Atomic Oxygen Effect to Performance of the Hollow Cathode of 20 mN Ion Thruster

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Abstract: We studied the effect of the hollow cathode for the ion thruster caused by atomic oxygen (AO) to be exposed below the altitude of 250 km. JAXA and MELCO develop the test satellite in super low altitude called SLATS. SLATS equips with the Kaufman-type Xe ion thruster to compensate for air drag. However the tolerance of the hollow cathode (HC) to AO was unknown. Therefore the thermionic electron emission test were conducted using partial samples of HC. The oxide on the dispenser cathode surface was estimated to be WO_3, which is the same as formed by moisture in the atmosphere. And the oxide was thicker than that of the prescript air exposure. Next we evaluated a simulated HC. The diode discharge voltage of HC was not change by AO exposure with the nominal flow rate of SLATS operation, since it seemed the oxide was almost sublimated during "activation" process heated to 1200 deg. We regarded some degradation occurs on the cathode surface, however the thruster operation in orbit will not be affected by AO flux.

I. Introduction

The satellite with super low altitude below 250 km has large merits for the high-resolution of the optical observations and the drastic low power consumption of the synthetic aperture radar. However, the life of the satellite is determined by the atmospheric drag. For example, at the altitude of 180 km, the satellite receives the resistance per unit area normal to the orbit direction of about 32 mN/m^2. Without compensation propulsion system, the satellite orbit decreases rapidly.

Super low altitude satellites under consideration at the Japan Aerospace Exploration Agency (JAXA) are applied the ion engine system (IES) as compensation propulsion, considering about the required thrust, propellant weight, long-term operation and thrust-to-weight ratio. SLATS[1,2,3)] is the experimental test satellite to demonstrate concepts above, designed to the installation of the 20 mN class IES of MELCO (Fig. 1) with the track record in orbit for north-south station keeping of geostationary satellite. The IE has two kinds of the electron source as shown in Fig. 1. One is called the main hollow cathode (MHC), supplying electrons into the discharge chamber to generate plasma from which beam ions are extracted. Another is a neutralizer hollow cathode (NHC). Both HC bring out the

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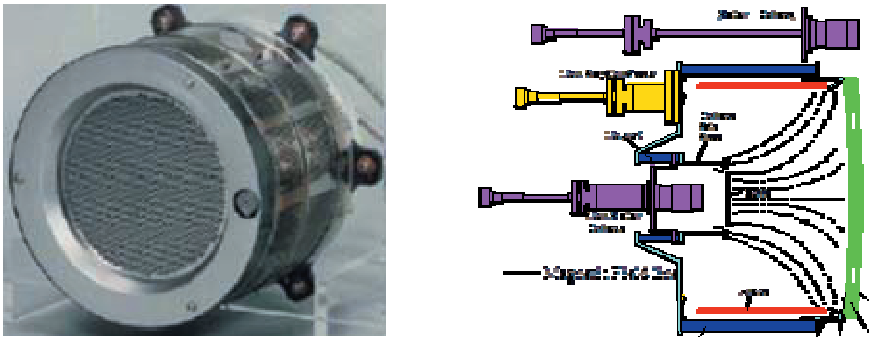


Figure 1. 20 mN class Ion Thruster and Configuration

principle of the thermionic cathode. Since HC generates an discharge plasma in the hollow cylindrical shaped cathode, it called a hollow cathode. The plasma performs self-heating the cathode using the discharge energy. Further, ions provided from the plasma work in the path of the electron extraction to diminish the space charge effect and to achieve high electron current density. Lowering the operating temperature, impregnated cathode is employed as the cathode material due to obtain a low work function surface of Ba monatomic layer adsorbed on the tungsten (W). Electron emission capability of impregnated cathode had been reported to decrease by oxygen of 10^{-5} Pa of partial pressure[4)]. In a super-low-altitude, there was the concern about the oxidation of the cathode surface by the residual atmosphere containing mainly atomic oxygen (AO). If the metal tungsten surface was oxidized, the characteristics of the low work function could not be obtained in principle, and then electron emission would be degraded. No literature in the past about the HC performance exposing AO, therefore we evaluated for the first time experimentally.

