Electrospray emission using porous emitters with flat ends

IEPC-2017-173

Presented at the 35thInternational Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October8 – 12, 2017

Xinyu Liu[1], Xiaoming Kang*[2], Dengshuai Guo[3], Weiguo He[4]
Shanghai Jiao Tong University, Shanghai 200240, China

and

Guanrong Hang[5]
Shanghai Institute of Space Propulsion, Shanghai Engineering Research Centre of Space Engine, Shanghai 201112, China

Abstract: Electrospray thrusters, with the advantages of high specific impulse, low power and high efficiency, are optional solutions for micropropulsion issues. As a crucial part of electrospray thrusters, emitters are designed in one dimension or two dimensions with different shapes. Usually, the ends of the emitters are fabricated in the shape of small sharp tips or linear sharp blades to provide a sufficiently high electrostatic field which provides enough energy for the conductive liquid to emit in the form of charged droplets, ions or a mixture of both. However, the number of emission sites and the thrust densities provided by emitters ended with sharp tips or blades are small. In this paper, electrospray thrusters using porous emitters ended with flat surfaces were designed to improve the thrust densities by increasing the number of emission sites. The numerous microscopic and uneven microstructures on the end surface of the porous emitters acted as emission sites. Experiments were conducted with electrospray thrusters using two different kinds of emitters: emitters ended with flat surfaces as well as emitters ended with sharp blades. The performances of electrospray thrusters with those two types of emitters were compared and analyzed. The initial tests showed that electrospray emission from the flat surface of porous emitters is applicable, and emitters ended with flat surfaces tend to produce higher current density, reaching 389μA/cm^2 at 4380V.

Nomenclature

I	=	electrospray beam current
A	=	opening area of extractor electrode
J	=	current density of electrospray thruster
ΔV	=	difference between the applied voltage and the startup voltage
V_{app}	=	voltage applied to the extractor electrode
V_{start}	=	emission startup voltage
d	=	distance between the emitter and the extractor electrode
E_{th}	=	emission threshold electric field
ε_0	=	vacuum permittivity

[1]Ph.D. candidate, School of Mechanical Engineering, liuxinyu@sjtu.edu.cn.
[2]Associate professor, School of Mechanical Engineering, xmkang@sjtu.edu.cn.
[3]Ph.D. candidate, School of Mechanical Engineering, gds@sjtu.edu.cn.
[4]Ph.D. candidate, School of Mechanical Engineering, Weiguo.He@sjtu.edu.cn.
[5]Senior engineer, Department of Electric Propulsion, hanggr@163.com.

γ	=	surface tension
r	=	characteristic size of meniscus
r_p	=	pore size

I.Introduction

Conductive fluids subjected to strong electric fields deform from a rounded shape into a conical structure and emit droplets, ions or a mixture of both, which is known as an electrospray. The study of electrospray can date from the nineteenth century when Rayleigh predicted the breakup of a charged liquid drop[1]. In 1917, the Rayleigh instability and cone-jet structures were observed by Zeleny[2]. After that in 1964, Taylor theoretically analyzed the structure of the cone and pointed out that the semi-vertical angle of the cone is 49.3°, which is independent of liquid properties and applied voltages[3]. Since then, distinct aspects of electrospray have been studied and electrospray science has been applied to enormous diversity of fields from biological analysis to aerospace technologies[4-7].

Electrospray propulsion is one of the most important applications of electrospray. In recent years, the number of Nanosatellites or CubeSats launched has risen rapidly, leading to an increasing demand for suitable propulsion systems. Electrospray thrusters, with the advantages of high specific impulse, low power and high efficiency, are excellent solutions for micropropulsion issues. Broadly speaking, electrospray thrusters are summarized into three categories: colloid thrusters, field emission electric propulsion (FEEP) thrusters and ionic electrospray thrusters, since they all utilize the electrostatic accelerators of charged species to provide thrusts. Unlike the other two categories, ionic electrospray thrusters use ionic liquids as propellants. Ionic liquids, which are molten salts at room temperature, are composed purely of positive and negative ions. Besides, ionic liquids have some unique properties: negligible vapor pressure, high electrical conductivities and nontoxicity[8]. Given those properties, electrospray using ionic liquids can achieve purely ionic regime (PIR)[9], discovered by Romero-Sanz et al in 2003, contributing to a higher specific impulse.

