Development of a Hall effect Hollow Cathode Thruster

IEPC-2019-245544

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

N. Zhongxi[11], L. Chenguang[22] and Y. Daren.[33]
Harbin Institute of Technology, Harbin, Hei Longjiang, 150001, China

Abstract: CubeSats have been developed rapidly with a huge potential of application in space. Hollow cathodes are widely used in industrial fields and space fields as electron sources. They are utilized as electron generators or neutralizers in electronic propulsion systems. This work proposes hollow cathodes to be micro-thrusters for small satellites. A hollow cathode plasma source device with a magnetic field is developed, which can generate a magnetic enhanced plasma beam. And it can work at a relatively low power and realize a considerable thrust. It is expected to be a useful option of electric micro propulsion for CubeSats.

I. Introduction

CUBESATS are very small satellites with a standard that 1U unit is a 10cm cube with a mass up to 1.33kg[1][1]. They are widely used for education or capability demonstration due to their low costs. With development of space industry in technology miniaturization, CubeSats have been increasingly developed for commercial purposes and science missions[2,3]. Especially, larger CubeSats such as 3U and 6U make up the majority of the launched, and they will more common in the near future due to significantly increased capabilities[2], such as Earth observation and space telescope reconfiguration[4,5]. Propulsion systems are vital for CubeSats to expand their capabilities by enabling atmospheric drag compensation, orbit change and raising, precise attitude control, formation flying as well as deorbiting capabilities at the end of the mission life in order to comply with orbital debris mitigation requirements[3,6]. To date, several kinds of propulsion systems for CubeSats have been developed, such as cold gas propulsion systems, solar sails, electric propulsion systems, etc, however, only cold gas propulsion systems was used successfully[2,7]. As CubeSates can provide a power 10W per unit and a limited space, propulsion systems are commanded to be small in size and low power. In addition, CubeSats such as 6U at orbit of ~250 km need a thrust ~0.5mN-1mN for atmospheric drag compensation[8]. Although cold gas thruster propulsion system and electro-thermal propulsion systems can provide a large thrust ~ 35mN, they can only provide a specific impulse ~60-100s[9-12]. To expand the life and capabilities of CubeSats, a thruster with high specific impulse is necessary.

---

[1] Professor, Harbin Institute of Technology, ningzx@hit.edu.cn
[2] Ph.D. candidate, Harbin Institute of Technology, 1036558146@qq.com
[3] Professor, Harbin Institute of Technology, yudaren@hit.edu.cn

Hollow cathodes as electron sources in Hall thruster propulsion systems are simple in structure and operation. And they are proposed to be developed into electric micro-thrusters, which can make thruster and cathode to integrate. Gabriel *et al*[13] develop two micro-thrusters based on T5 and T6 hollow cathodes. It is found that gas thermal expansion effect plays a major role in thrust generation, and that plasma potential hill acceleration effect also make an effect on thrust generation when hollow cathode in plume mode[14,15]. Sasoh *et al*[16] developed central-cathode electrostatic thrusters with gas supplying from both anode and cathode. And it is found that electrostatic acceleration and electromagnetic play important roles in thrust generation. To apply hollow cathode thrusters on CubeSats, energy consumption needs to be lower and gas supplying needs simplified. This work develops a low power hollow cathode thruster with propellant only being injected from cathode. And thrust characteristics and discharge characteristics are measured. The work mechanism of the magnetic enhanced hollow cathode thruster (MHCT) is introduced.

II. Experimental setup

As shown in Fig.1, the hollow cathode thruster consists of a heatless hollow cathode, a stainless steel conical anode, ceramic insulators and an annular magnet. The emitter of the hollow cathode is a BaO-W with an orifice of 0.5mm diameter in it, and what is different with the traditional hollow cathode applied in electric propulsion system is that the emitter is mounted on the tip of the hollow cathode tube of which diameter is 10mm. Xenon gas is supplied by the gas tube and can go through the orifice in the emitter. A ceramic insulator is around the cathode tube to insulate heat from the cathode to the magnet on the insulator. A conical anode is downstream of the cathode and the angel of cone is 30°. A ceramic insulator is between the anode and cathode to prevent the heat from the anode to magnet. The magnet is samarium-cobalt permanent magnet and the inner diameter is 17 mm and outer diameter 29 mm. The right end of the magnet is 4 mm away from the left end of the anode, and a divergent magnetic field is applied to the anode region and downstream of the anode. The maximum of magnetic field is ~300G at the position of the inlet of the anode and then magnetic field decrease along the center axis.