Initially we evaluated the electron emission characteristics as a simple hot cathode by using the partial samples of the HC exposed by AO and air, and investigated with surface analysis. Subsequently, the simulated cathode being able to replace the parts related to the discharge characteristics was tested to evaluate the discharge characteristics.

II. Evaluation of Main Components of Hollow Cathode

2-1 Equipment and procedure

The structure of the HC used in the 20 mN class ion engine is shown in Fig. 2. Xenon (Xe) gas flows from the upstream side through the cathode insert and the orifice to the keeper electrode. The cathode insert is impregnated to the porous tungsten with the mixture consisting of BaO, CaO, Al_2O_3. Orifice plate is the same potential as the cathode insert is made of thoriated tungsten. Keeper electrode is a tantalum disk with the hole at the center, to generate a discharge by applying a voltage. Although the insert emits mostly electrons of HC, it would be considered that the orifice plate contribute some emission, especially at discharge ignition. Therefore, we evaluated the electron emission in a vacuum and investigated these samples by surface analysis by using a partial sample of the insert and the orifice under the various exposure conditions of AO and humidity. The specifications of the partial samples are shown in Table 1. All samples are disk-shaped. The samples with electrical insulation ceramic disk for electron emission measurement have a structure for attaching a heater to the rear face. At electronic emission test in a vacuum chamber, the sample faced to the anode with a gap of 5 mm. As the preparation before the measurement, baking, heater flushing (1200 C_b, 20 min.), emission aging (1150 C_b, 120 min., 2kV) was carried out (C_b is the brightness temperature). it measured the relationship between the emission current vs. applied voltage of the anode with various sample temperature. The applied voltage was negative pulses with a width of 3 μs and a repetition of 100 Hz.

As the surface analysis we carried out SEM, energy dispersive X-ray analysis (EDX), thermal desorption spectroscopy (TDS), auger electron spectroscopy (AES) and X-ray photoelectron spectroscopy (XPS). The purpose of the SEM / EDX is to confirm the surface appearance. AES and XPS evaluated the oxidation by water vapor and oxygen atom. Since the insert samples contain originally oxides of the impregnating agent and the measured diameter of AES is sufficiently smaller than sintered metal grains, we applied AES to measure the insert samples. Meanwhile, the orifice samples were analyzed by XPS being capable to determine the valence evaluation of bonding with oxygen. And we carried out the depth profile analysis with FIB. Exposure conditions are shown in Table 2. SD is the non-exposed sample. AT1 is the regulation of the HC air exposure determined by previous experiments and actual operations. AT2 is an air exposure level that can be omitted the nitrogen purge of ion thruster at the launch

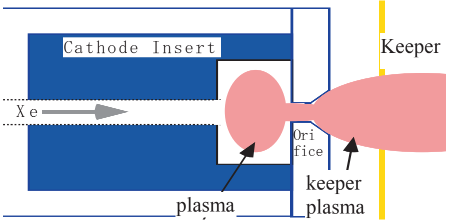
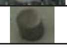


Figure 2. Hollow Cathode Configuration.

Table 1. Partial Samples of Hollow Cathode

sample	size	appearance	intended use
Insert sample	ϕ1.45 t0.6		Evaluation of electron emission
	ϕ 2 t2		SEM/EDX, AES
Orifice sample	ϕ 5.5t1		SEM XPS

bv

Table 2. AO and Atmospheric Exposure Condition for Partial Samples

Method \ Abbreviation	SD	AT1	AT2	AO1	AO2	AO3	CO1	CO2
AO ($X10^{24}$atoms/m^2)	-	-	-	0.3	1	3	1	3
25℃60%RH (hrs equivalent)	-	1000	3110	-	-	-	3110	3110

site. AO1 ~ AO3 are the AO exposure. For the prediction of AO exposure amount of SLATS operation, we ignored the flux during the IE forward to wake direction, only accumulated that to RAM direction. In AO1 exposed the flux of 1/30 of the predicted flux on the operation of the SLATS. We chose the conditions of 1/9 (AO2) and 1/3 (AO3). CO1, CO2 were composite exposures, these combined the AT2 and AO2 or AO3. The air exposures were in a constant temperature and humidity chamber (Espec SH221). The AO exposure was carried out with the "Combined Space Effects TEST Facility[5)] in the Tsukuba Space Center. This equipment generates the AO by laser detonation method using a pulsed CO_2 laser. AO beam velocity is approximately 8 km/s, flux ~ $5X10^{19}$ atoms/ m^2s.

