

Experiment of Hall thruster plume effects on different ground experimental conditions

SU Yang¹, CAI Guobiao¹, HE Bijiao¹, SHANG Shengfei²,
LIU Peng³, LIANG Wei³

(1. School of Astronautics,

Beijing University of Aeronautics and Astronautics, Beijing 100191, China;

2. Science and Technology on Reliability and Environmental Engineering Laboratory,
Beijing Institute of Spacecraft Environment Engineering,

China Aerospace Science and Technology Corporation, Beijing 100094, China;

3. Electric Propulsion Department, Shanghai Institute of Space Propulsion,
China Aerospace Science and Technology Corporation, Shanghai 201112, China)

Abstract: Reducing the influence of back-sputtering effect can effectively improve the accuracy of the measurement of the Hall thruster plume effect. Quartz crystal microbalance (QCM) was used to measure the deposition and sputtering distribution of HET-40 thruster plume on two different experimental conditions: case 1, using liquid nitrogen heat sinks and case 2, without using liquid nitrogen heat sinks. Meanwhile, X-ray photoelectron spectroscopy (XPS) was used to analyze the composition of the QCM surface after two experiments. The results of the two experiments showed that the sputtering rate under the condition of case 1 was slightly higher than case 2. Especially within the range of 90° to 110° relative to the thruster axis, case 1 experiment result showed sputtering effect, while case 2 experiment showed deposition effect. Through analysis of the experimental results, it can be found that using liquid nitrogen heat sink to reduce the temperature of the inner wall surface of vacuum chamber can effectively adsorb the particles sputtered by the plume and reduce the concentration of back-sputtering particles, leading to the above phenomenon.

Key words: vacuum exhaust plume; sputtering effect; deposition effect; Hall thruster; HET-40

CLC number: V439⁺.2

Document code: A

Hall thrusters are Hall-effect-based electric propulsion devices that use electrostatic forces to accelerate an ionized propellant, while magnetic forces limit the mobility of electrons and provide efficient ionization^[1]. This type of thruster has been widely used for on-orbit satellite propulsion because of its high specific impulse and thrust efficiency^[2-3]. For many years, researchers have studied the characteristics of the Hall thruster plume and achieved remarkable results^[4-5]. However, two primary risks become exposed when the Hall thruster plume interacts with sen-

sitive on-board equipment; the erosion of exposed surfaces due to the impact of high energy plume ions and the deposition of contamination products that emanate from the thruster. Therefore, many ground experiments have been carried out to characterize the deposition and sputtering of Hall thruster plumes in different vacuum facilities.

Pencil, et al. conducted a series of experiments to measure the distribution of the deposition and sputtering effects of an SPT-100 plume^[6]. These experiments were carried out in

a vacuum facility pumped by a gaseous helium cryogenic pumping system. The results showed that the sputtering effect was dominant at angles lower than 70° from the axis, and the deposition effect was dominant at angles greater than 70° . Since then, Jaworske conducted a similar experiment on the SPT-140 thruster^[7]. The facility used in this experiment was included twelve cryogenic pumps. The researchers found that, unlike the SPT-100, all the materials in the 90° range were sputtered by the plume from the SPT-140 thruster. Trevisani, et al. used QCM to test the effect of a Hall thruster plume at 80° from the axis in a small vacuum chamber^[8]. Pumping out of the chamber was done by a mechanical pump and two cryopumps. The experiment clearly showed the depositional effect at 80° . Khartov, et al. measured the contaminants in the SPT-70 plume with self-designed devices and proved that B element, which came from the thruster, was one of the contaminants^[9]. It can be found from the above studies that the sputtering and deposition distribution of different types of thrusters were not the same. Therefore, the plume effect of the Hall thruster HET-40 developed by ourselves still needs to be experimentally studied.

Meanwhile, the researchers found that the back-sputtering effect from the electric thrusters has an adverse effect on the experiments^[10-11]. Therefore, several vacuum chambers are equipped with an anti-sputtering target (AST) to reduce the impact of back-sputtering^[12-13]. However, in the most vacuum chambers, the back-sputtering particles were still adsorbed by local low temperature methods such as cryopumps, which adsorbed only when particles collide with their surfaces. In this way, the back-sputtering particles will exist for a period of time and cannot be adsorbed in time. For this reason, some researchers used liquid nitrogen heat sinks to cool the inner wall of vacuum chamber and carried out experiments with ion thruster^[14]. But they did not compare the results with those unused liquid nitrogen heat sinks. Therefore, whether the

use of liquid nitrogen heat sink is beneficial to the experiment and the degree of influence on the experimental results remain to be studied.

