Study on Performance of Ionic Liquid Electrospray Thruster in Atmospheric and Vacuum Environment

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Abstract: Ionic liquid electrospray thruster has the advantages of high thrust accuracy, low power consumption and low noise. It has been tested in-orbit as a ST7-DRS payload in LISA Pathfinder mission. It is one of the best micro-thruster candidates for space gravitational wave detection mission. In this paper, ionic liquid electrospray process in the atmosphere and the performance of thruster in vacuum are studied. The experimental results in the atmosphere show that corona discharge exists in the ionic liquid electrospray process. The inevitability of corona discharge in the electrospray process is analyzed theoretically, and the interaction between corona discharge and electrospray is analyzed. The basic performance of passive ionic liquid electrospray thruster prototype was tested in vacuum environment, and the current-voltage curve was obtained. The composition of plume in positive and negative modes was preliminarily determined by time of flight method. The results showed that monomer ions were dominant in positive mode, while ions and droplets accounted for the same proportion in negative mode, resulting in average specific charge is low. This may be the cause of current asymmetry in positive and negative modes.

I.Introduction

Gravitational wave detection is an important technique to explore the origin and the evolution of the universe. On the earth ground, there are laser interferometer gravitational wave observatory (LIGO) in the United States and VIRGO Observatory in Europe to detect gravitational wave signals. Three scientists have won the Nobel Prize of physics in 2017 for their outstanding contributions to the detection of gravitational waves. However, the detection of gravitational waves on ground observatories is often disturbed by the vibration and noise of the earth, and due to the distance factor, the observation frequency band of gravitational waves on the ground is limited to more than 10 Hz, which is helpless for the medium and low frequency gravitational waves generated by the larger scale celestial bodies. Therefore, the European Space Agency (ESA) and the United States Aerospace Administration (NASA) proposed a plan to launch three identical spacecrafts into space to form an equilateral triangular gravitational wave observatory millions of kilometers apart, namely Laser Interferometer Space Antenna (LISA)[1]. In China, the Chinese Academy of Sciences and SUN YAT-SEN University have proposed similar schemes for the detection of gravitational waves in space, named "Taiji" and "Tianqin" respectively. Spacecraft for such space exploration mission must keep their distance very precisely when they are millions of kilometers away from each other. Solar pressure and other disturbances will have a great impact on the attitude and position of spacecraft. The disturbance reduction system (DRS) is very important for such spacecraft. At the same time, the drag-free technology makes the spacecraft payload at the state of zero gravity for interference experiment. All these require that the thrust precision of the thruster of the

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spacecraft reach 0.1 μN, and the thrust noise ratio is less than 0.1 μN√Hz. In addition, the thruster also requires a certain thrust (5-30 μN) and a low power cost (≤5 W). Ionic liquid electrospray thruster has the advantages of simple structure, small thrust, high thrust precision, low power cost and high efficiency, which makes it especially suitable for space missions requiring very high thrust precision. It is considered as one of the best candidate micro thrusters for LISA mission and has been widely studied[2-7].

In this paper, the research progress about ionic liquid electrospray thruster in the electric propulsion group of Beijing Institute of Technology in recent two years is introduced[8]. The paper is divided into two parts: the first part is the experiment in the atmospheric environment. A syringe pump is used to supply ionic liquid to the end of the metal capillary, then electrospray and discharge are formed under the strong electric field. The cause of corona discharge in the ionic liquid electrospray process and the interaction between them are studied. In the second part, the passive thruster prototype was tested in vacuum environment, and the current and voltage curves, positive and negative polarity responses were obtained. The plume components in positive and negative modes were measured by time-of-flight method, and the effect of plume components on total emission current asymmetry is analyzed.

II.Ionic Liquid Electrospray Experiments in Atmospheric Environment

A. Experimental Setup and Methods

A schematic of the experimental setup under the atmosphere pressure (~10^5 Pa) and room temperature (~25 ℃) is shown in Fig. 1. A DC high voltage source (±30kV, 30W) was used to supply high potential between the stainless-steel capillary (ID=0.23 mm, OD=0.7 mm) and the ground. Two counter electrodes are grounded and one is with 8 mm diameter aperture. The distances between the capillary and the counter electrodes are 3 mm, which controlled by a 3-axis stage. One resistor is connected in series between the power supply and the capillary to avoid the over current, and the other two resistors are connected in series after the two electrodes, respectively. All resisters are 1 MΩ. The current signals over the resistors were measured by voltage probes (Tektronix P2220) and a digital oscilloscope (Tektronix TBS2104). Total current is measured by a picoammeter (Keithley 6485). High speed camera (Phantom VEO410) and digital camera (Nikon D7000) are used to observe the shape of the Taylor cone and the plume of corona discharge. The ionic liquid used in experiment was 1-Ethyl-3-methylimidazolium tetrafluoroborate ($EMIBF_4$), and its physical properties are listed in Table 1.

