On the Hollow Cathode for an Oxygen Discharge*

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An old Kaufman ion thrusterwas remade to operate by using oxygen as working gas. A simple device was designed to protect its hollow cathode from direct exposing to the oxygen environment. The cathode has a small diameter and long insulator tube on its downstream end (at keeper electrode). When it is attached to the discharge chamber, the lead tube is located between the cathode and the discharge chamber. If the cathode used xenon as working gas, oxygen could be used in the discharge chamber. The hollow cathode discharge occurs in usual sequence and a main discharge started by applying a slightly higher voltage between the cathode and discharge chamber. The cathode works well in the oxygen discharge without oxidation. A new small scale line cusp ion source is also studied, which will be used with the hollow cathode in order to improve ionization efficiency. A stable operation was obtained in a reasonable magnet configuration.

Introduction

Ion thruster technology using inert gases as propellant has been attained to a matured state.[1-4] Recently several practical applications of space ion propulsion system have been conducted in success. In future, oxygen ion thrusters could be used for ion propulsion at an oxygen rich site, for instance, on the Moon. The ion source of reacting gases may be demanded for future space activity or material processing. Oxygen discharge will be very useful in relation with an atomic oxygen generator. A hollow cathode is one of the most useful components in the ion thruster and is used as a main cathode and a neutralizer. It is desired to have a long life and effective hollow cathode, which could be used for an oxygen discharge. The cathode has, however, a weak point that it goes easily into malfunction and falls into great damage by a little bit attack of oxygen. Its main part may be oxidized and eroded in the existence of oxygen. For such an ion source a device is necessary to reject dangerous reacting gases entering the critical part of the hollow cathode. This device could be used for other gases erosive to a non-protective hollow cathode.

We have another problem for developing oxygen ion thruster. Oxygen requires much larger energy for ionization in comparison with mercury or inert gas. Cusp type ion source will give better ionization efficiency than Kaufman type ion source. The present paper describes about operation capability of hollow cathode for oxygen ion source with a protective device and a small scale cusp ion source.

Device Protecting Cathode from Oxygen Attack

We think of placing a long and small diameter tube between the hollow cathode and main discharge chamber in an ion thruster. The working gas for the main discharge is oxygen while that for the hollow

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cathode is xenon. The particle density around the hollow cathode exit and inside the tube is high compared with that in the discharge chamber. We expect a dominant xenon flow from the cathode to the discharge chamber and very frequent particle collisions inside the tube. Therefore, the oxygen introduced to the discharge chamber cannot come up to the hollow cathode, and then cannot attack the high temperature cathode tip. The problem was whether the electrons generated in the cathode could go through the narrow tube and the plasma tunnel, or bridge, could be made up as a path for electrons in the starting time.

Studies should be performed on the safety dimensions of the lead tube (plasma Tunnel) for the cathode operation in the relation to the discharge properties and performance. If the lead tube is long enough compared to its diameter and the mean free path of the cathode gas, oxygen molecules could not come to the cathode. On the other hand, too large length might make discharge ignition and electron supply from the cathode to the discharge chamber difficult and impossible.

Design and Remaking of Ion Thruster

A present Kaufman ion thruster was originally fabricated and tested as a preliminary engineering model (PreEM) of the ETS-III 5 cm mercury ion thruster. [5] This thruster was also used for testing on the operation capability using inert gases for working gases. [6] Its durability test (long time operation test) was conducted in the flight configuration with vaporizers and a propellant tank containing full 600 gram mercury.[7] In the development years (1975 to 1985) many hollow cathodes were fabricated and tested. Some of them are still operable if their insert, for instance, were refurbished or changed with new ones. In this study, first, the possibility of hollow cathode operation in the oxygen ion thruster (source) was tried by using a remade ion thruster with a hollow cathode. The configuration of the old ion thruster without mercury tank and vaporizer is shown in Fig. 1.