In this study, an experimental investigation was performed to characterize the distribution of deposition and sputtering from HET-40 plume on two different experimental conditions: case 1, using liquid nitrogen heat sinks and case 2, unused liquid nitrogen heat sinks. QCM devices were used in these two experiments to measure the mass deposition rate and the mass sputtering rate. X-ray photoelectron spectroscopy (XPS) was used to analyze several QCM surfaces to determine the pollution components after the two experiments were completed.

1 Experimental investigation

1.1 Vacuum facility

The experiments were conducted in the vacuum plume effect system (PES)^[15-17]. The vacuum chamber in the PES has a cylindrical horizontal body, and two elliptical head structures with an inner diameter of 5.2 m and a length of 12.6 m as illustrated in Fig. 1.



Fig. 1 Vacuum chamber of the PES

The facility is equipped with an external vacuum pumping system, an internal cryopumping system, and a double-layer anti-sputtering target (AST)^[18]. The external vacuum pumping system consists of a coarse pumping system and a high pumping system. The former comprises two SP630 screw pumps and two WSU2001FC root pumps, and the latter comprises two TW1 600 molecular pumps, two Coolvac 60 000 BL-V

cryopumps, and their forepumps. The internal cryopumping system consists of double layers of heat sinks. The double-layer anti-sputtering target (AST), with graphite sheets, was designed to effectively reduce the backflow rate of sputtered materials. The AST also has liquid nitrogen heat sink on the inner surface.

The first experiment, case 1, was performed using the external vacuum pumping system and both layers of heat sinks that were cooled by liquid nitrogen. In this case, the dynamic vacuum was stable at 1.5×10^{-3} Pa and the temperature of inner face of vacuum chamber was 77 K during the experiment. The second experiment, case 2, was performed using only the external vacuum pumping system. The dynamic vacuum was stable at 2.5×10^{-3} Pa and the temperature of inner face of vacuum chamber was 297 K.

1.2 Thruster

These two experiments were performed by a single HET-40 thruster. The thruster was designed to operate with a discharge current of 1.9 A and a discharge voltage of 300 V. The xenon flow rate of the thruster's anode was 27 mL/min and the volumn flow rate for its cathode was 3 mL/min. A photograph of the thruster is provided in Fig.2. During the two experiments, the discharge current of the thruster remained at about 1.873–1.879 A and the discharge voltage was stabilized at 313 V. The current density uncertainty for each experiment was estimated to be 0.3%.



Fig. 2 HET-40 thruster

1.3 Measuring apparatus and procedure

A series of the same type of quartz crystal microbalances (QCMs) were utilized in the present study to record the deposition and sputtering rates from the plume of HET-40 thruster. The QCMs were provided by the Beijing Institute of Satellite Environmental Engineering. The crystal surface of the QCM is plated with Au and the crystal sensitivity was $1.1 \text{ ng}/(\text{cm}^2 \cdot \text{Hz})$. The frequency error of QCM is $\pm 5 \text{ Hz}$. The QCM surfaces, before and after the experiments, are shown in Fig. 3.

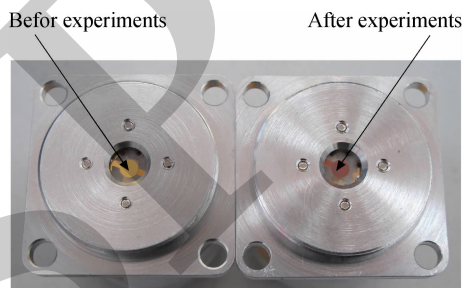


Fig. 3 QCM surface before and after experiments

Supports for the QCMs were provided by L-type brackets that were connected to two arc plants. The L-type brackets and the arc plants were all made of aluminum. The two plants were placed symmetrically on the left and right sides of the thrust axis, and $(1160 \pm 1) \text{ mm}$ from the thruster's center. The QCM distribution angle range (θ) was 40° to 110° , with respect to the thrust axis, in (10 ± 0.1) degree increments on each side (shown in Fig. 4). Eight QCMs (QCM 1–8) were placed on the right side plant, and the symbol “×” indicates that the QCM was not available at that position. A $\phi 50 \times 100 \text{ mm}$ aluminum collimator was installed on the front of each QCM on the right side to make sure that only the materials from the thruster could reach the sense crystal. The inner surface of the collimator was covered with foil. Another eight QCMs (QCM 9–16) were placed on the left-side plant and six of them had no collimator installed so that the results could be compared to the QCMs on right-side plant. Two QCMs, which were placed at 50° and 60° on left