Table 1 Physical properties of $EMIBF_4$* (at 25℃)

Liquid	Density (kg/m^3)	Surface tension coefficient (N/m)	Conductivity (K/m)	Relative permittivity
$EMIBF_4$	1294	0.052	1.3	71

*The physical properties of $EMIBF_4$ are from Ref. [9-11].

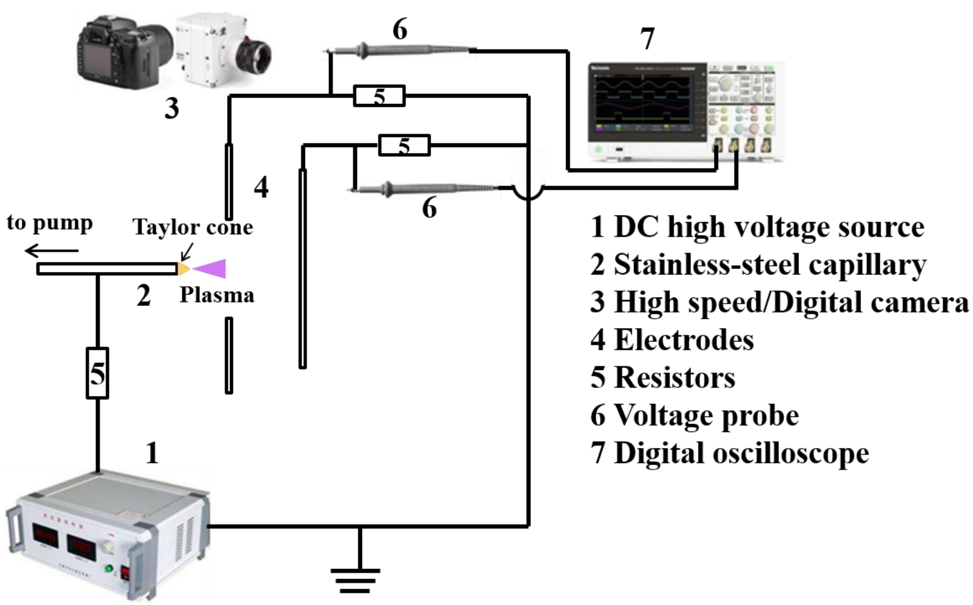

Fig. 1 Schematic of experimental setup in atmospheric environment (not to scale).

B. Results and discussion

In the atmospheric environment experiment, we find that electrospray is often accompanied by corona discharge. Fig. 2 shows the images of corona discharge at the tip of the Taylor cone formed by $EMIBF_4$. The capillary is applied positive high voltage in the top row (Fig. 2a), while negative in the bottom row (Fig. 2b). In these images we can see that the characteristic plume of corona discharge. In positive mode, the shape of ionic liquid can keep almost Taylor cone at different voltage, and a streamer discharge plume is emitted from the tip of the cone. In contrast, the shape of Taylor cone in negative mode changes from sharp to blunt, and gradually becomes hemispherical with increasing voltage. The emission area of the negative corona discharge on the liquid surface becomes larger, and the plume is fan-shaped. In both of these two modes, the emission plume intensity increases with increasing voltage.