As a crucial part of ionic electrospray thrusters, emitters play an important role in providing paths for propellants to transport from the reservoir to the end of the emitters. Generally, there are three types of emitters: externally wetted emitters, internally wetted porous emitters and capillary emitters. In addition, some even use the propellant itself as emitters aided by magnetic field or ultrasonic waves[10,11]. As for externally wetted and porous emitters, the ends are usually fabricated in the shape of small sharp tips, linear sharp blades or other sharp structures to form a sufficiently high electrostatic field. However, the number of emission sites and the thrust densities provided by those sharp structures are small. In order to obtain higher thrusts, sharp structures are traditionally designed and fabricated into arrays in either one dimension or two dimensions. However, this poses great challenges in micro machining techniques to create uniform geometries.

This paper presents a kind of ionic electrospray thrusters using porous emitters with flat ends. Those emitters are created out of porous stainless steel substrates using wire electrical discharge machining (WEDM) techniques. Then we investigate the performance of the ionic electrospray thrusters and compare it with ionic electrospray thrusters ended with sharp blades. Electrostatic field are also analyzed by use of the Comsol software.

II.Porous Electrospray Emitters Fabrication

The quality of emitters has a significant effect on the performance of thrusters. To obtain the designed shapes and high machining quality, various processing methods have been applied based on the properties of the materials. Table 1 investigates emitter materials and manufacturing strategies explored in published literatures. From the table, it is found that the machining methods have been changed from wet processing to dry processing. This is because dry processing methods are more conducive to form uniform emitter arrays. In this paper, porous metal electrospray emitters are machined using wire electrical discharge machining (WEDM). Then the machined emitters are electrochemically etched using DC voltage to prevent pores from blocking. After being wetted in the ionic liquid 1-ethyl-3-methyl-imidazolium bis(triflouromethylsulfonyl)imide(EMI-Im), the emitters are finally installed to the ionic electrospray thrusters.

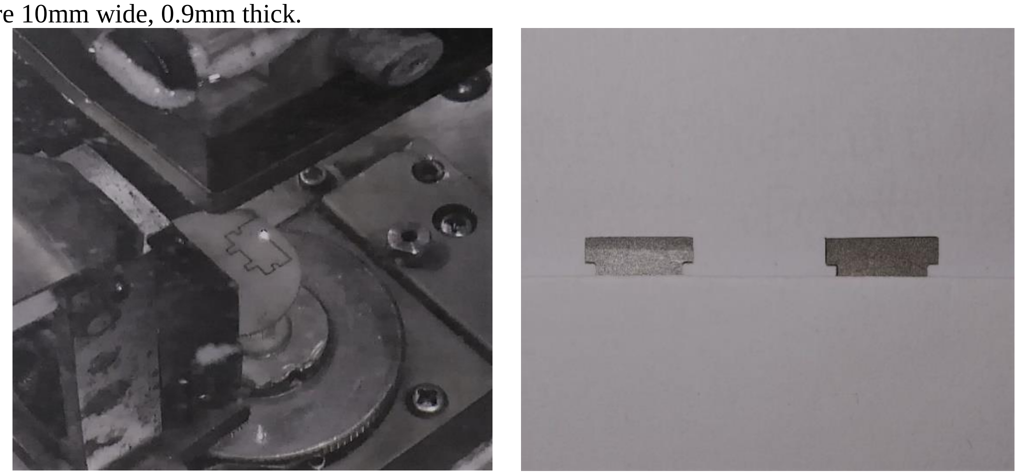
Table 1. Emitter materials and fabrication techniques in previous published literatures

Publication Date	Research Institutes	Emitter Type	Emitter Material	Emitter Geometry	Fabrication Techniques
2004	MIT	Externally Wetted	Tungsten	Needle	Electrochemical Micromachining[12]