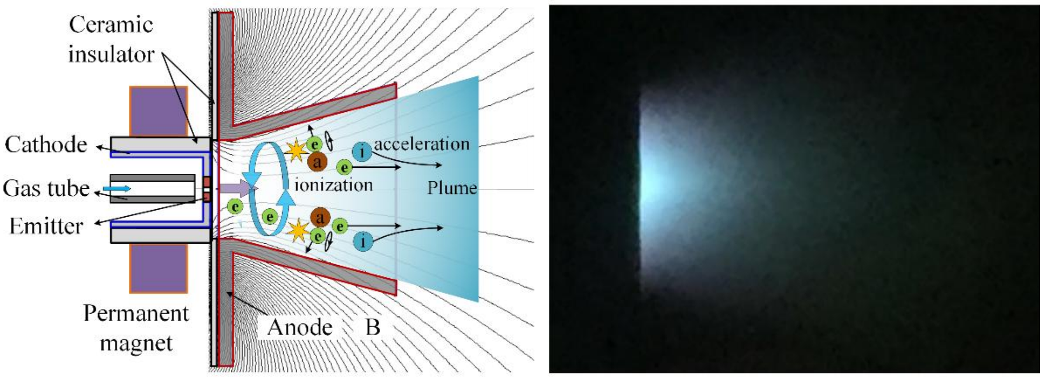

Figure 1. The structure of the hollow cathode thruster and a discharge picteure of the thruster

A discharge picture is shown in the Fig.1, and it can generate a plasma beam downstream of the anode outlet. To analyze the thrust characteristics of the hollow cathode thruster, a torsional pendulum thrust measuring device is used to measure the thrust that it can generate[17]. A retarding potential analyzer is utilized to analyze the plasma beam potential distribution, and a Langmuir probe is utilized to measure the electron density and temperature distribution in the anode region along the central axis and radial direction[18]. A double side probe is applied to measure Hall drift current in anode region. Based on the above conclusions, a working mechanism of the hollow cathode thruster is simply analyzed.

III. Results

A hall drift is found in the experiment as shown in the Fig.2, which is common in hall thrusters. A double side probe is utilized to demonstrate the hall drift current in the anode area. As shown in the Fig.2, hall drift current decreases along axis, which is a powerful evidence that hall drift current exists in anode area. As mentioned in the Fig.1, electrons make a whirling motion in the magnetic field, and make hall drift under the effect of the magnetic field and electric field. It is an important factor to guarantee a high ionization ratio of the hollow cathode thruster.

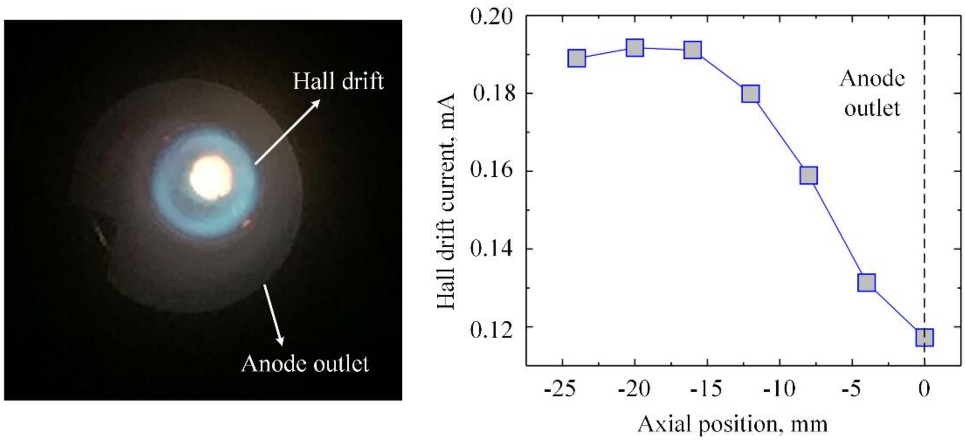

Figure 2. The picture of Hall drift in anode (left) and hall drift current along the central axis of the anode (right)

The discharge characteristics of the hollow cathode thruster is shown in Fig.3. It shows that there is an inflection point on the IV-curves. It is a negative resistance character when anode current is below the current of the inflection point, and then it is a positive resistance character after the current of the inflection point. Plasma density will increase with current, which can increase the electron conductivity, and which is the reason that anode voltage decreases. However, the plasma density reaches saturation at the current of the inflection point, and anode need to improve potential to collect more electrons which conduct to anode cross magnetic field. And with gas flow rates increasing, the anode voltage decrease, which is the result of plasma density will increase when gas flow rate increases.