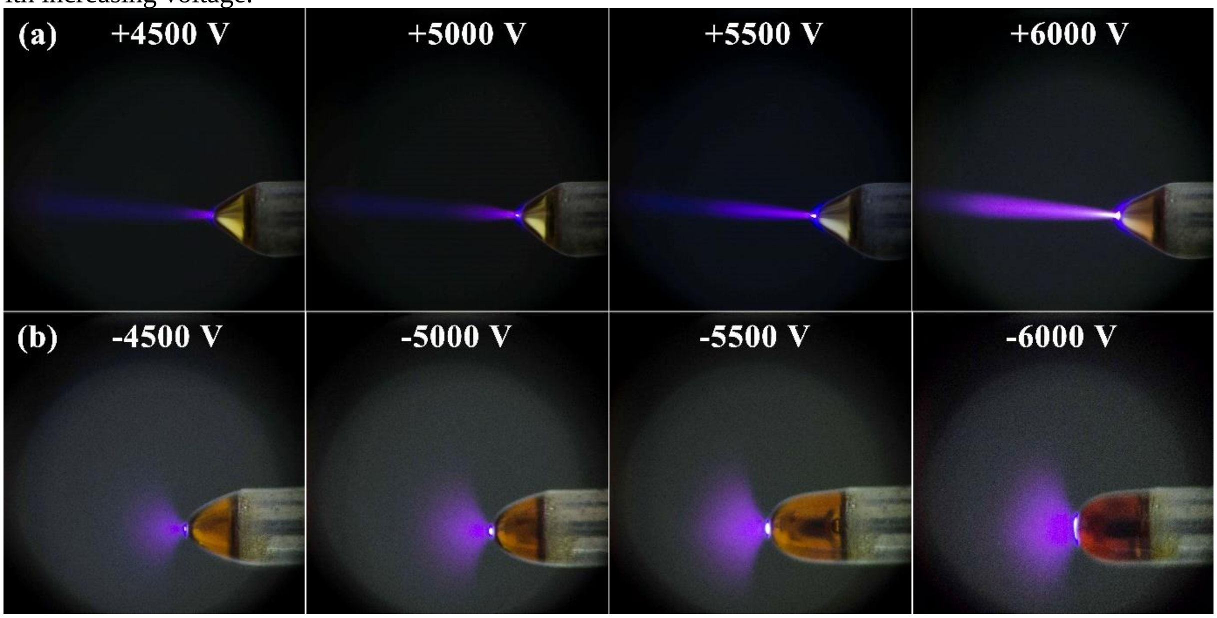

Fig. 2 Images of liquid surface morphology of $EMIBF_4$ accompanied by corona discharge in both positive and negative voltage. (*ISO* is 400, exposure time is 10 s, flow rate is 0.1 nL/s).

First, we analyzed the causes of corona discharge in electrospray process. Smith has pointed out that the ionization potential of air was exceeded before the field required for EHD mode was reached if liquid surface tension coefficient was large enough[12]. Based on the experimental results, Rousse[13] proposed an empirical formula of the onset electric field strength of cornoa discharge (E_c) as follows

$$E_c = 30 + \frac{9}{r^{0.5}} \text{ (kV/cm) for } r > 100\ \mu\text{m}$$
$$E_c = 62.7 + \frac{1.74}{r^{0.75}} \text{ (kV/cm) for } 15\ \mu\text{m} < r < 100\ \mu\text{m} \tag{1}$$

where r is the radius of the discharge needle tip.

The critical electric field of a stable Taylor cone jet changing to a spray (E_s) is

$$E_s = \sqrt{\frac{2\gamma}{r\varepsilon_0}} \tag{2}$$

where γ is the surface tension coefficient of the liquid and ε_0 is the vacuum permittivity.

Then we can get the values of these two electric fields depending on the radius of the tip from Equation (1) and (2), the result is shown in Fig. 3. From the figure we can see that the curve of corona critical electric fields is tangent to the line of electrospray when the surface tension coefficient is about 0.05 N/m. For liquids with surface tension coefficient greater than 0.05 N/m, it is possible that there exists a radius that makes the critical electric field of electrospray larger than that of the corona discharge. When this happens, the air is first ionized and corona discharge occurs prior to electrospray. For liquids with surface tension coefficient less than 0.05 N/m, the critical electric field of electrospray is lower than that of corona discharge at any radius, so that a stable Taylor cone jet electrospray can be formed. This explains why there is corona discharge in the electrospray process with $EMIBF_4$ as the liquid. In addition, we can also speculate that corona discharge exists in the electrospray process of other high surface tension liquids such as water, formamide etc.