2006	MIT	Externally Wetted	Silicon	Planar Array of Pencils or Volcanoes	Deep Reactive Ion Etching(DRIE)[13]
2006	Yale	Capillary	Silicon	Planar Array of Nozzles	Deep Reactive Ion Etching(DRIE)[14]
2007	MIT	Porous	Porous Tungsten	Linear Array of Sawtooth Emitters	Electrochemical Micromachining[15]
2007	EPFL	Capillary	Silicon	Planar Array of Capillaries	Deep Reactive Ion Etching(DRIE)[16]
2011	MIT	Porous	Porous Nickel	Planar Array of Sharp Tips	Electrochemical Micromachining[17]
2013	MIT	Porous	Porous Borosilicate	Planar Array of Sharp Tips	Laser Ablation[18]
2015	EPFL	Porous	Porous Borosilicate	Planar Array of Sharp Stripes	CNC Mill[19]
2015	MIT	Porous	Xerogels	Planar Array of Sharp Tips	Mechanical Polishing[20]
2017	MIT	Porous	Xerogels	Planar Array of Sharp Tips	Laser Ablation[21]

A. WEDM Process Details

WEDM process was carried out in the State Key Laboratory of Mechanical System and Vibration in Shanghai Jiao Tong University using a MAKINO U32J machine tool. The basic working principle of WEDM is to use pulse spark discharge generated between a mobile thin metal wire electrode and the workpiece to melt and remove the work material and create the desired geometry and surface integrity. It has been employed extensively to machine micro features and difficult-to-machine materials. Figure 1(a) shows that a small round piece of 0.9mm thick porous stainless steel plate was being cut by a 0.2 mm diameter wire electrode. Using WEDM we can obtain the designed shapes of emitters, emitters ended with sharp blades and flat surface, as shown in Figure 1(b). The machined emitters are 10mm wide, 0.9mm thick.



a) b)

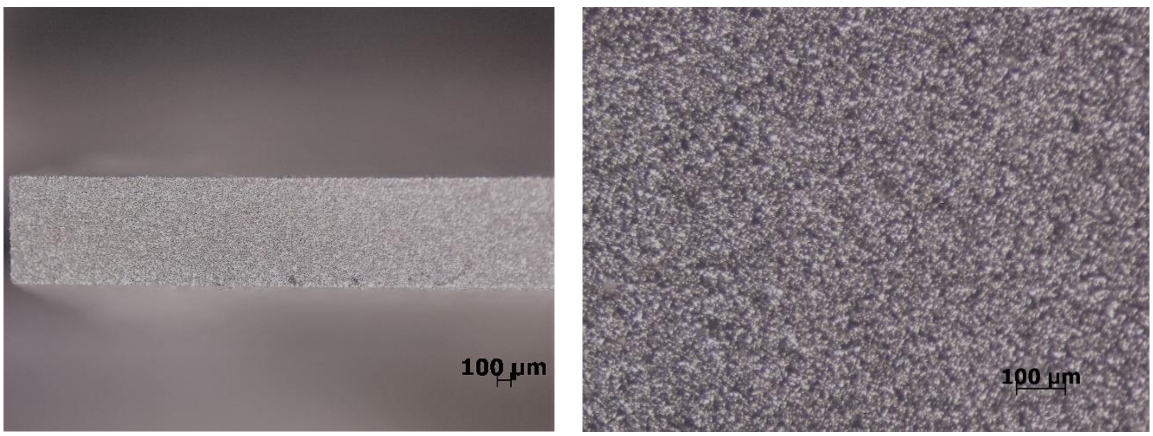
Figure 1. a) Wire electrical discharge machining (WEDM) of a porous stainless steel plate and b) Two types of machined emitters

B. Electrochemical Etching

The micro pores in machined emitters may be blocked during the WEDM process. To achieve a better emission performance, the machined emitters are required to be further processed. The method introduced here is to use electrochemical etching to remove the surface material of the emitters. Specifically, the emitter was placed into a container filled with dilute solution of phosphoric acid. Then a DC electrical potential was applied between the emitter and a stainless steel cathode to conduct electrochemical etching. This process lasted tens of seconds and it was observed that the surface of the emitter was polished. After electrochemical etching, the emitter must be dipped into alcohol and cleaned with ultrasonic washer for 5 minutes to remove residual acid and other impurities. Figure 2 presents the micro geometries of the emitter observed by use of Stereo Microscope.