side, were equipped with the same collimator as the right side to verify the symmetry of the two plants.

The same group of QCMs was used in the two experiments and no QCM was moved during the two experiments. Case 1 experiment was performed first and lasted for 8 h and case 2 experiment lasted for 4 h. During the case 1 experiment, some QCMs, which were closer to the axis, were over range due to the severe sputtering. Therefore, only parts of the QCMs were still usable for case 2 experiment. Fig. 4(a) shows the configuration for the QCMs used in case 1 and Fig. 4(b) shows the configuration of the QCMs

used in case 2. The QCMs have been heated to 323 K for 10h to keep clean before each experiment.

During these two experiments, the vacuum chamber was connected to a dedicated ground terminal. The thruster and its mounting structure were insulated from the vacuum compartment. The QCMs, the L-type brackets, and the arc plants were electrically connected to the vacuum chamber, but the collimators were electrically isolated from the vacuum chamber and any other equipment.

In summary, the two experimental conditions are shown in Table 1.

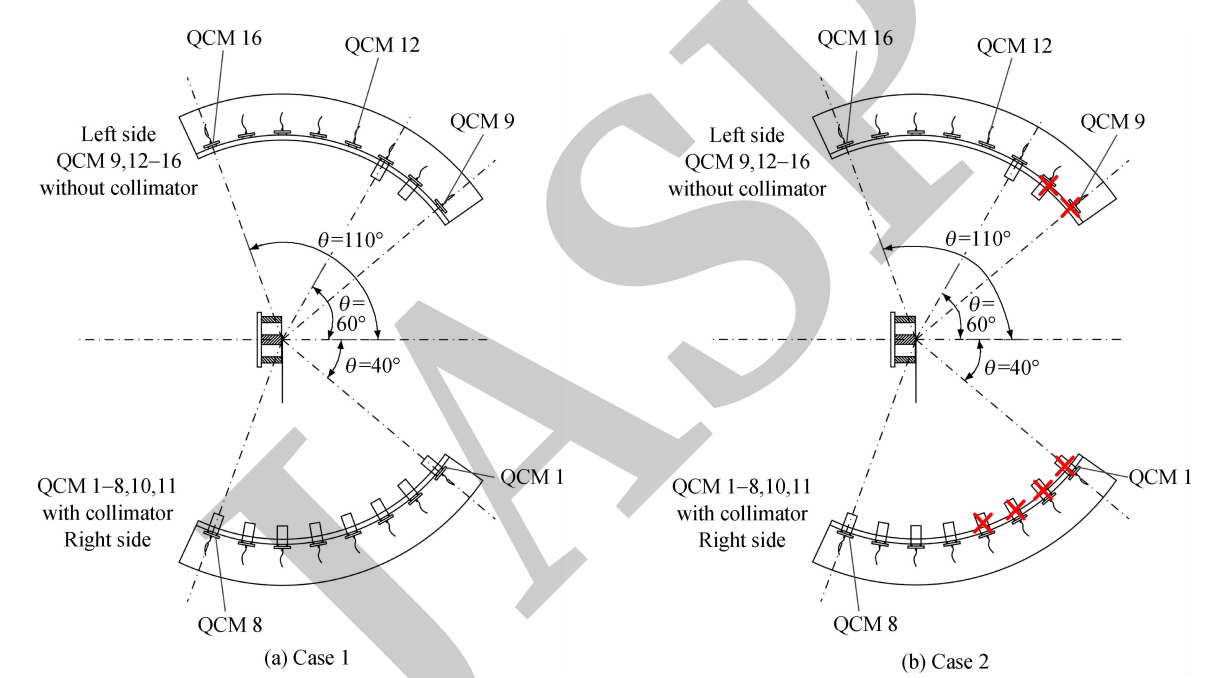


Fig. 4 Configuration of the two experiments

Table 1 Two experimental conditions

Experiment	Vacuum pumping system	Inner wall temperature of vacuum chamber/K	Background pressure/ 10 ⁻³ Pa
Case 1	External vacuum pumping system & liquid nitrogen heat sinks	77	1.5
Case 2	External vacuum pumping system	297	2.5