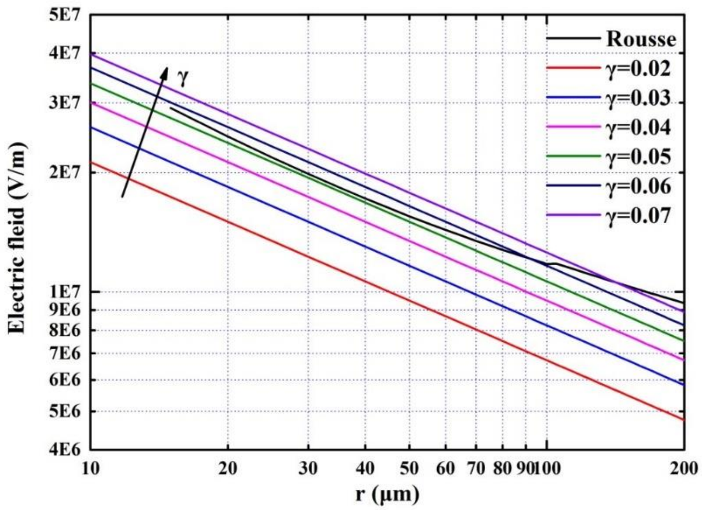

Fig. 3 Electric field depends on *r*. (The curve is the corona critical electric field calculated according to the Rousse's formula. The straight line is the electrospray critical electric field corresponding to the different surface tension coefficients.)

III.Vacuum Test of Ionic Liquid Electrospray Thruster

A. Vacuum System and Test Methods

The vacuum test system includes thruster prototype, vacuum system, power source and measurement system, as shown in Fig. 4. The size of the vacuum chamber is 0.5 m in diameter and 0.8 m in length. The pumping system consists of two rotary vane pumps and one molecular pump. The limit vacuum degree of the system is $5*10^{-4}$ Pa and a working vacuum degree is $3*10^{-3}$ Pa. Two DC power supplies are used to supply high voltage (Tianjin Dongwen, ±30 kV, 30W). The emitter is connected with high voltage and the extractor is grounded. The total current is obtained by measuring the voltage drop across the resistance (1MΩ) in series in the circuit with a multimeter. The data is transmitted to the computer through Bluetooth and recorded. A voltage probe (TPP0250) is used to measure the voltage drop across the resistance (100 kΩ) in series on the extractor and collector to measure the current, which is recorded by an oscilloscope. The emitter is conical and machined by CNC method. The radius of the emitter tip is about 50 μm, the height is 1.5 mm, and the distance is 1 mm. The extractor is stainless steel sheet with 0.1 mm thickness, and the aperture is 1.5 mm. The distance between emitter and extractor is 0.5 mm, which can be adjusted by the height of the ceramic spacer. The size of the thruster is 5*5*1 cm, and the weight is less than 25 g. The propellant used in the vacuum experiment is also $EMIBF_4$.

