{q}{m} \right\rangle = \frac{I}{\rho Q} \qquad (2)$$

Where <…> indicates an average value. Based on the assumption that the spray droplets are fully charged, the Rayleigh instability criteria can then be employed to calculate the average radius of the droplet [13]:

$$\langle R \rangle = \left(\frac{36\sigma\varepsilon_0}{\rho^2 (q/m)^2} \right)^{1/3} \quad (3)$$

According to the acoustic and vibrational theory, the wavelength of the CSWs on the emission surface is directly related to the frequency of the ultrasonic vibration. The relationship between the wavelength of CSWs and the ultrasonic frequency is given by：

$$\lambda = \left(\frac{8\pi\sigma}{\rho f^2}\right)^{\frac{1}{3}} \quad (4)$$

III. Experiment setup

The experimental system consists of several major subsystems: an ultrasonic nozzle, a high voltage power supply, a propellant feed device, a broadband function generator， a metal extractor and an optical system, as shown in figure 3. The ultrasonic nozzle is powered by a pair of piezoelectric transducers, which can convert oscillating electrical signals to a mechanical vibration at the same frequency, and such mechanical vibration can be transferred to the tip of ultrasonic nozzle (emission surface) by an ultrasonic horn. The propellant feed system is used to provide an accurately controlled liquid flow to the tip of ultrasonic nozzle. The ultrasonic nozzle can work under a wide scope of frequencies from kHz level to MHz. In this study, ultrasonic nozzles with frequency of 25 kHz, 60 kHz and 120 kHz are studied. The ultrasonic nozzle and the extractor (stainless steel) are mounted on a Teflon stand. The entire experimental system was operated in an atmospheric environment.

The high-speed camera in the optical system is Memrecam HX-6 from NAC, Japan, as shown in Figure 4. Its maximum shooting rate and maximum resolution are 65 million frames/sec and 2560 * 1920. The detailed parameters are shown in Table 1.

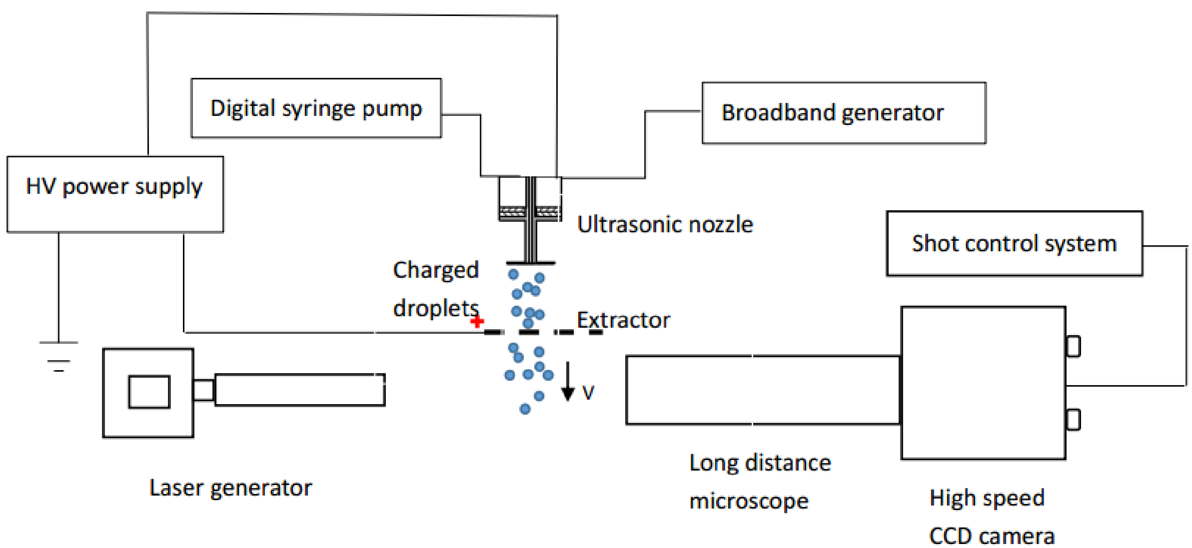


Figure 3. Lay out of experimental system

Fig.4 NAC HX-6 high speed camera

Table 1 Parameters of HX-6

Camera parameters	Performance
Camera model	Memrecam HX-6
Sensor resolution	2560×1920
Light sensitivity	Colours IS010,000
Maximum shooting speed	650,000 fps
Wavelength	250nm-1100 nm
25000fps resolution	384×576
50000fps resolution	448×176