2-2 Result

2-2-1. Electron Emission Result

Figure 3 shows the the electronic emission characteristics of the non-expose (SD), the air exposure prescript in the regulation (AT1) and AO exposure $3X10^{24}/m^2$ (AO3). Comparing with AT1 and AO3 in the cathode temperature of 1050 ℃ and lower temperature, AO exposure was higher electron emission performance than air exposure one.

To summarize the results of the electronic emission ability for each exposure condition.

a. All exposure conditions showed a deterioration compared with non-exposure one. The deterioration are more remarkable in lower measurement temperature.
b. In the AO expose levels tested in this section, the degradation were not proportional to the flux, and it was smaller than the deterioration of 1000 hrs. of exposure to the atmosphere (AT1). The degradation of AO exposure were considered that air exposure on handling (10 hrs. or less) would be affected.
c. We inferred that the HC performance by the AO exposure above-mentioned is rarely affected, since "b" and there is no performance problem in actual ion thruster operation under similar condition as AT1.
d 3000 hrs. atmospheric exposure case (AT2) was remarkable deterioration. Referring to CO1 and CO2 cases, emission performances recovered to AT1 level with 10 hrs. in ultra high vacuum and AO expose environment.

2-2-2. Surface Analysis

SEM images and depth dependant AES of the insert sample of the unexposed (SD) and the AO exposure (AO3) are shown in Fig. 4. In SEM and EDX there was not a quite difference between exposed and non-expose samples. The horizontal axis of AES graph was converted the sputtering time to the depth with SiO_2 sputtering rate. The left end is surface and the right end is 5 min of etching equivalent for the depth of 40 nm (converted with SiO_2 sputtering rate). Unexposed surface showed natural oxide layer. On the other hand, O component of AO exposed penetrated into a depth of about 20 nm.

Fig. 5 shows the spectra of XPS (measured depth about 3 nm). The peaks of the W metal is in the vicinity of 31 eV and 33 eV. The oxide peak shows the different energy, of which WO_2 and WO_3 show the shifts of 1.4 eV, 4.4 eV, respectively. It is clear that the oxide is WO_3, which is the same as formed by moisture in the atmosphere. In Fig. 6, we estimate the oxide amount by using the ratio of the peak height between the oxide and the metal. The oxide amount is estimated to be 4 nm or less by FIB. The oxide / metal ratio by XPS showed in good order from SD to CO2 with oxide amount increasing, The amount of CO2 was more than six times that of AT1. Air exposure and AO exposure, it is believed that increasing the oxide content by superimposing.

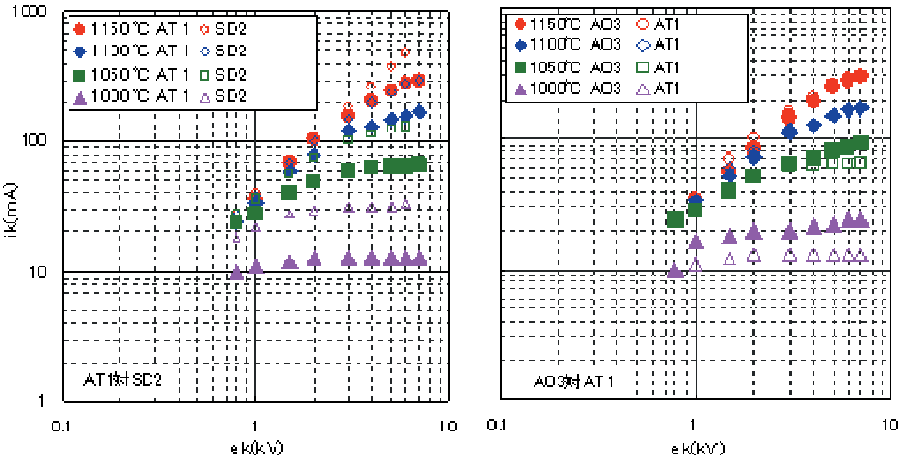


Figure 3. Electron Emission Test Result.