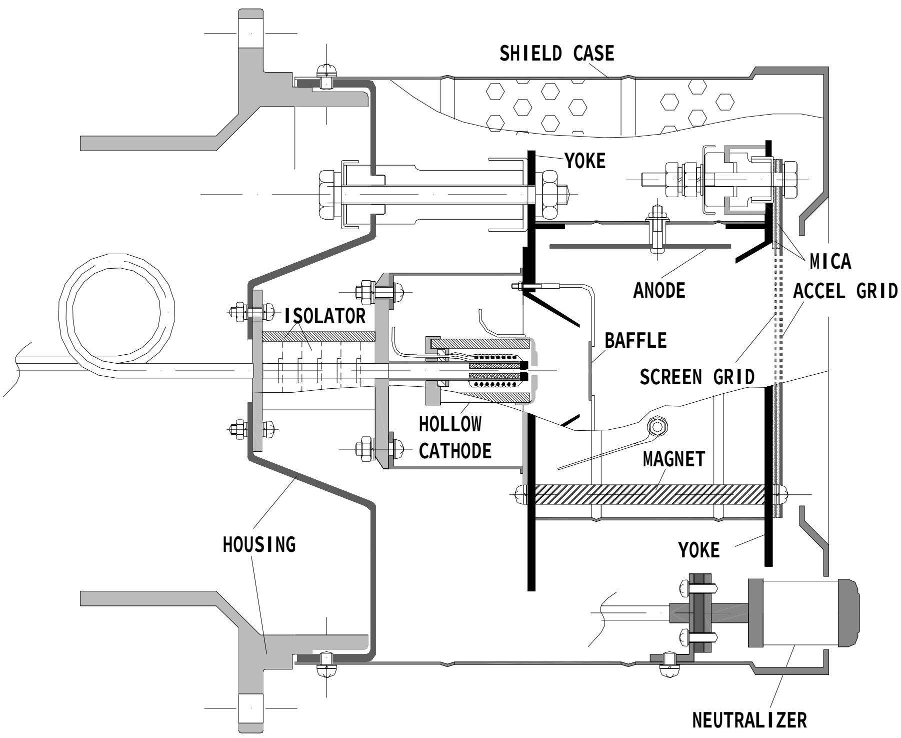


Fig. 1 The PreEM of ETS-III ion thruster (without mercury tank and vaporizer) operated by using inert gases.

The thruster was revised to a new model with (1) a plasma tunnel (or bridge) made of an alumina (Al_2O_3) tube, (2) a distributor in the discharge chamber for introducing oxygen and (3) a single accelerator grid system as shown in Fig. 2. A plasma tunnel works as a one way path of cathode generated plasma prohibiting oxygen coming up to the cathode region from the discharge chamber.

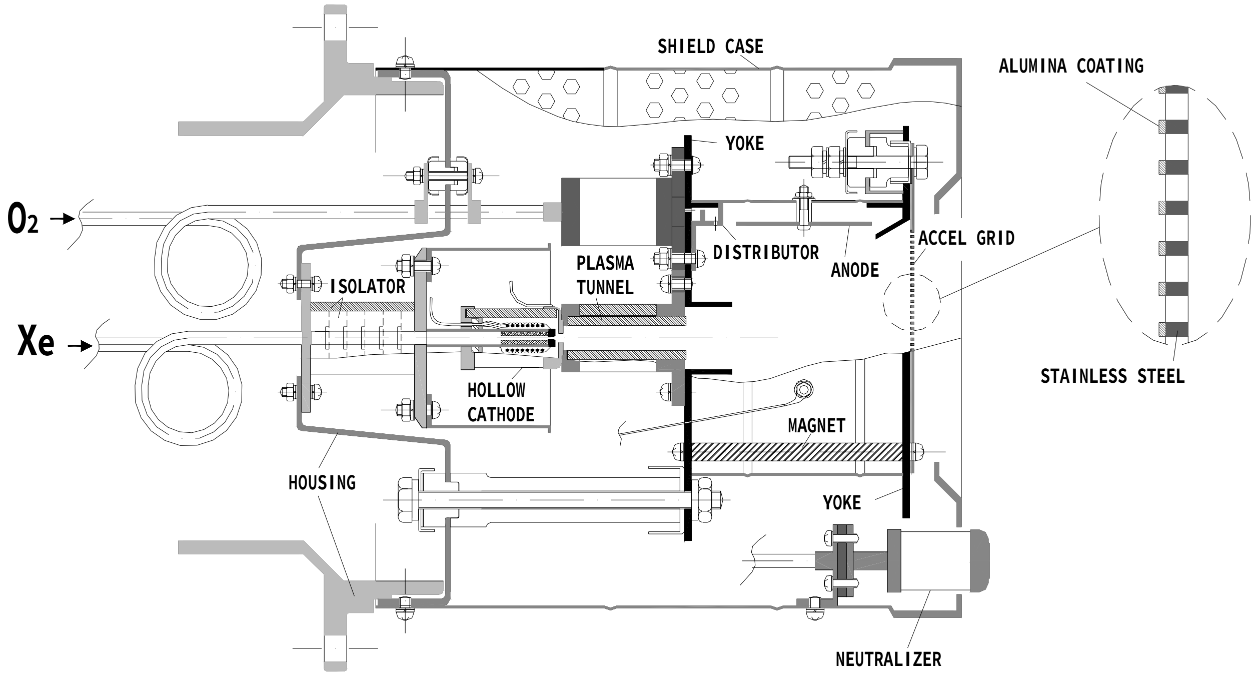


Fig. 2 The oxygen ion thruster configuration with a plasma tunnel (a long and small diameter tube) to protect a hollow cathode from oxygen.