The propellant of UEP system should have a relatively low vapor pressure because a working propellant with a high vapor pressure will evaporate rapidly and freeze in a vacuum environment. The formamide is a kind of organic liquid which has low vapor pressures and can remain in the liquid phase in vacuum for a long time. In this study, we use solution of formamide and lithium chloride as propellant, which has a higher electrical conductivity, and thus their cone-jets can produce charged particles of improved specific charge and specific impulse [14].

Table 2 Critical components and corresponding parameters of the experiment system

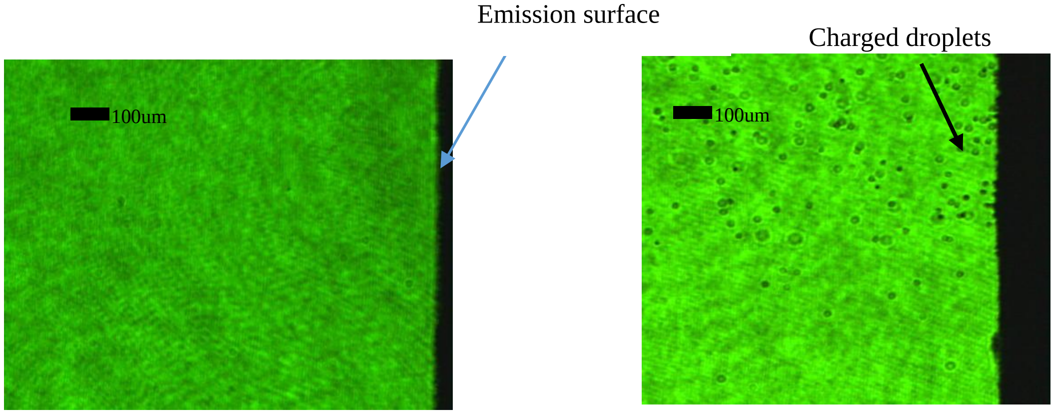
	Name of devices	Operation parameters
1	Ultrasonic generator	25 kHz, 60 kHz,120 kHz
2	HV power suplier	0 W-5 W
3	Electrometer	20 fA-20 mA
4	Digital pump	0.001 ml/min-30 ml/min
5	Extractor	Annular，inner diameter 28 mm

IV. Experimental results and discussion

The objective of this experimental study is to understand the extraction process of the UEP system. Specifically: 1) experimental and theoretical calculations of the diameters of charged droplets, and 2) Movement characterization of charged droplets in the extraction process. The effects of different operating parameters such as flow rate, vibration frequency etc. are also investigated. μ

A. Experimental and theoretical calculations of the diameters of charged droplets

The uniformity and size of the charged droplets have great effects on the specific impulse and charge-mass ratio of UEP thruster. A charged droplet with larger size will have a lower charge-to-mass ratio, and then affects specific impulse and efficiency of a thruster. In order to study diameters of charged droplets in UEP system, a high speed imaging technique is used to shoot the extraction process of charged droplets from crests of CSWs in the critical stable condition, the diameters of charged droplets can be achieved through pictures directly.