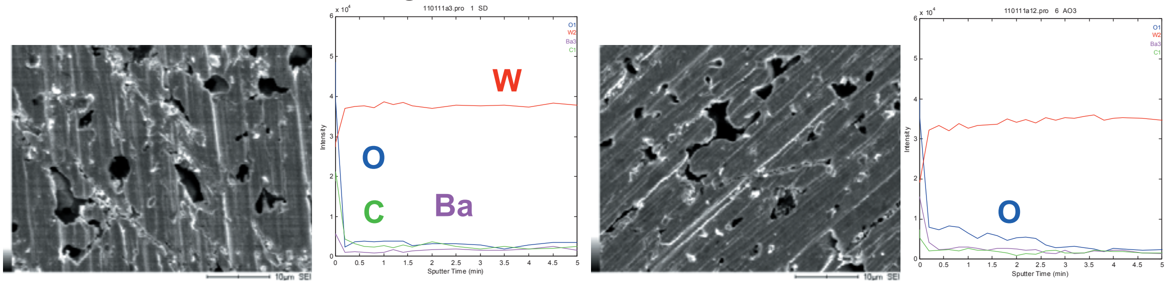


Figure 4. SEM Image and Depth Dependant AES of Insert Samples (L: SD, R: AO3).

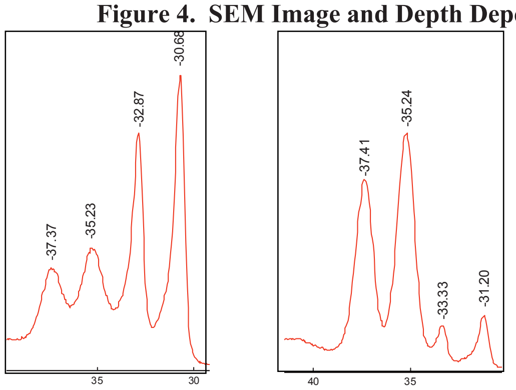


Figure 5.XPS spectra of Orifice Sample (SD/AO3).

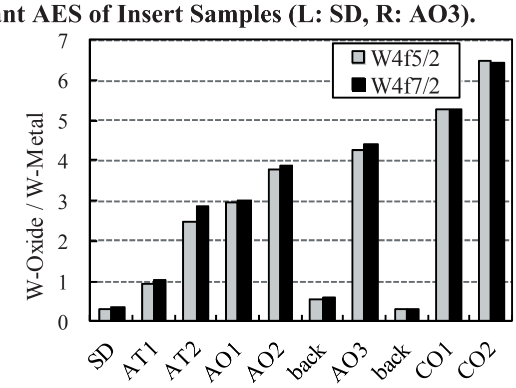


Figure 6. Oxide Amount of Orifice Samples.

III. Discharge Test of Simulated Hollow Cathode

Although the electronic emission evaluation using a partial samples showed insignificant effect, the oxide layer increased with increasing AO exposure. And AO exposure was a third of the actual level. Therefore it was contemplated the discharge test by simulated cathode.

3-1 Simulated Hollow Cathode

The large difference of the simulated HC from the actual HC is that the insert and the orifice can be replaced. The actual cathode can not be disassembled because the respective parts containing the insert and orifice are brazed and welded. In order to replace the different inserts and the orifice exposed AO, we designed the simulated HC. It shows an exploded view of a simulated cathode in Fig. 7. From left to right, gas feed adaptor, cathode insert, orifice attached to cathode pipe, pBN / PG heater, radiation shields for heat insulation, keeper electrode, it is designed to for fitting by screwing in the order of the housing. The cathode insert and the orifice are the same as actual shape and material. We checked the thermal operation at the firing heated by the pBN / PG heater and at the self-heated discharge by the thermal analysis (One result example is shown in fig. 8), then it was confirmed that the insert was