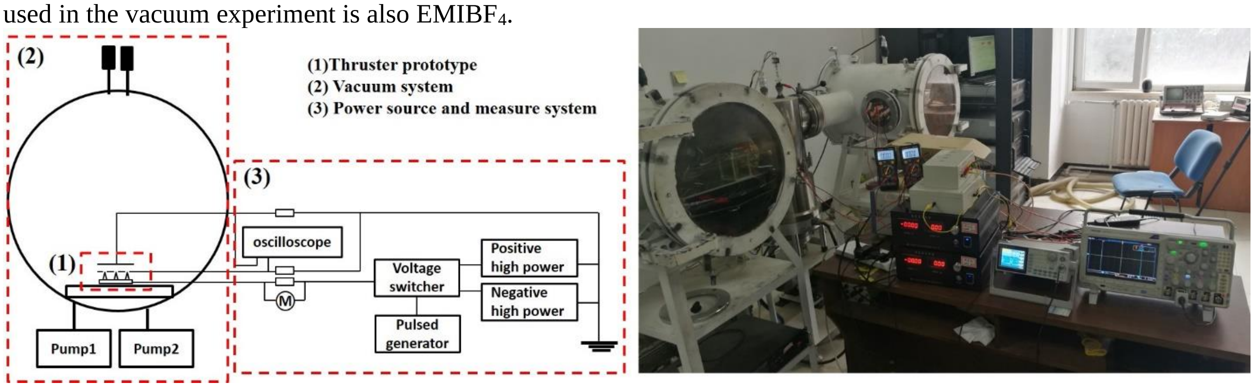

Fig. 4 The schematic and the device of the vacuum experiment

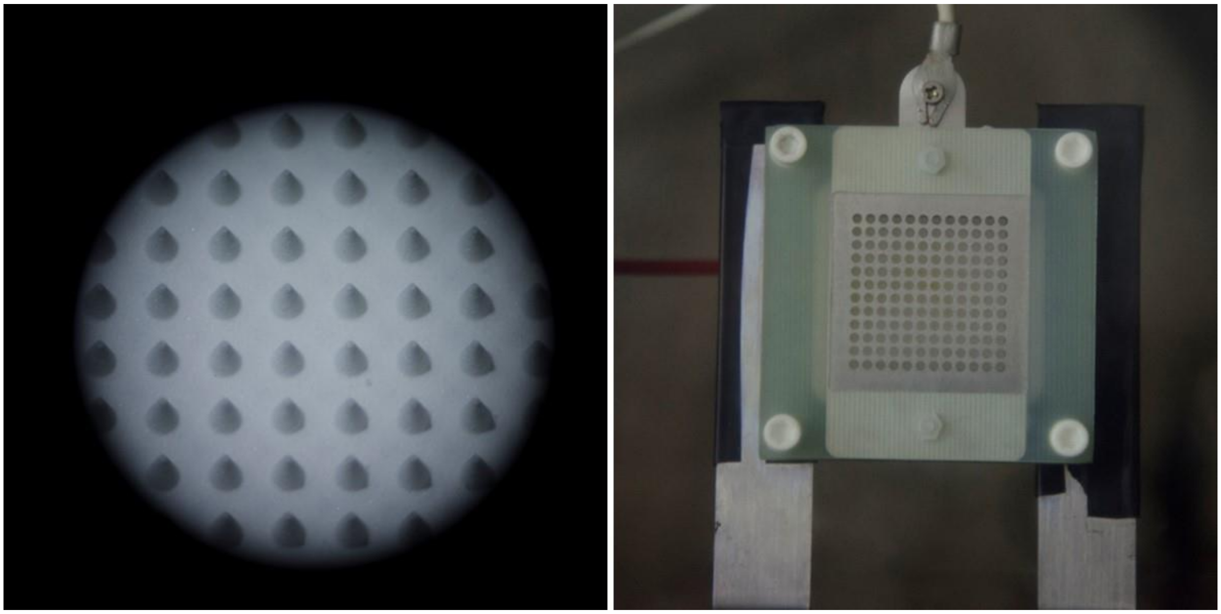

Fig. 5 Porous glass type emitter and thruster prototype

Time-of-flight (TOF) is an effective method for detecting thrust performance of the ionic liquid electrospray thruster. This system contains a group of TOF gate and a collector, as shown in Fig. 6. When a pulsed high voltage is applied on the middle of the gate electrode, the charged particles will not enter the TOF gate. The particles that have passed through the gate will arrive at the collector one after another because of different velocities. The current signal on the collector plate will gradually decrease from the maximum to zero. According to the TOF I-t curve, we can calculate the mass flow, thrust, specific impulse and efficiency of the thruster[3]. In this study, the distance between the collector and the gate electrode is 0.5 m. The TOF gate consists of three stainless steel electrodes. The distance between them is 5 mm. The front and last electrodes are grounded, while the middle electrode is connected with a pulse high voltage power supply (PVX-4130, ±6000V, rising edge is less than 100 ns). The size of the gate electrode is 50 mm*50 mm*0.1 mm, with a square aperture of 0.9 mm and 0.1 mm width between the apertures. The collector is a square stainless steel plate and the size is 80 mm*80 mm. The current of the collector is measured through a high-speed current amplifier (DHPCA-100) and recorded on the oscilloscope. The initial time of TOF, t_0, can be obtained from the oscilloscope signal triggered by the rising edge of the pulse voltage.