X-ray photoelectron spectroscopy (XPS) was used to analyze the composition of the crystal surface of several QCMs after the two experiments. The XPS data were obtained with an ESCALab220i-XL electron spectrometer from VG Scientific using 300 W AlK α radiation. The base

pressure was about 3×10^{-7} Pa. The binding energies were referenced to the C1s line at 284.8 eV, which was from adventitious carbon.

2 Results and discussion

Fig. 5 shows the Δf of the two QCMs dur-

ing case 1 experiment and the result of curve fitting. Δf is the change value of QCM frequency. Positive Δf means sputtering effect. The description ‘right-with collimator 80°’ means that the QCM was placed 80° with respect to the right side plant and equipped with collimator as shown in Fig. 4. The curve before 200 min in Fig. 5 is nonlinear. This was because the thruster was in an unstable state when it was turned on. Therefore, the last 100 min of the experiments were selected as valid data. The slope of the curves ‘ b ’ means the frequency sputtering rate. According to the relationship between the mass sputtering rate ‘ $\dot{m}$ ’ ($\text{ng}/(\text{cm}^2 \cdot \text{min})$), the frequency sputtering rate ‘ b ’ (Hz/min) and the crystal sensitivity, $\dot{m}=b \times 1.1$, the mass sputtering rate ‘ $\dot{m}$ ’ can be calculated.

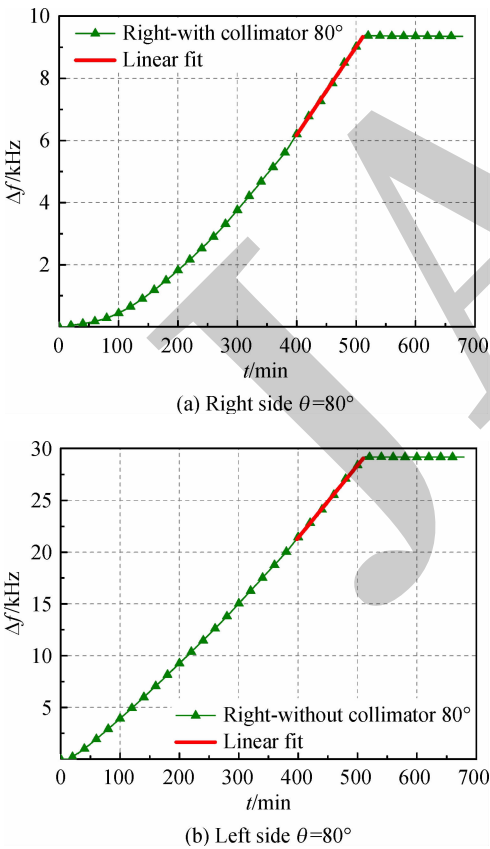


Fig. 5 Δf for two QCMs during case 1 experiment and the result of curve fitting the data

Fig. 6 and Fig. 7 show the mass sputtering rates ($\dot{m}$) recorded by the QCMs in the two experiments respectively. Fig. 6(a) shows all the data for the QCMs placed on both sides from 40°

to 110°, and Fig. 6(b) shows part of the QCMs on both sides from 90° to 110°. $\dot{m} > 0$ refers to sputtering effect, $\dot{m} < 0$ refers to deposition effect. As shown in Fig. 6(a), the mass sputtering rate of the QCMs installed at 50° and 60° on both sides were basically the same. This phenomenon proves that the two plants had a good symmetry.