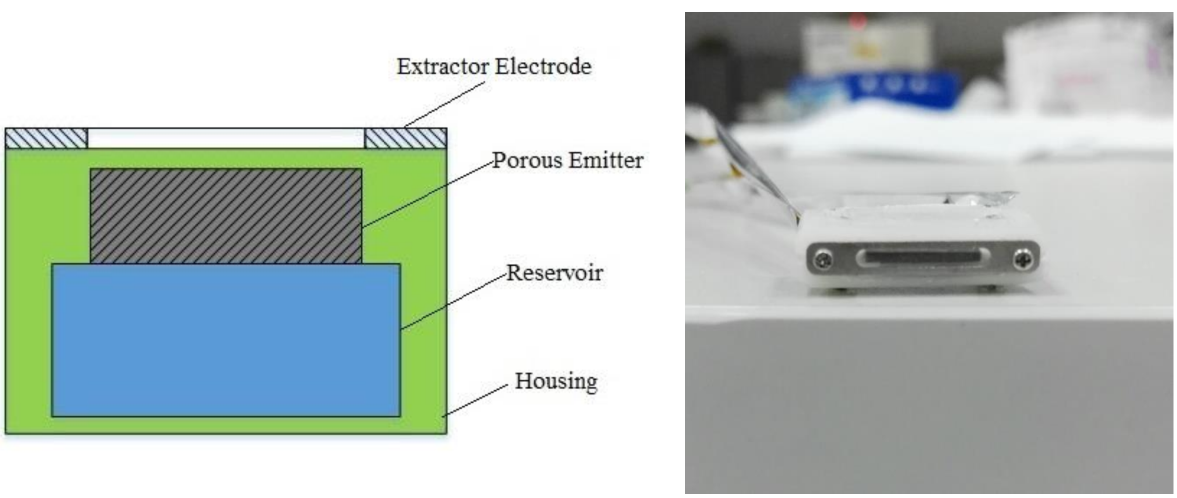
C. Thruster Prototype Design and Fabrication

A miniaturized prototype of ionic electrospray thruster is designed and fabricated. The designed thruster is composed of three parts: an emitter, an extractor electrode and a housing which contains a reservoir inside. Figure 3(a) depicts the schematic overview of the thruster. The assembled thruster is approximately 21.6mm×13.5mm×4.1mm, as shown in Figure 3, with a weight less than 3g. The fabrication of the housing was achieved by use of the 3D Printing. The propellant is passively fed to the end of the emitter from the reservoir without any active propellant feed systems. The extractor electrode, which is a piece of 0.5mm thick stainless steel machined by laser cutting, is installed on the upstream of the emitter. The distance between the emitter and the extractor electrode is around 200μm. It should be noted that the emitter should be wetted in the ionic liquid EMI-Im before assembling.



a) b)

Figure 2. Micro geometries of the emitter observed by stereo microscope magnifying a) 13 times and b) 100 times



a) b)

Figure 3. a) Schematic of the ionic electrospray thruster and b) a prototype of ionic electrospray thruster

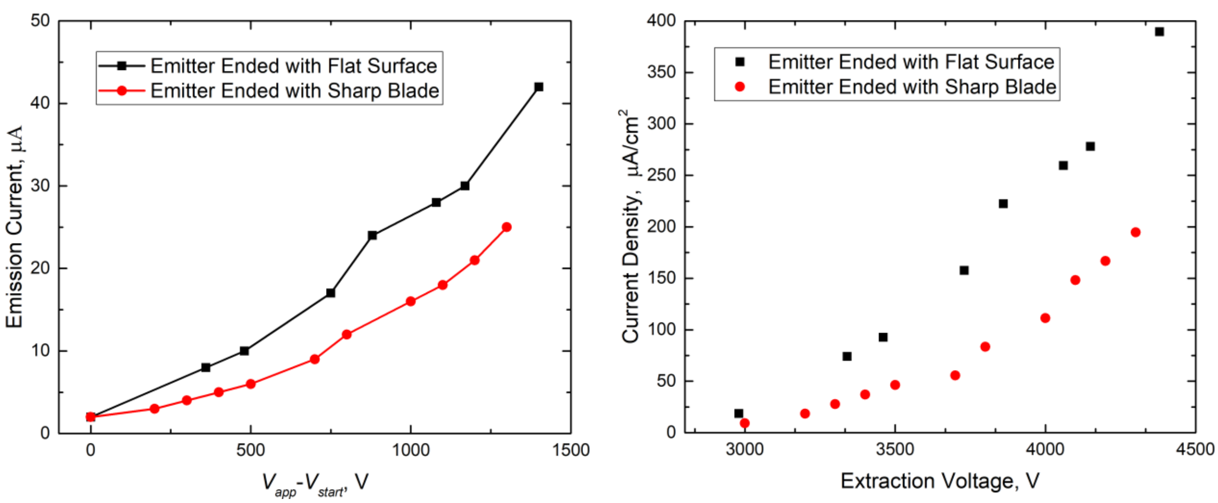
III.I-V Characterization and Electrostatic Field Analysis