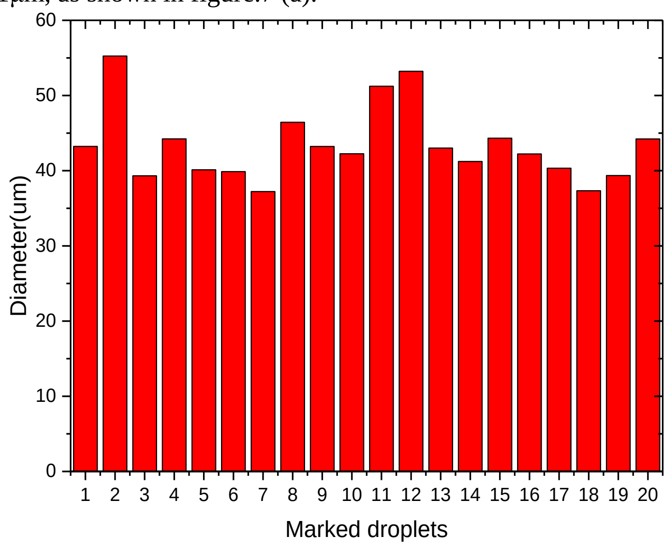


（a） (b)

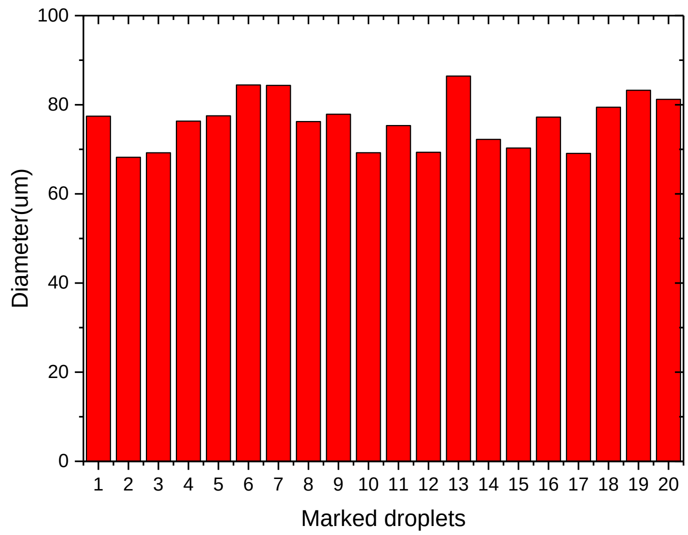
Fig.6 Images of emission surface
(a: no droplets are extracted, b:lots of droplets are extracted)

The critical stable condition of CSWs is determined by the vibration power and frequency for a given liquid. In this calculation, the vibration power is set to 0.8W， and vibration frequency is 120 kHz. No particles are extracted from crests of CSWs without applying electric field as shown in figure 2 (a). After the electric field is applied (5 kV), the droplets are extracted as shown in figure 2(b). Figure 2(b) also indicates that the extraction of charged droplets is uneven and droplets are not extracted in some area on emission surface.

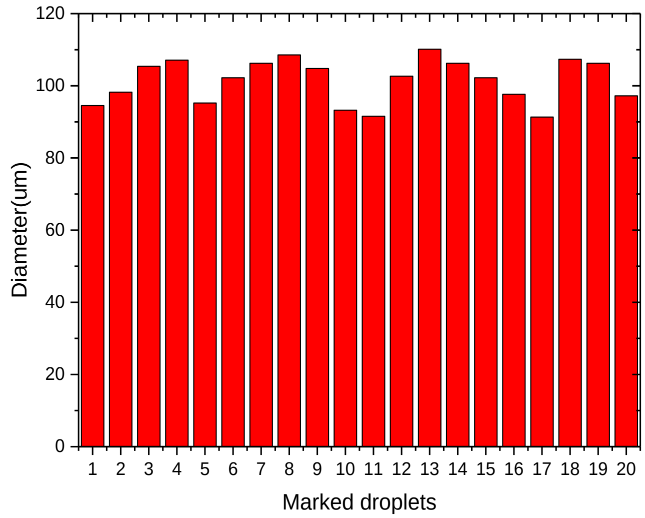
Experiment is also designed to study the effect of vibration frequencies on diameters of droplets at 5 kV with all other parameters remaining constant. The liquid flow rate is set to 5ml/hr to avoid liquid accumulation at the nozzle tip. For all three vibration frequencies, the diameters of charged droplets decrease with the increase of the applied frequencies. Specifically, at 120 kHz, the maximum and minimum diameter is 55.25 μm and 37.22 μm respectively, and the mean value is 43.381μm, as shown in figure.7 (a).