Plasma tunnel

This is a device connecting a cathode plasma with a main discharge chamber, to concentrate xenon plasma flow and to refuse oxygen gas from coming upwards. The principle of the required function is illustrated in Fig. 3. Oxygen molecules fed to the discharge chamber would not come up to the cathode due to collisions with flowing xenon atoms and ions many times. The density inside the small diameter tube is so high that each oxygen molecule experience many collisions with xenon particles to reach the cathode. If inner diameter is 5 mm and length is 30 mm, and the cathode flow rate of xenon is 0.3 sccm, then the mean free path of a particle in the tube is estimated to be 2 mm. The density of oxygen would be lowered toward upstream region to be roughly $3x10^{-4}$ time that at the exit.

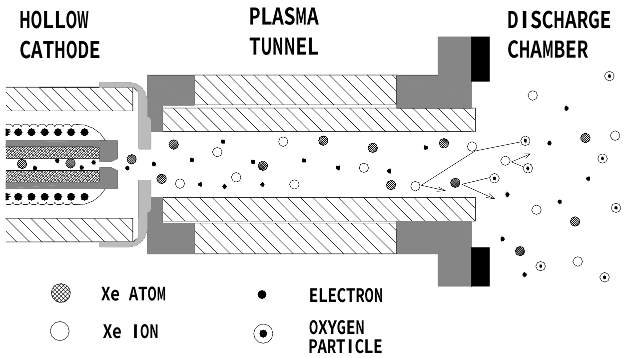


Fig. 3 Functions of the plasma tunnel.

Distributor

An original discharge chamber had no distributor, and all propellant was supplied through the hollow cathode. An annular distributor is placed at the corner of base plate and circumferential wall. Oxygen gas is fed toward the ionization region into the chamber through small holes of the distributor.

Accelerator grid system

A single stainless steel grid with many small holes was used for an accelerator grid. It had 0.03 mm thickness and 0.1 mm hole diameter Thin alumina layer was adsorbed on the upstream side of the grid to anchor a discharge plasma. We considered the low exhaust ion velocity would sometimes also required. The screen-accel grid distance as well as hole diameter should be small, the order of 0.1 mm, to attain high current density of ion beam for a low extracting voltage. . For instance, a single accel grid system for a large (30 cm) ion thruster were designed and tested in 1970's.[8] The configuration is appropriate for a high ion current density.

Operation by Using Oxygen Gas

Higher discharge voltage (about 120 V) than ordinary thruster. The hollow cathode worked well at cathode xenon flow rate about 0.3 sccm during feeding oxygen gas into the discharge chamber. Representative voltage vs. current characteristics is shown Fig. 4. The exhausted ion current is also shown. The exhaust current increases with the discharge voltage. The hollow cathode operated well, but the ion production rate is not good.

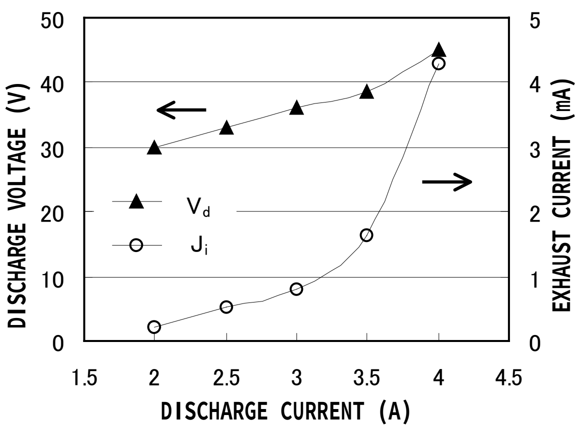


Fig. 4. The discharge voltage and exhaust ion current vs. discharge current by using oxygen.
Hollow cathode Xe flow rate = 0.3 sccm
Main Discharge O_2 flow rate = 0.9 sccm

Cusp Ion Source to Improve Performance

In order to improve discharge performance, we decided to develop cusp ion thruster (source). The beam diameter will be 5 cm or less. A line cusp rather than a ring cusp was chosen due to our thinking of the simplicity of magnet shape and something left to be investigated in the discharge of this magnetic configuration. A line cusp discharge chamber was designed and fabricated as shown in Fig. 5. The same old hollow cathode was used.