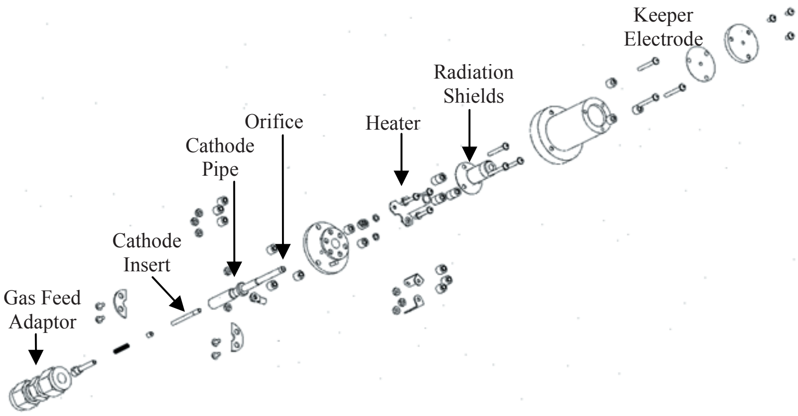


Figure. 7. Assembly of Simulated HC

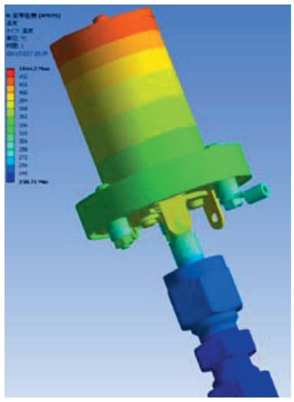


Figure 8. Thermal Analysis Result

maintained the temperature required.

Figure 9. AO Exposed Appearance

Table 3. AO Flux to Samples.

Sample	AO expose (atoms/m^2)
Insert 1	$1.8X10^{23}$
Insert 2	$4.3 X10^{24}$
Insert 3	$9.8 X10^{24}$
Insert 4	$9.8 X10^{24}$
Orifice A	$4.3 X10^{24}$
Orifice B	$9.8 X10^{24}$

3-2 AO exposure

Four inserts and two orifices were exposed in the conditions shown in Table 3. The maximum AO exposure amount is same as to be supposed in SLATS. The expose appearance in the chamber is shown in fig. 9.

3-3 Equipment and procedure of Discharge Test

In the same test before and after AO exposure, it was investigated the effect of the AO exposure. Fig. 10 shows the test configuration. The orifice temperature was measured using the two-color radiation thermometer outside the vacuum chamber during heater heating. Table 4 shows the test procedure assuming orbit operations. Initially in Idling the cathode was baked out the absorbed molecules in the air storage with low heater current. Subsequently the activation is carried out by increasing the heater current heated over 1250 ℃. Inserted cooling during 30 minutes, the heater ON again with supplying Xe gas, and applying a voltage about 150 V between keeper and the orifice. After a while the discharge was ignited. Time required for the firing is an important parameter indicating the deterioration of the cathode.

The test four cases are shown in Table 5, for example, the combination of the insert 1 and orifice A (1-A).

3-4 Discharge Test Result

Table 5 shows the test results of the discharge ignition time. The influence of AO exposure were not shown. Keeper voltage was also almost comparable before and after AO exposure. For the collector voltage in the diode configuration shown in Table 7, the voltages increased in part. The difference between the voltage raised by the AO exposure and the voltage without exposure was shown in fig. 11. Rise of the collector voltage in low Xe flow conditions was obvious. The electron emission ability degraded caused by AO exposure occurred. However, the voltage rise at the flow rate of 2 sccm, it rated on the ion thruster of SLATS did not occur. It was assessed that there would be no influence in actual operation.

While HC were exposed by decent amount of AO, it promised nothing but a little noticeable effect. It was considered to be the oxide on the cathode surface was sufficiently removed by the activation process. In the activation the orifice temperature of 1275 ℃ was measured at 30 min. heating. As estimated from the thermal analysis of the simulated cathode results, the insert temperature was reached 1240 ℃, to achieve the heater flashing temperature of the partial sample (in section 2-1). It was possible that substantially sublimating the oxide layer on the insert and the orifice formed by AO was the reason why there were slight effects to the ignition characteristics and the discharge characteristics. Although the temperature rise during activation is effective for the oxide layer removal, we set the activation temperature not to exceed 1350 ℃ considering for the lifetime of HC.