From the experimental data shown in Fig. 6 and Fig. 7, it can be observed that the mass sputtering rate of the QCMs on the same side

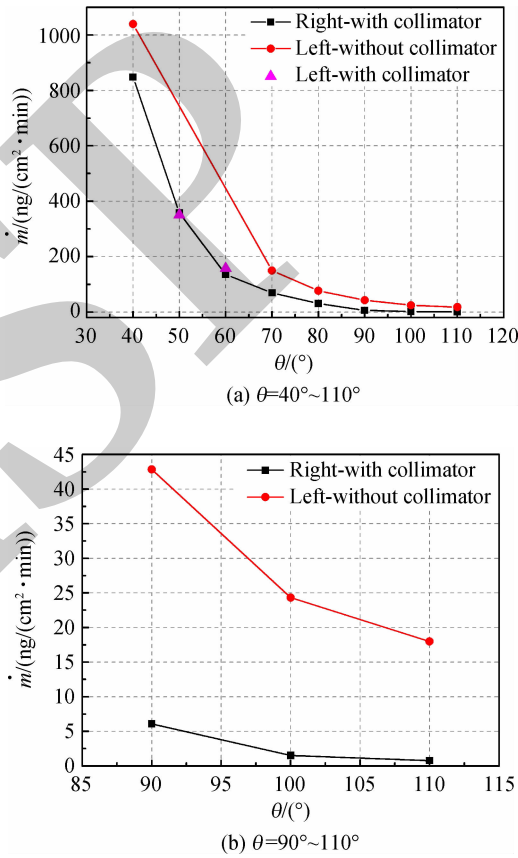
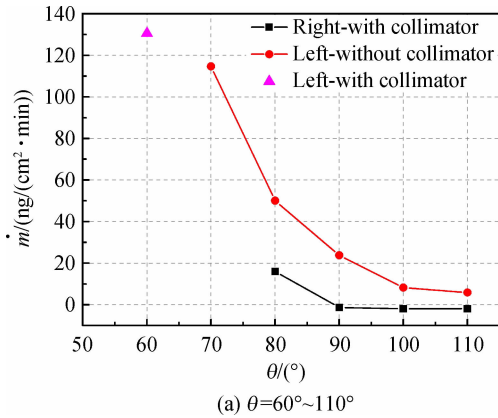


Fig. 6 Mass sputtering rate of the QCMs in case 1 experiment



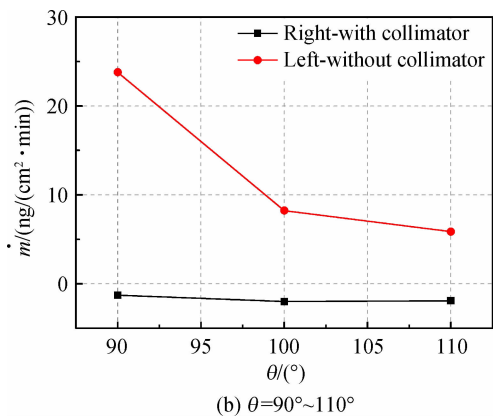


Fig. 7 Mass sputtering rate of the QCMs in case 2 experiment

decreased with an increasing QCM distribution angle in both experiments. This result was caused by the decrease of the current density supplied to the Hall thruster plume as the QCM distribution angle increased^[19-21]. In addition, the mass sputtering rate of the QCMs without collimators was significantly higher than the QCMs with collimators at the same QCM distribution angle. This was because the collimator effectively prevented interactions between particles coming from an oblique incidence and the surface of the QCM. Thus, the QCMs without collimators were subjected to more particles from environment than the QCMs with collimator.

Fig. 8 compares the mass sputtering rate obtained from the two experiments. From the comparison of the results for QCMs without collimators, it can be found that the sputtering rate in the case 1 experiment was higher than in case 2 experiment. The results for the QCMs with collimators showed the same phenomenon. But the difference was much smaller than the QCMs without collimators. Besides, it is worth noting that the sputtering effect occurred in case 1 experiment over the QCM distribution angles of 90° to 110°, but the deposition effect occurred in case 2 experiment at the same QCM distribution angles.