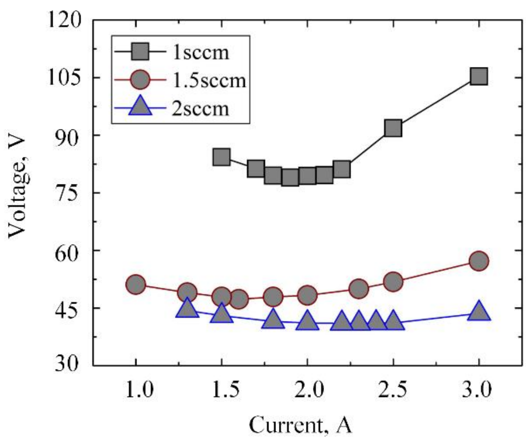

Figure 3. The Volt-ampere characteristics of the hollow cathode thruster at different gas flow rates.

The thrust characteristics of the hollow cathode thruster is shown in the Fig.4. It shows that thrust increases with current due to more ions are accelerated to generate thrust. In addition, increase in anode voltage in the positive resistance region leads to an increase in ions' potential, which is also the reason that thrust increase in the positive resistance area. And thrust is higher when gas flow rate is 2 sccm than that is 1 sccm and 1.5 sccm, which is the result that more ions will generated and accelerated to generate thrust when gas flow rate increase. And specific impulse increase with current which is also the result that ions density and ions' energy increase in plasma beam. At lower gas flow rate such as 1 sccm, it can achieve a higher specific impulse compared to 1.5 sccm and 2 sccm, which means that particles' velocity is higher. It is because that particle collisions between ions and atoms lead to a larger loss of ions' energy at higher gas flow rate, and that ions per unit mass can gain higher energy at lower gas flow rate.

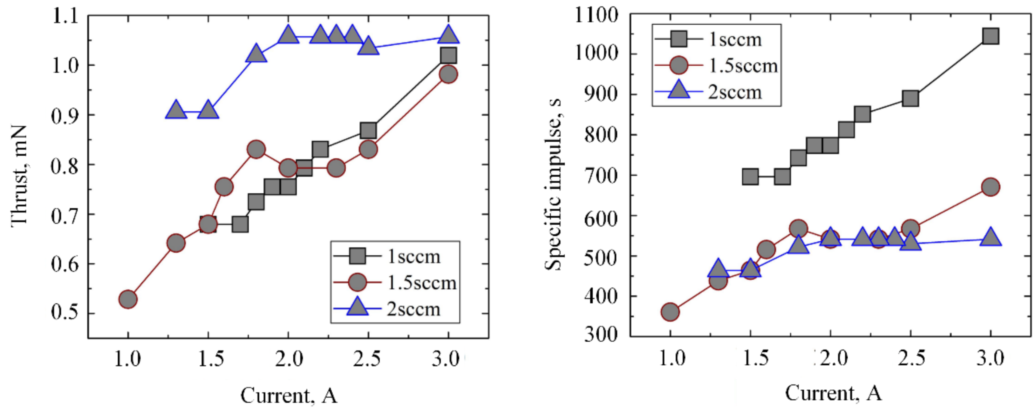

Figure 4. Thrust characteristics (left) and specific characteristics (right) of the hollow cathode at different current and different gas flow rates.

A Langmuir probe is applied to analyzed plasma parameters distribution including electron density and plasma potential in anode and plume regions. The electron density distribution and plasma potential distribution in anode and plume regions is shown in Fig.5. It shows that the electron density in central region is relatively high reaching 2.5-3 $\times 10^{16} m^{-3}$. And it is found that plasma potential at central axis is the lowest along radial direction. The plasma potential at 0 mm reaches to 0 V, which is the potential of the cathode. Combined the electron density distribution, the high density of plasma extends the low potential of the cathode to the central regions of anode and plume, which can be regarded as a virtual cathode area. Therefore, there is a potential difference along radial direction, which leads to the electron conduction across the magnetic field. In addition, under the potential difference along radial direction, ions can be accelerated out of the anode as mentioned in Fig.1.

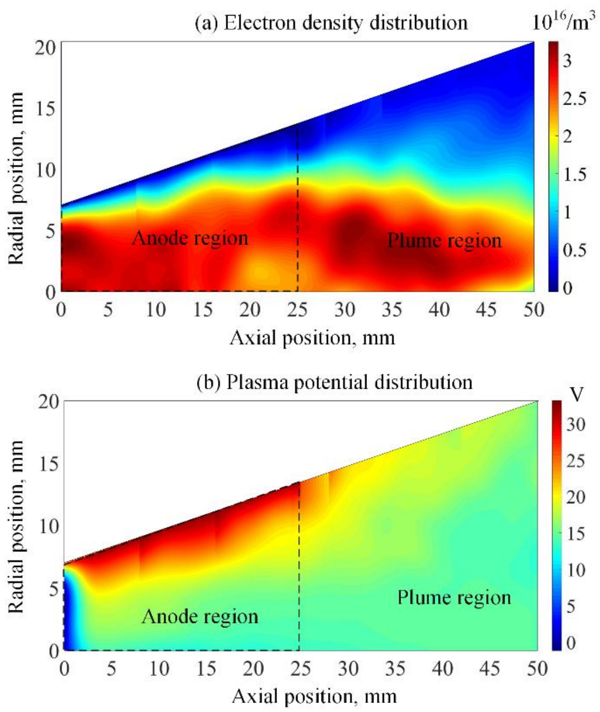

Figure 5. The electron density distribution (a) and plasma potential distribution (b) in anode region and plume region, the gas flow rate is 5 sccm and the discharge current is 1.5A.