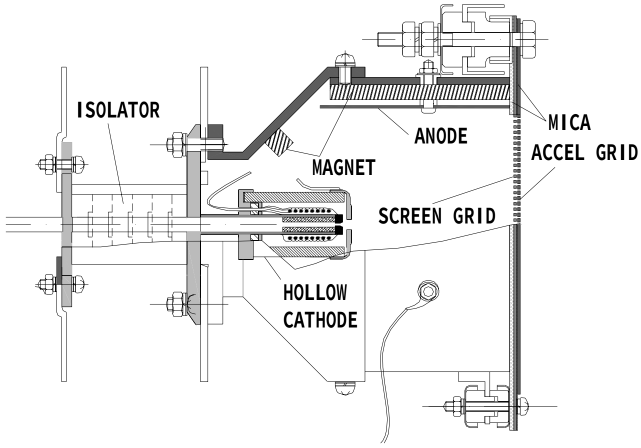
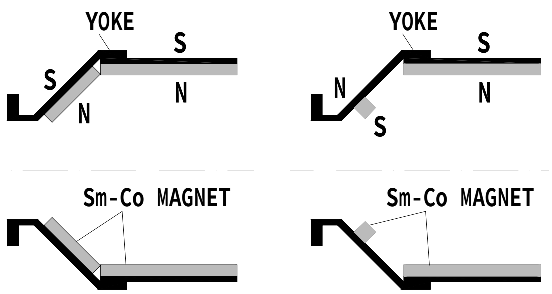


Fig. 5. The present line cusp ion source.

A discharge chamber has a main cylindrical yoke connected with a conical part to which a hollow cathode is attached at the upstream end. The longitudinal arrangements of magnets are shown in Fig. 6. At first, long bar magnets of the same polarity were placed on both the cylindrical and conical walls as seen in the figure (a). However,

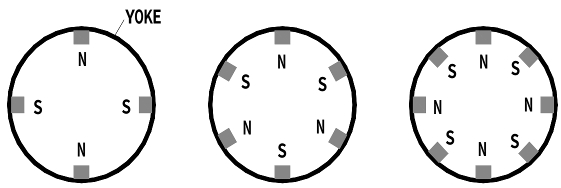


(a) Long magnets of the same polarity. (b) Short magnets of opposite polarity.

Fig. 6. Magnets arranged on the conical wall.

the configuration did not give a stable discharge. This might be caused by the distortion of the magnetic field at the connection region.
We had a stable discharge when short magnets with opposite polarity were placed at the station apart from the magnets on the cylindrical wall as seen in the figure (b). This may be due to another cusped field formed along the longitudinal direction. The configuration (b) was selected thereafter.

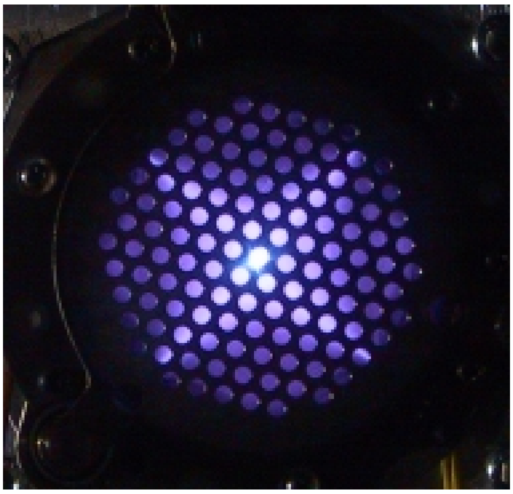
Concerning to the circumferential magnet arrangement, three configurations were examined as shown in Fig. 7. Six poles configuration as seen in the figure (b) did not give a stable discharge. In this case, the magnet poles of opposite polarity are directly facing to each other at a comparatively short distance and lines of magnetic force go through the center. There may be no confined region around the center.