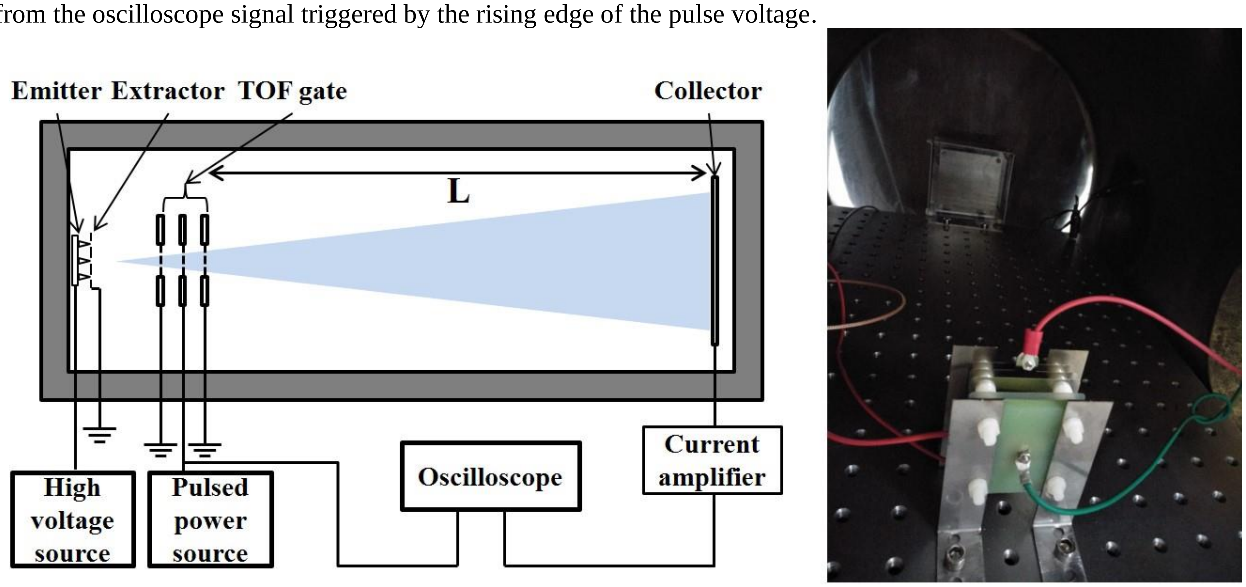

Fig. 6 The schematic and the device of TOF experiment

B. Results and Discussion

Fig. 7 is the passive type ionic liquid electrospray thruster prototype emission images under different voltages in vacuum environment. It can be seen that thruster can be fired in both positive and negative mode, and the plume light intensity increases with the increase of emission voltage. We measured the response of total current, interception current (extractor current) and emission current (collector current) to alternating voltage (Figs. 8a and b), and obtained the curve of current-voltage relationship, as shown in Fig. 8c. From the current-voltage curve, we can see that the starting voltage of this thruster is about 2000V, and the stable operating range is 2000-3500V. In both modes, the sum of the interception current and the emission current is close to the total current. The ratio of interception current and emission current to total current can be calculated, as shown in Fig. 8d. It can be seen that in the positive mode, the proportion of the interception current is lower than 10%, while it is higher than 10% even above 20% at 3500V in the negative mode. It results in the decrease of the emission current ratio, which is obviously not conducive to the efficient emission of the thruster. We conclude that it may be related to the difference trajectory of positive and negative ions in the electric field, resulting in different divergence angles. The reason still needs further experimental verification.

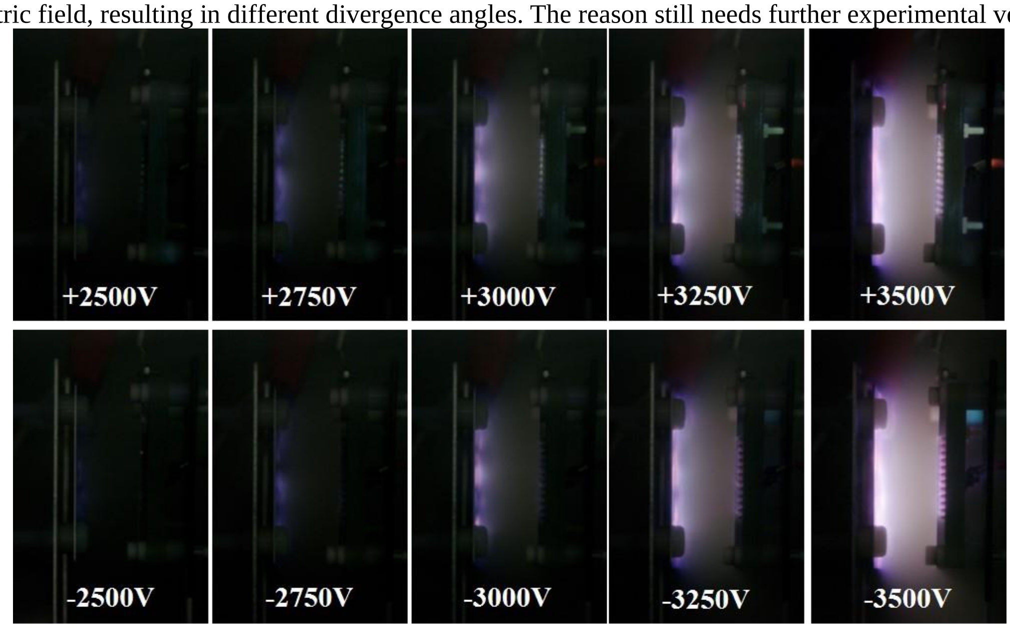

Fig. 7 Thruster prototype emission images at different voltages (top: positive mode, bottom: negative mode)