According to the different experimental conditions shown in Table 1, the above phenomenon may be caused by the following reasons; (1) the sputtering and deposition distributions were affected by the background pressure; (2) differ-

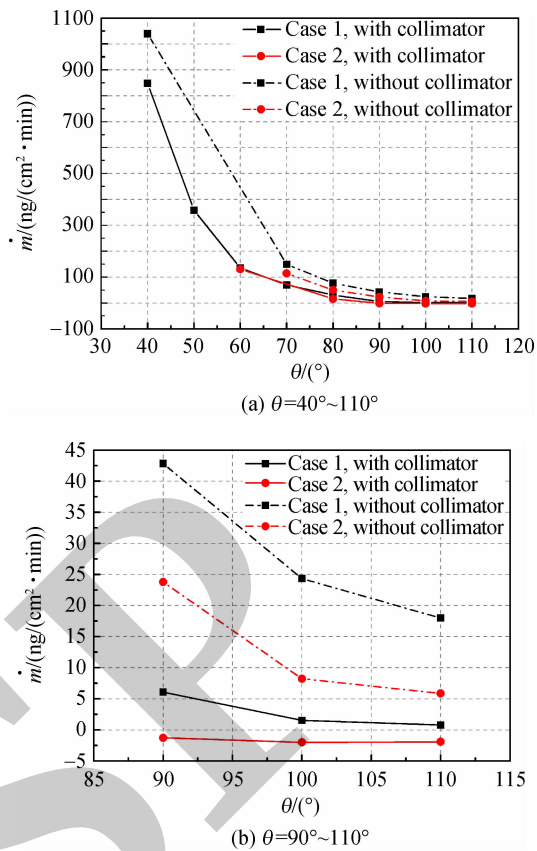


Fig. 8 Comparison of mass sputtering rate of two experiments

ent inner wall temperatures affected the concentration of back-sputtering particles, which affected the experimental results.

Background pressures in the two experiments were a little different. According to the literature, it can be find that the plume performances of Hall thruster are indeed affected by the background pressure^[22-24]. The results in Ref. [24] indicated that, as the background pressure decreased, the energy of low energy ions at large angles increased, and the number of low energy ions decreased. However, in the two experiments, the difference of the background pressure is so small that it should not cause significant changes.

The influence of the back-sputtering effect of the Hall thruster was hard to be monitored during the two experiments. The ionization gauge used in the chamber can only monitor the gas pressure and cannot measure the content of elements such as C and Al. Therefore, X-ray photoelectron spectroscopy (XPS) was used to

analyze the composition of the crystal surfaces of some QCMs. Considering that the transition of sputtering to deposition effect occurs at θ of $90^{\circ}\text{--}110^{\circ}$, the QCMs placed at these locations were selected for XPS analysis.

Table 2 shows the analysis result obtained

with XPS (unused in Table 2 means that the QCM was not used in the two experiments). As shown in Table 2, for the unused QCM, the main components were Au, C, and O elements. Due to oxidation, the content of the C and O elements were a little higher.

Table 2 Analysis result of XPS

QCM	Mass fraction/%							
	Au	C	O	N	Al	Si	B	Cl
Unused	82.87	9.20	4.48	0.88	2.58			
Without collimator, $\theta=90^{\circ}$	90.73	3.47	1.54	0.16	4.09	0.00		
Without collimator, $\theta=100^{\circ}$	89.44	3.33	2.60	0.32	3.35	0.96		
Without collimator, $\theta=110^{\circ}$	88.84	3.37	2.42	0.30	3.98	1.09		
With collimator, $\theta=90^{\circ}$	81.28	4.84	7.99	0.46	1.83	3.42		0.18
With collimator, $\theta=100^{\circ}$	77.57	11.32	5.85	1.05	2.70		1.51	
With collimator, $\theta=110^{\circ}$	60.45	18.33	10.13	0.49	2.58	8.02		

For the QCMs without collimators, the mass fraction of Au elements was much higher than the unused QCMs and the QCMs with collimator. That was because the QCMs without collimators had been sputtered in both experiments. However, because of the deposition effect, the mass fraction of Au on the QCMs with collimators was lower than 82% after the two experiments. For the QCMs with collimators, the mass fraction of Au decreased as the QCM distribution angle increased and the mass fraction of C increased as the QCM distribution angle increased. Therefore, it can be considered that the depositional effect was mainly due to the C element sputtered by the Hall thruster plume from graphite sheets on AST. It proves that the concentration of C element in the case 2 experiment was higher than the case 1 experiment.

The effect of the surface temperature on sputtering has been studied for many years^[25-26]. According to the research by Besorçe, et al., it can be found that the sputtering yield is hardly affected by the wall temperature^[26]. Therefore, the different between the two experiments may not be caused by the sputtering effect on liquid nitrogen heat sinks.