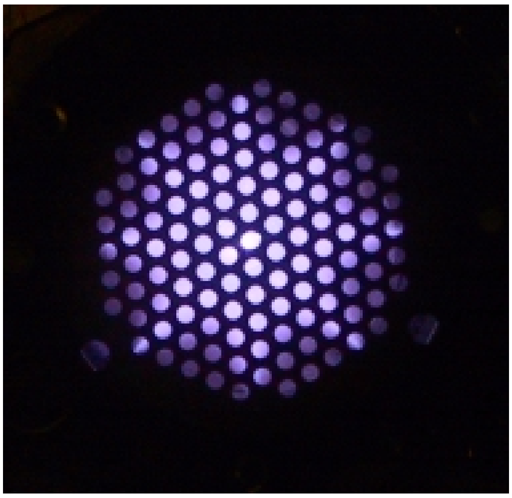
(a) 4 poles. (b) 6 poles. (c) 8 poles.

Fig. 7. Circumferential arrangements of magnets used in line cusp ion source.

A stable discharges occurred in the field of four or eight poles configuration (seen in Fig. 7(a) and (c)).
We have not conducted ion extraction for the line cusp ion source, but could judge roughly by the color and brightness whether a discharge is good or not.
In the central part the discharge has a bright region indicating a shape of cusped magnetic field. When propellant flow rate is lowered, the discharge voltage increase slightly、and discharge color changes from dim pink to preferable blue at flow rate of 0.3 sccm. As seen in Fig. 4, eight poles offered a blue discharge region of larger cross section than four poles.



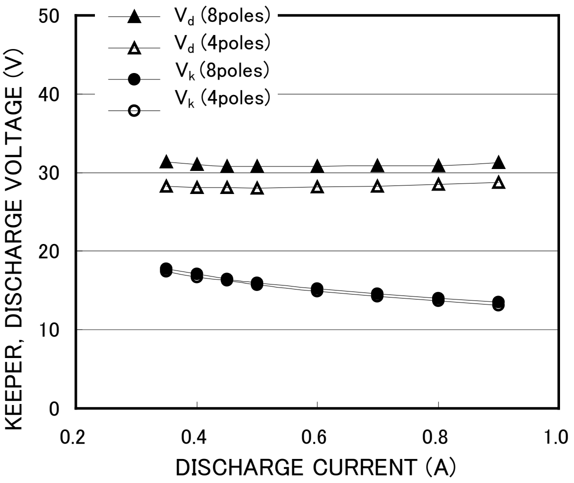
(a) In four poles line cusped magnetic field.
Xe flow rate=0.3 sccm, J_d = 0.3 A



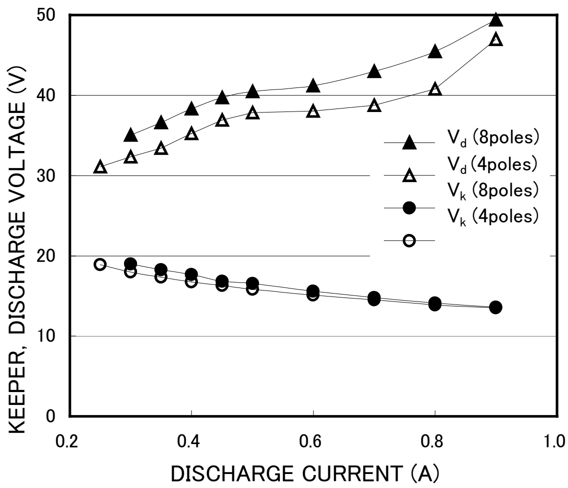
(b) In eight poles line cusp magnetic field.
Xe flow rate = 0.3 sccm, J_d = 0.3 A

Fig. 8. Xenon discharge indicating cusped field

The discharge voltage vs. current characteristics are shown in Fig. 9. At present ion extraction has not been conducted, but we expect its high propellant utilization efficiency when the acceleration voltage is applied. After the optimization we would like to integrate the cusp discharge chamber with a plasma tunnel previously tested.



(a) Xe flow rate = 0.3 sccm, J_k = 0.2 A



(b) Xe flow rate = 0.2 sccm, J_k = 0.2 A

Fig. 9. Discharge voltage vs. current characteristics.

Conclusions

In future, oxygen ion thruster or source will be very useful for propulsion and material processing.

It is desired to have high performance discharge and hollow cathode to work in an oxygen discharge.

A device to protect a hollow cathode from oxygen attack was designed and tested in a 5 cm size oxygen discharge though xenon was used as working gas for hollow cathode operation. The hollow cathode could work for appreciably long time in the oxygen discharge. At present the performance is not good.

In order to improve the discharge performance, a small diameter line cusp discharge ion source was designed, tested and showed stable operation.

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