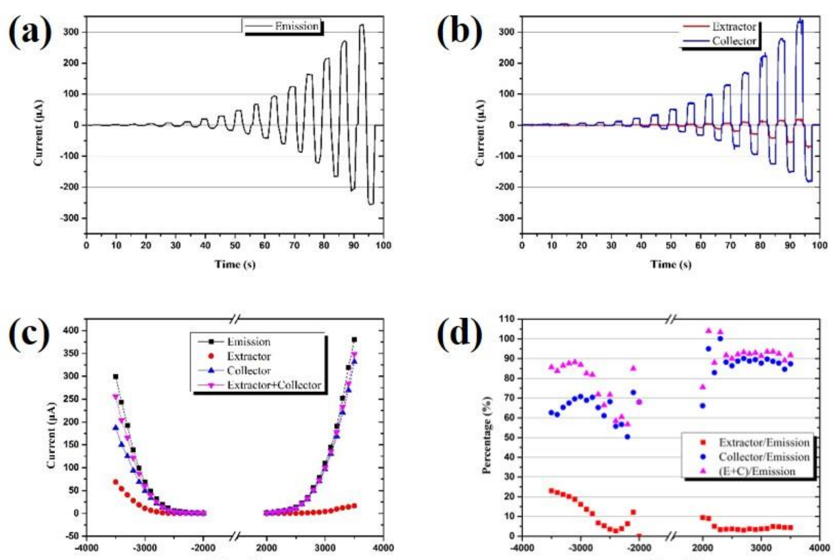

Fig. 8 Current variation and proportional curve under alternating positive and negative voltages

In addition, from the current-voltage curve, we also find that the total current is asymmetric in the positive and negative modes, and the total current in the positive mode is larger than that in the negative mode. This phenomenon has also appeared in other researchers' papers[5, 14]. It is known that one advantage of the ionic liquid electrospray thruster is that it can alternately emit positive and negative ions, which is conducive to alleviating the electrochemical corrosion at the emitter[15], and also to achieving plume self-neutralization[5, 16]. However, the asymmetric current in the positive and negative modes will obviously lead to an excess of ions, which is not conducive to the long-term stability of the thruster. We have studied this phenomenon and tested it many times, and found that the phenomenon of asymmetric current appears in most cases. The statistical results are shown in Fig. 9. It can be seen that the total emission current of the thruster is greater in positive mode than in negative mode in the whole working range, and the ratio of the two modes is stable at about 1.2 with the increase of voltage. We attribute this phenomenon to the different emission characteristics of positive and negative ions. Under the same electric field, the positive ions (EMI^+) of ionic liquid $EMIBF_4$ are more likely to form monomers, while the negative ions ($BF4^-$) are more likely to form dimers, trimers or polymers, resulting in lower specific charge particles in the plume under the negative mode. Assuming that the flow rate of propellant is the same in both modes, the current decreases with the decrease of specific charge. Table 2 gives the theoretical current ratios calculated for different plume compositions under the positive and negative modes. When both modes emit monomer charged ions, the total current ratios should be 0.78. However, the experimental results are not the same, approaching 1.2. It may be close to component case 2 given in Table 2. Of course, this is only the theoretical assumption of plume particle composition, the real composition needs to be further confirmed.