The test of the ionic electrospray thruster was conducted in the Shanghai Institute of Space Propulsion. EMI-Im was chosen as the ionic electrospray propellant. The emitter was tied to the ground and high positive voltage was applied to the extractor electrode. Experiments showed that both two types of the ionic electrospray thrusters functioned well. Moreover, the electrospray from emitter with flat end tended to have a greater emission current density compared to sharp blade emitter, which means an increase of thrust density.

A. I-V Characterization

The startup voltages for the emitter with a flat end and the sharp blade emitter are 2980V and 3000V respectively when the electrode distance is around 200μm. To have a better comparison and avoid the influence of electrode distance difference between two types of thrusters, emission current varying with ΔV (difference between the applied voltage and the startup voltage) is drawn, as shown in Figure 4(a). It is clear that the emitter with a flat end produces higher emission current than the sharp blade emitter. And the current gap between the two types of emitters grows larger as ΔV increases. Figure 4(b) presents current density of the thrusters calculated using Eq. (1). It is found that the emission current density is raised with rise in extraction voltage. The results also indicate that electrospray thruster using emitters with flat ends can improve the current density effectively (reaching 389μA/cm^2 at 4380V), which contributes to a higher thrust density.

$$J = I/A \tag{1}$$



a) b)

Figure 4. a) *I-V* Characterization and b) Emission Current Density

B. Electrostatic Field Analysis

When conductive liquid is subjected in a strong electric field, the liquid surface will form a meniscus. To destabilize the liquid meniscus, the external electric field is required to exceed a critical value which is called threshold electric field. Over the threshold value, the liquid surface will become instable and rapidly deform into a shape with a progressively sharper tip. Ion emission occurs at the tip and the electric field intensity at the tip will reach an order of 10^9 V/m for ions to emit. The threshold electric field to destabilize the meniscus can be estimated by Eq. (2)[22].

$$E_{th} = \sqrt{\frac{\gamma\pi}{2\varepsilon_0 r}} \tag{2}$$

Here, γ is surface tension of the liquid and r the characteristic size of the meniscus. For a porous material, r can approximately equal to the pore size r_p. In this case, γ=0.0349N/m and r_p≈1.5μm, the estimated threshold electric field is on the order of 10^7 V/m.

In this paper, the electrostatic field of the ionic electrospray thruster using emitter with flat ends is analyzed by software Comsol. Figure 5 depicts surface electrostatic field distribution on the surface of the emitter and the extractor electrode when the distance between electrodes is 200μm and applied voltage is 3000V. From the figure, we can find that the electrostatic field distribution is not uniform. The edge of the emitter has higher electric field intensities (an order of 10^7 V/m) than central area (an order of 10^6 V/m), which means the edge area will reach the threshold electric field earlier than the central area of the emitter as the applied voltage increases. As a result, it was found that edge of the emitter started firing earlier than the central area at a relatively low voltage, as shown in Figure 6.