The difference of the concentration of C element in the two experiments can be explained by the relationship between the surface temperature and the adsorption ability of the surface^[27]. In a rarefied gas environment, the equation for deposition rate can be expressed as

$$\dot{m}_d = \alpha \dot{m}_i - \frac{m}{\tau}$$

(1)

where $\dot{m}_d$ is mass deposition rate; α is sticking coefficient; $\dot{m}_i$ is mass incident flux; m is mass deposit at time t ; τ is deposit residence time on the surface.

In Eq. (1), τ is defined as

$$\tau = \tau_0 \exp\left(\frac{E_d}{RT}\right)$$

(2)

where τ_0 is lattice fluctuation time, on the order of 10^{-13} s; E_d is effective heat of desorption; R is universal gas constant; T is surface temperature.

The sticking coefficient α can be expressed as^[28]

$$\alpha = \frac{T_i - T}{200}$$

(3)

where T_i is source temperature.

According to the Eq. (1) to Eq. (3), it can be found that as the surface temperature decreases, the residence time increases and sticking co-

efficient increases. This will lead to an increase in mass deposition rate. During case 1 experiment, the temperature of inner face of vacuum chamber was 77 K, which was much lower than case 2 experiment. Thus, it can be considered that the deposition rate of C element on heat sinks was more in case 1 experiment than that in case 2 experiment. Therefore, concentration of C element that could be deposited on the QCM surface in case 2 experiment was higher than case 1 experiment. This phenomenon eventually caused the sputtering rate in case 1 experiment to be higher than case 2.

3 Conclusion

In this paper, the mass sputtering and deposition effects of Hall thruster (HET-40) plume has been investigated on two different ground experimental conditions: case 1, using liquid nitrogen heat sinks and case 2, unused liquid nitrogen heat sinks. According to the experimental data, it can be observed that the mass sputtering rate of HET-40 plume decreased with an increasing QCM distribution angle in both experiments. However, the results also showed that the sputtering rates during case 1 experiment were higher than case 2 experiment. The sputtering effect of the HET-40 plume occurred over a range up to 110° in case 1 experiment, and only up to 80° in case 2 experiment. After analyzing the experimental data and the XPS results, it can be found that the difference between the two experiments was mainly caused by the different concentrations of back-sputtering particles.

Compared to the local cooling method, it can be found that using liquid nitrogen heat sinks to decrease the temperature of vacuum chamber can effectively adsorb back-sputtering particles and reduce its effect on experiments. This discovery has certain guiding significance for the ground experimental research of electric propulsion.

References:

[1] KIM V. Main physical features and processes determining the performance of stationary plasma thrusters[J]. Journal

of Propulsion and Power, 1998, 14(5): 736-743.