IV. Conclusion

A magnetic enhanced hollow cathode thruster is developed and a magnetic enhanced plasma can be observed. Under the effect of the crossed electric and magnetic field, there exists hall drift current in anode area. With the effect of virtual cathode, ions can be accelerated out of anode by the plasma potential. And the hollow cathode thruster can generated specific impulse ~450s with power ~50W, which can be provide by a 6U CubeSat. However it remains a low efficiency ~ 7%, so a further work about improving the efficiency of the hollow cathode thruster is important to apply it on CubeSats.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under the grant Nos. 61571166, 11775063, and 51736003.

References

[1] J. Puig-Suari, R. Coelho, S. Williams, "CubeSat design specification Rev. 12", The CubeSat program, Cal. Poly SLO, 2009.

[2] Poghosyan A , Golkar A . "CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions", *Progress in Aerospace Sciences*, 2016, pp. 59-83.

[3] Lemmer, Kristina. "Propulsion for CubeSats". *Acta Astronautica*, 2017, pp. 231-243.

[4] Selva D , Krejci D . "A survey and assessment of the capabilities of Cubesats for Earth observation", *Acta Astronautica*, 2012, vol. 74, No. 27, pp. 50-68.

[5] Underwood C , Pellegrino S , Lappas V J , et al. "Using CubeSat/micro-satellite technology to demonstrate the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST)", Acta Astronautica, 2015, pp. 112-122.

[6] N.L. Johnson, E.G. Stansbery, "The new NASA orbital debris mitigation procedural requirements and standards", *Acta Astronaut*. 2010 pp. 362–367.

[7] Sarda K, Grant C, Eagleson S, et al. "Canadian Advanced Nanospace Experiment 2: Om-Orbit Experience with an Innovative Three-Kilogram Satellite", *22nd Annual AIAA/USU Conference on Small Satellites*, Sarda, 2008, pp. 1-15.

[8] Wei-Yong Z , Yu-Lin Z , Kun L . "Aerodynamics Analysis and Reduced Drag Design for the Lower LEO Spacecraft", *Journal of Astronautics*, 2010, Vol. 31, No. 2, pp. 342-348.

[9] Zandbergen. B.T.C, Cervone. A, "Cubesat Micro-Propulsion Systems for Extending the Capabilities of Academic Projects" *the 65th International Astronaut Congress*, Toronto, 2014, pp. 1-12.

[10] Guo J, Bouwmeester J, Gill E, "In-orbit results of Delfi-n3Xt: Lessons learned and move forward", *Acta Astronautica*, 2016, pp. 39-50.

[11] Arestie S, Lightsey E G, Hudson B, "Development of A Modular, Cold Gas Propulsion System for Small Satellite Applications", *Journal of Small Satellites*, 2012, Vol. 1, No. 2, pp. 63-74.

[12] Hruby V, "High Isp CubeSat Propulsion", *Proceedings of the 1st Interplanet. CubeSat Work*, Cambridge, 2012.

[13] Grubisic A N and Gabriel S B, "Assessment of the T5 and T6 Hollow Cathodes as Reaction Control Thrusters", *J. Propul. Power*, Vol. 32, No. 4, 2016

[14] Grubisic A N and Gabriel S B, "Understanding Hollow Cathode Thrust Production Mechanisms", *the 31st International Electric Propulsion Conference*, Michigan, 2009.

[15] Grubisic A N and Gabriel S B, "Thrust Production Mechanisms in Hollow Cathode Micro-thrusters" *IEEE Aerospace Conference*, 2010.

[16] Akihiro S, Hayato K, Yoshiya N, etc. "Electrostatic-magnetic-hybrid thrust generation in central–cathode electrostatic thruster (CC–EST)", *Acta Astronautica*, 2018, pp. 137-145.

[17] Zhongxi N, Jinfan F, "On-line measurement method and uncertainty analysis of micro-thrust of three-wire torsional pendulum", Measurement and control technology, 2012, Vol. 31, No.5, pp. 45-48.

[18] Tuszewsk M I and Tobin J A, "The accuracy of Langmuir probe ion density measurements in low-frequency RF discharges", *Plasma Sources Science and Technology*, 1996, Vol. 5, No. 4, pp. 640-647.