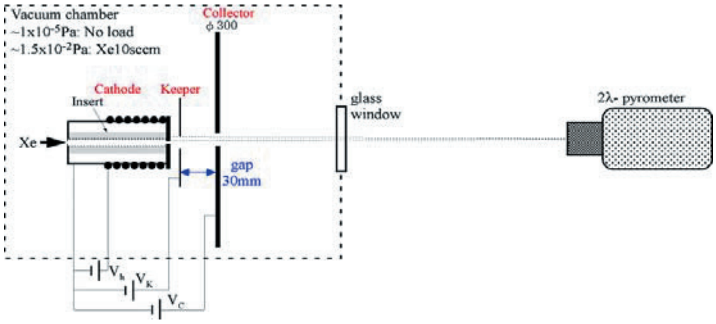


Figure 10 Diode Discharge Configuration.

Table 4 Hollow Cathode Ignition Procedure.

Procedure	Temp. (°C)	Term (min)	Primary purpose
Vacuum	RT	>480	
Idling	~ 500	120	degas adsorbed in the atmosphere
Activation	1250	30	Sublimate tungsten oxide
Ignition	1050~1100	< 5	Ignite applied the voltage with Xe flow

Table 5 Firing Time.

Sample Configuration	1-A	2-A	3-B	4-B
before EXP	137~183	144~206	118~175	161~180
after EXP	124~206	107~190	135~189	143~211

Table 6 Voltage of Diode Discharge (after / before AO Exp.).

Collector Current(A)	Xe Flow rate (mg/s, sccm)	1-A	2-A	3-B	4-B
0.3	(0.5)	43.7/44.1	44.0/43.5	43.9/42.6	44.5/42.9
	(0.7)	36.5/36.0	36.2/35.9	35.4/35.3	36.3/35.5
	(2.0)	34.5/34.4	34.2/34.2	32.6/33.9	33.2/34.2
0.4	(0.5)	43.1/43.6	43.2/42.4	45.0/41.8	45.8/42.2
	(0.7)	36.0/35.4	35.7/35.0	41.2/36.6	42.1/40.4
	(2.0)	32.7/32.6	32.6/32.8	30.8/31.7	31.7/32.3
0.5	(0.5)	55.0/57.6	57.6/50.9	>55/55.1	>55/>55
	(0.7)	44.1/45.7	43.2/43.9	48.6/46.1	50.3/48.0
	(2.0)	32.1/32.0	32.0/32.2	31.2/30.7	31.6/31.8

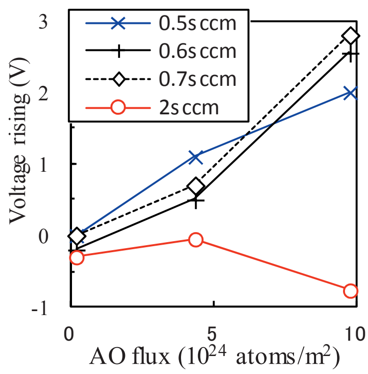


Figure 11. Diode Voltage Rising.

IV. Conclusion

In the application to the ion engine of the super low altitude satellite, the influence of AO to the HC has been concerned. The electron emission measurement and surface analysis using a partial sample of HC and the simulated HC was conducted to evaluate the tolerance against AO.

As a results, although WO_3 layer formed on the cathode surface by AO exposure on super low earth orbit, the activation process heated up to the temperature of 1200 C bring the sufficient sublimation of the oxide, and was determined not to cause effects on the HC operation.

These result is reflected in the SLATS and subsequent on-orbit operation technique of ion thruster of super low altitude satellite.

The future investigation is whether the deterioration of the electron emission ability in the low flow region could be improved by the extension of the activation process time.

References

1) Noda, A., et al., "The Study of a Super Low altitude Satellite, " 26th ISTS, 2008-f-05, Hamamatsu, Japan, 2008.
2) Yamamoto, S. and Kohata, H., "Investigation Status of Super Low Altitude Test Satellite (SLATS)," JAXA press release (in Japanese), 2013.9.4.
3) Nagano, H., et al., "A New Orbit Control Algorithm for the 20 mN Class Ion Engine System, " IEPC-2013-064
4) J.L.Cronin,: Practical aspects of Modern Dispenser Cathodes, Microwave Journal, vol.22 pp.57-62, Sep. 1979
5) Shimamura, H. and Miyazaki, E., "Investigations into Synergistic Effect of Atomic Oxygen and Ultraviolet," J. of Spacecrafts and Rockets, **46**, #2, 2009, pp.241-247