- [2] PIDGEON D J, COREY R L, SAUER B, et al. Two years on-orbit performance of SPT-100 electric propulsion[R]. AIAA-2006-5353, 2006.
- [3] HARGUS W A. Investigation of the plasma acceleration mechanism within a coaxial Hall thruster[D]. San Francisco, US: Stanford University, 2001.
- [4] KING L B, GALLIMORE A D. Mass spectral measurements in the plume of an SPT-100 Hall thruster[J]. Journal of Propulsion and Power, 2000, 16(6): 1086-1092.
- [5] KING L B, GALLIMORE A D. Ion-energy diagnostics in an SPT-100 plume from thrust axis to backflow[J]. Journal of Propulsion and Power, 2004, 20(2): 228-242.
- [6] PENCIL E J, RANDOLPH T, MANZELLA D H. End-of-life stationary plasma thruster far-field plume characterization[R]. AIAA 96-2709, 1996.
- [7] JAWORSKE D A. Hall effect thruster plume contamination and erosion study[R]. NASA TM-2000-210204, 2000.
- [8] TREVISANI L, NEGRINI F, MARTINEZ-SANCHEZ M. Material deposition measurements from a Hall thruster using a quartz crystal microbalance[R]. Chia Laguna, Sardinia, Italy; 4th International Spacecraft Propulsion Conference, 2004.
- [9] KHARTOV S, EGOROV V, NADIRADZE A, et al. Angular distribution of ceramic isolator sputtered material in the SPT jet[R]. Toulouse, France; 30th International Electric Propulsion Conference, 2003.
- [10] BIAGIONI L, BOCCALETTO L, MARCUCCIO S, et al. A large space simulator for electric propulsion testing: design requirements and engineering analysis[R]. AIAA-2000-3750, 2000.
- [11] BIAGIONI L, KIM V, NICOLINI D, et al. Basic issues in electric propulsion testing and the need for international standards[R]. Toulouse, France; 28th International Electric Propulsion Conference, 2001.
- [12] SCORTECCI F, BONELLI E, MICHELOZZI B, et al. Performance of a large vacuum facility for spacecraft propulsion testing[R]. Chia Laguna, Sardinia, Italy; 4th International Spacecraft Propulsion Conference, 2004.
- [13] SAVERDI M, SIGNORI M, MILANESCHI L, et al. The IV10 space simulator for high power electric propulsion testing: performance improvements and operation status [R]. Florence, Italy; 30th International Electric Propulsion Conference, 2007.
- [14] YANG Zhe, CAI Guobiao, GU Zuo, et al. Ground simulation of contamination induced by plume of LIPS200 ion thruster[J]. Chinese Journal of Vacuum Science and Technology, 2016, 36(10): 1156-1161. (in Chinese)
- [15] WANG Wenlong, CAI Guobiao, ZHOU Jianping. Large-scale vacuum vessel design and finite element analysis[J]. Chinese Journal of Aeronautics, 2012, 25(2): 189-197.
- [16] LING Guilong, WANG Wenlong, CAI Guobiao, et al. Liquid helium heat sink design for experimental study of

- engine's plume and vacuum effects[J]. Journal of Aerospace Power, 2011, 26(11): 2630-2635. (in Chinese)
- [17] LING Guilong, CAI Guobiao, ZHANG Jianhua. Oil-free vacuum system design based on vacuum plume experiment [J]. Journal of Aerospace Power, 2013, 28(5): 1173-1179. (in Chinese)
- [18] SHANG Shengfei, CAI Guobiao, ZHU Dingqiang, et al. Design of double-layer anti-sputtering targets for plume effects experimental system[J]. Science China (Technological Sciences), 2016, 59(8): 1265-1275.
- [19] ABSALAMOV S, ANDREEV V, COLBERT T, et al. Measurement of plasma parameters in the stationary plasma thruster (SPT-100) plume and its effect on spacecraft components[R]. AIAA 92-3156, 1992.
- [20] MANZELLA D H, SANKOVIC J M. Hall thruster ion beam characterization[R]. AIAA 95-2927, 1995.
- [21] GALLIMORE A D, GILCHRIST B E, KING L B, et al. Plume characterization of the SPT-100[R]. AIAA 96-3298, 1996.
- [22] WALKER M L, VICTOR A L, HOFER R R, et al. Effect of backpressure on ion current density measurements in hall thruster plumes[J]. Journal of Propulsion and Power, 2005, 21(3): 408-415.
- [23] WALKER M L, HOFER R R, GALLIMORE A D. Ion collection in Hall thruster plumes[J]. Journal of Propulsion and Power, 2006, 22(1): 205-209.
- [24] DIAMANT K D, LIANG R, COREY R L. The effect of background pressure on spt-100 hall thruster performance [R]. AIAA-2014-3710, 2014.
- [25] SHIMIZU H, ONO M, NAKAYAMA K. Effect of target temperature on surface composition changes of Cu-Ni alloys during Ar ion bombardment[J]. Journal of Applied Physics, 1975, 46(1): 460-462.
- [26] BESOCKE K, BERGER S, HOFER W O, et al. A search for a thermal spike effect in sputtering: I temperature dependence of the yield at low-keV, heavy-ion bombardment [M]. Passaic County, New Jersey, US: Humana Press, 1982.
- [27] FONG M C. General sticking coefficient theory for neutral and photochemically excited molecules[C]// International Symposium on Optical Science, Engineering, and Instrumentation. San Diego, US: Surface Accommodation of Molecular Contaminants, 1998: 238-249.
- [28] CHEN P T, HEDGELAND R J, THOMSON S R. Surface accommodation of molecular contaminants[C]// 34th Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering. San Diego, US: Surface Accommodation of Molecular Contaminants, 1990: 327-336.

(编辑:陈 越)