(a) 120kHz



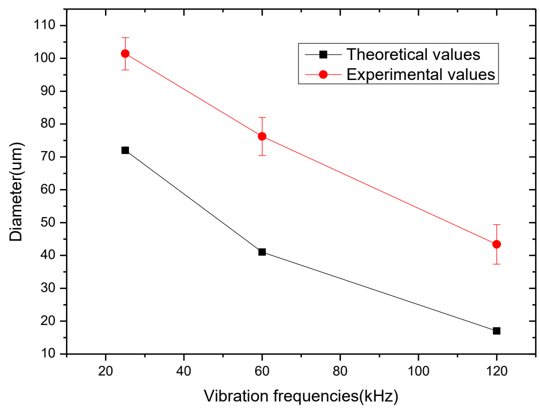
(b) 60kHz

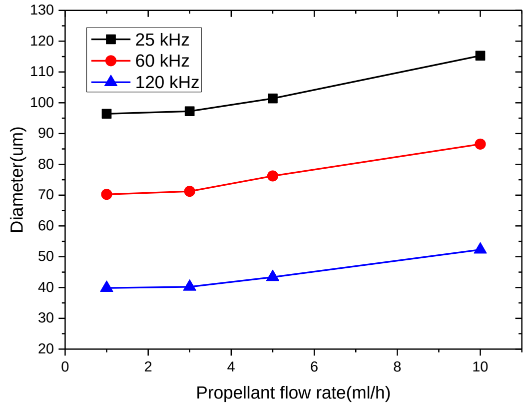


(c) 25kHz

Figure.7 Diameters of charged droplets at different vibration frequencies

Figure.8 presents the mean values of diameters at different vibration frequencies. It can be observed that a larger vibration frequency will result in smaller droplets. The charge-to-mass ratio of charged droplets in UEP system is affected by its size according to the Rayleigh stability criterion. The smallest droplets are produced at 120 kHz, having an average diameter of 43.381μm. At the same time, theoretical values are calculated, as shown in figure.8, it can be concluded that the diameters of charged droplets decrease with the increase of vibration frequencies, though the theoretical and experimental values are close, all the three theoretical values are a little smaller than experimental values, which can be explained by that the calculation of theoretical values is based on vacuum atmosphere, while the experimental counterpart is air. Since the experiments are conducted in air, the movement of charged droplets is inevitably impeded by the air drag force. When the charged droplets are surrounded by air, the electrostatic force has to overcome both the inertial force and the air drag force due to the collision between the charged particles and air molecules. To generate a certain spray current in air, a stronger applied electric field is therefore needed to move the charged droplets at the same acceleration as in vacuum, or in other words, if the applied electric field is the same, the spray current in an atmospheric environment is lower than that in the vacuum environment.





Fiure.8 Mean diameters of charged droplets   Firgure.9 Droplet diameter at different flow rate

In order to further study the effect of operating conditions on diameter of droplets, the flow rate is adjusted from 1ml/hr to 10ml/hr. As shown in figure 9, it can be concluded that the diameter will increase with the increase of propellant flow rate. One of the advantages of the UEP technology is that it supports a relatively higher propellant flow rate than other electrostatic propulsion technologies. With the same specific impulse, a higher propellant flow rate can produce a higher thrust. The figure 9 also indicates that when the propellant flow rate is less than 3 ml/h, the effect is insignificant, yet it becomes more significant with the increase of the flow rate.

B. Movement characterization of charged droplets

Fig. 10 presents the curves of the velocity with respect to different voltages for the three vibration frequencies at 5 ml/h, the distance between the extractor and emission surface is 10mm. It can be observed that the velocities for the three vibration frequencies present the similar trend, i.e., the velocity increases with the increase of applied voltage.