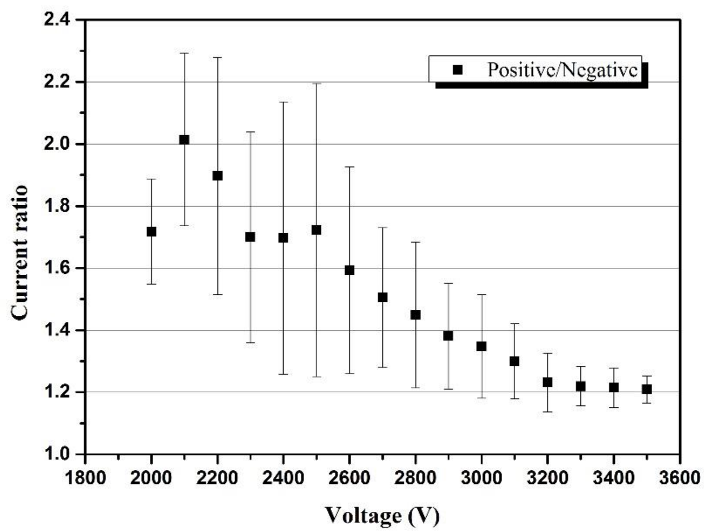

Fig. 9 The variation trend of the ratio of positive and negative currents with emission voltage

Table 2 Current ratio of different ion components in positive and negative plumes

Case	Cations	Mass	Percentage/%	Anions	Mass	Percentage/%	Current ratio (+/-)
1	EMI^+	111	100	$BF4^-$	87	100	0.78
2	EMI^+	111	100	$BF4^-$	87	50	1.20
				$BF4(EMIBF4)^-$	285	50	
3	EMI^+	111	100	$BF4^-$	87	25	1.64
				$BF4(EMIBF4)^-$	285	75	
4	EMI^+	111	100	$BF4(EMIBF4)^-$	285	100	2.57

C. TOF

Fig. 10 is the current curve obtained by time-of-flight test under different positive and negative voltages. The abscissa is ion mass and the ordinate is the TOF current. All curves are processed as follows: first, the baseline is subtracted, then the FFT method is used for smoothing, and finally the time is transformed into the corresponding mass (assuming that all ions are single charged). The irregular variation of the mass number less than 60 in the figure is due to baseline subtracted. The dotted lines are the corresponding mass of n from 0 to 5 in $EMI(EMIBF_4)_n^+$ and $BF_4(EMIBF_4)_n^-$ respectively. From the figure, we can see that the pure ion EMI^+ accounts for the vast majority of the ions in the positive mode plume, and only a small proportion of dimers, trimers and polymers (less than 10%). In the negative mode, the compound ion of n=0-5 accounts for 50%, the compound ion of n>5 accounts for 50%, and the maximum particle mass can reach more than 10,000. The results show that a considerable proportion of droplets in the plume, leading to a lower current value than that in the positive mode. This also proves the validity of our previous hypothesis.

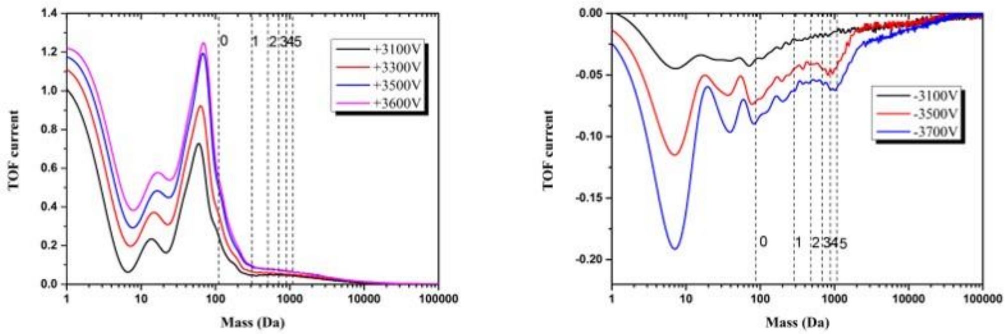

Fig. 10 TOF curves of positive and negative mode under different voltages

IV.Conclusion

The experimental results of ionic liquid electrospray in air indicate that corona discharge is inevitable in the electrospray process of $EMIBF_4$ ionic liquid. Corona discharge and its space charge are detrimental to the formation of stable electrospray.

The prototype of ionic liquid electrospray thruster was tested in vacuum environment. The results show that it can be fired in both positive and negative modes. The onset voltage and stable operating range of the thruster are obtained from the current-voltage curve. At the same time, it is found that the total current is asymmetric in positive and negative modes. The ion components in plumes are obtained by TOF test. In positive mode, EMI^+ is dominant, while in negative mode, there are more droplets. This may be the reason for the current asymmetry in positive and negative modes. The reason why the ion distribution of plume under positive and negative modes is obviously different needs further study.

Acknowledgments

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