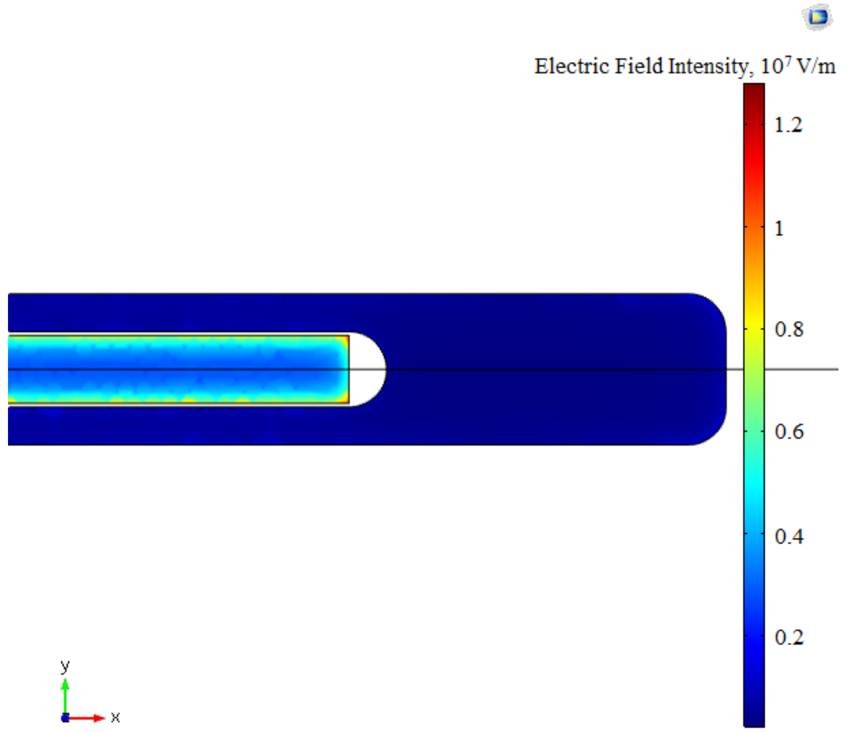


Figure 5. Surface electrostatic distribution at V_{app}=3000V, d=200µm

Figure 6. Emission starting at the edge of the emitter due to the electrostatic field nonuniformity

IV.Future Work

Due to the nonuniformity of the electrostatic field on the emitter surface, the shape of the emitter need further optimization to make the electrostatic field as uniform as possible to obtain better performance. Besides, this generation of ionic electrospray thruster prototypes utilizes only one piece of emitter to provide thrust. To improve the thrust, more emitters need to be organized and assembled in arrays in one electrospray thruster. A prototype of three-emitter-array ionic electrospray thruster has been developed and tested as shown in Figure 6. Initial test showed that the emission current was up to 195µA at V_{app}=4250V.And some important performance characteristics, such as specific impulse, thrust and efficiency will be measured next.

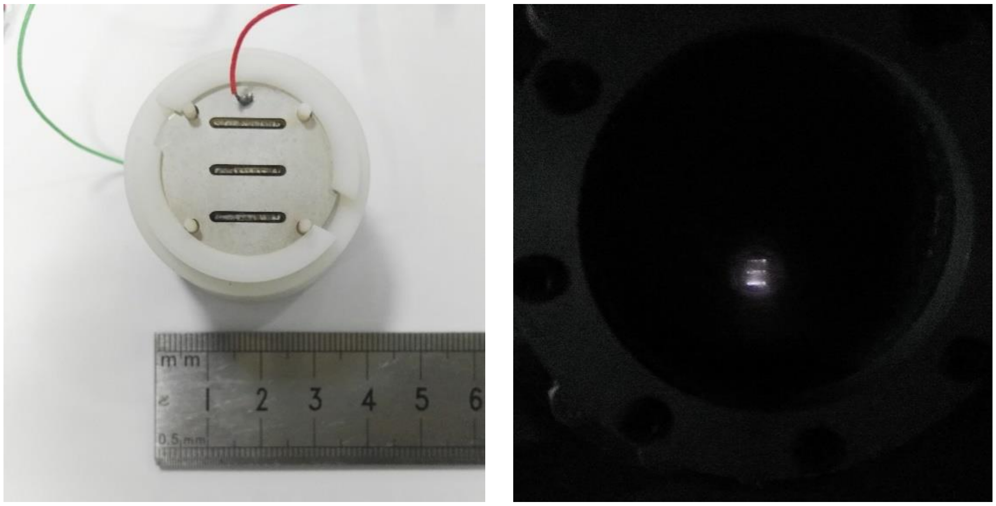


Figure 3. Prototype of a three-emitter-array ionic electrospray thruster and its operation status at V_{app}=4250V

V.Conclusion

A type of miniatured porous ionic electrospray thruster has been successfully developed. Manufacturing methods, such as WEDM and 3D printing have been used in the fabrication process which has reduced the difficulty of processing. Besides, this investigation successfully demonstrates the applicability of ionic electrospray thrusters using emitters with fat ends. Compared with sharp blade emitters, emitters with fat ends produce a higher current density up to 389μA/cm^2 at 4380V. This improvement of current density will be conducive to an increase in thrust, so it is promising in space propulsion missions. Furthermore, multiple-emitter-array ionic electrospray thrusters make it possible to provide more variable thrust in future applications.

Acknowledgements

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

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