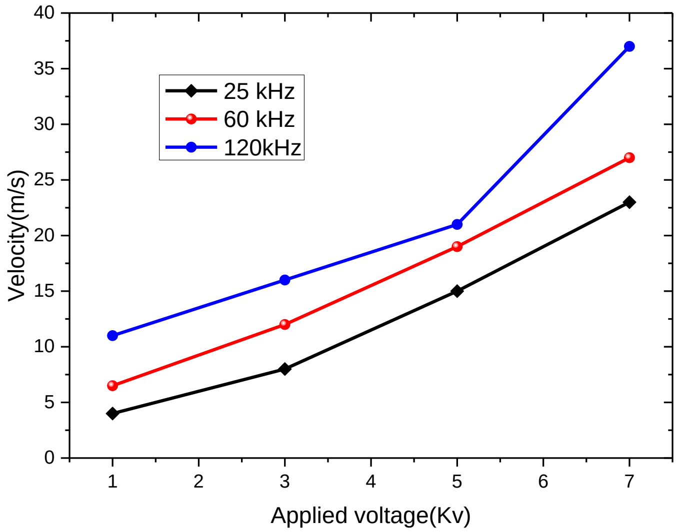


Figure.10 Droplet velocity under various voltages

Figure.11 indicates that there are three typical movement trajectories after the extraction of droplets, as shown by arrows. Since the UEP experiment is conducted in an atmospheric environment, the movement of charged droplet is impeded by the air drag force, further, the intensity of electric field is uneven between the emission surface and the extractor, all of these factors will result in divergence of droplets movement directions.

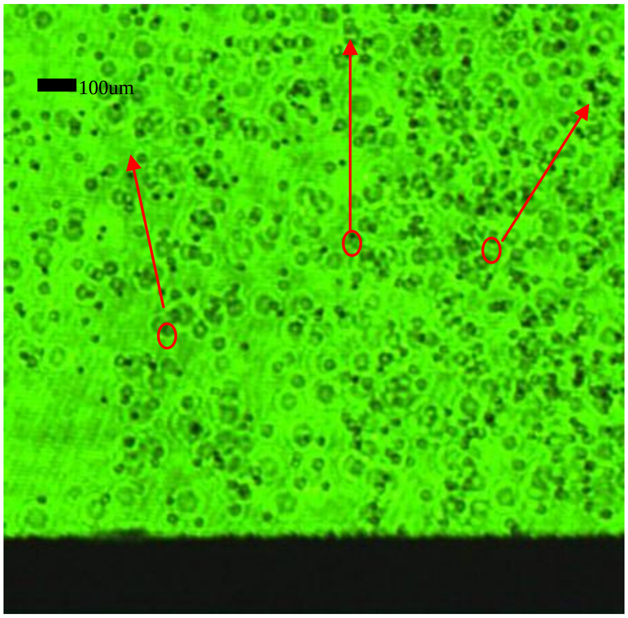


Figure.11 Three typical movements after the extraction of droplets

On the other hand, different charged conditions of the droplets also affect the formation and movement of the droplets in electric field. For a droplet, the greater amount of charge it brings, the greater force it is stressed in electric field. While the charged condition of a droplet is affected by the relaxation time, for example, when a droplet has a long relaxation time, it means it needs a long time to charge the droplet. When the conductivity of the propellant is large, the relaxation time of its droplets will be reduced, so that the amount of charge the droplets bring will increase, further increasing their specific impulses and charge-to-mass-ratios.

V. Conclusions

The Ultrasonically Electric Propulsion (UEP) technology, using crests of capillary standing waves(CSWs) as emitters， provides a novel method to produce a high flux of charged particles for space propulsion applications. In this study, extraction process of charged droplets in UEP system is investigated by an ultra-high speed imaging technique. The experimental and theoretical diameter values of charged droplets are calculated with respect to different operating conditions. At the same time, movement characteristics of charged droplets are also studied. It is found that the diameters of charged droplets decrease with the increase of vibration frequencies, and the theoretical diameter values are a little smaller than the experimental ones, which can be explained by different environment condition. The propellant flow rate also affects diameters of charged droplets, specifically, the diameter increases as the flow rate rise, but such effect is insignificant when the flow rate is very low. The experimental results indicate that charged droplets are not uniformly accelerated and the motion directions are also divergent.

Acknowledgement

The research is supported by the National Natural Science Foundation of China (Grant No.51675341).

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