Preview of characterization of hollow cathodes for ion thruster

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***Abstract*— Studies on hollow cathodes (HC) are currently being carried out at the LAP/ INPE (Associated Plasma Laboratory of The Brazilian National Institute for Space Research) with the purpose of characterizing such devices aiming a performance acceptable for use in ion thrusters. The study consists in analyzing the performance based on the variation of geometries of components and parameters of the HC. Plasma diagnostics to aid analysis and understanding of the HC behavior are based on experiments using Langmuir probes.**

Keywords— hollow cathode; plasma plume; ion thrusters; electric thrusters; electric propulsion

I. INTRODUCTION

The electric propulsion investigations in the LAP/INPE have been under development since the 1980s with the initial purpose of making ion thrusters for both attitude and orbital controls of a MECB mission satellite [1]. The investigation continues until the present day with the aim of developing thrusters for use in future Brazilian missions and to provide thrusters and parts that can be used in propulsion systems for others countries interested in this technology. The hollow cathode (HC) is a key component in several types of electric thrusters, such as gridded ion thrusters (GIT), Hall effect thrusters (HET), microwave or radiofrequency ion thruster, colloidal ion thrusters, magnetoplasmadynamic thrusters (MPDT), among others. The HC often determines the lifetime of the whole electric propulsion system. The study of such component is paramount for the development of a reliable electric propulsion system.

Ion thrusters rely on the hollow cathodes as its main source of electrons for the electric discharge generation in the discharge chamber and also in the ion beam neutralization. The basic fundamental principle is the thermionic emission of electrons, where thermic energy of vibrational type in a metal (or metal oxide), cause an electrostatic force that pushes electrons towards the emitter surface. Therefore, the emitter materials are very important in hollow cathode practice. The HC made at LAP/INPE is a “rolled tantalum foil inserts” type, mainly due to simplicity in its construction and low cost, allowing a variable degree of dopants (aluminates, carbonates, among others) to be used.

In the current study, different HC geometric parameters and the distance between anode and cathode is varied to observe and analyze the behavior of the cathode, looking for better performance. Experimental data are collected using electric probes theory and plasma sheath theory. A comparison between data obtained in this work and in previous works will be carried out. It will also be observed the differences in performance when using a rolled tantalum foil inserts cathode, compared to previous works from other researchers.

II. BRIEF REVIEW ON HOLLOW CATHODES

The first cathodes used in ion thrusters were the tungsten filaments as the source of electron emission for both main discharge and ion beam neutralization. Due to the high work function of tungsten the filaments had to operate at high temperatures to emit the required electron current density. This generated a high loss in power and therefore a reduction in the thruster performance. Other disadvantages of the tungsten filaments were a limitation of lifetime because of a rapid evaporation of the filaments because of the high temperature of operation and by the sputtering of the tungsten surface exposed to the discharge plasma or the beam by ion bombardment. So it was concluded that the filaments are unsuitable for use in space applications of long lifetime [2].

The hollow cathode (HC) was conceived in an attempt to produce a long lasting electron emitter. The HC consists of an outer refractory metal tube, usually tantalum, covered on its downstream end by an orifice plate usually made of thoriated tungsten (that is a type o tungsten electrode that contains about 2% of thorium that has higher thermal conductivity and in general is more durable). The HC also normally incorporates a refractory metal insert either coated or impregnated with such chemicals as barium compounds, which aid the emission process by reducing the work function of the insert surface [3]. Their characteristics, such as reliability, long lifetime and capability of producing high electron current densities with low heating power consumption make these devices the best option for electron sources in electric propulsion, especially when compared to tungsten filaments [2].

For ion thrusters typically the HC have inner diameters of a few millimeters and orifice diameters of a few tenths to one millimeter. The insert length is usually a few tube diameters. The HC have a heater that is normally used to heat the cathode as an aid to start the electron emission process. However, the discharge is self-sustaining (self-heating) once established and the heater can be turned off or have its power reduced. HCs generally utilize a small secondary anode, called a keeper, which is used to initiate the discharge and during the operating process the electron current is collected by an anode biased positive with respect to the cathode [3].

The HC are used for producing the main plasma in the discharge chamber of electric thrusters and to neutralize the space charge in the ion beam ejected by ion thrusters with demonstrated lifetimes exceeding 30.000 hours (Sengupta, 2005). HCs are complex devices for specific applications, and its details demand many experimental tests and parametric optimizations for a reliable and safe use [2].

A. LAP HC

The HCs under experimental studies are composed by a ¼ inch diameter tantalum body equipped with rolled tantalum foil inserts coated with carbonates or aluminates mixture and tips with different geometries and orifices sizes. Two types of heaters will be used: a commercial one from Heat Wave Labs and another developed by the LAP/INPE.

The first cathode chosen to be studied uses an enclosed keeper which body was made using stainless steel and a graphite plate having a 3 mm diameter orifice in its center located at its downstream end. The cathode consists of a 6.35 mm diameter tantalum tube equipped with a tungsten plate with a 0.64 mm diameter orifice in its center and an external wrapped sheathed heater. A 25 µm thickness tantalum foil covered with carbonates solution (Ba, Sr, Ca) is rolled to conform the insert in the shape of 5.2 mm external diameter and 2.5 mm internal diameter multilayer tube. This HC is shown schematically in Figure 1.

The LAP/INPE HCs are coated refractory metal insert type because this technology is more affordable than the impregnated HC and because they are simpler and the performance parameters are acceptable for use in ion thrusters.

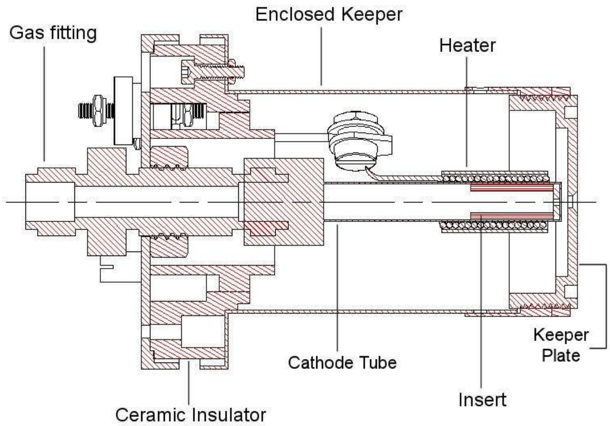

Figure 1. LAP hollow cathode schematics

III. EXPERIMENTAL FACILITIES

A. Vaccum Chamber

The vacuum chamber, shown in Figure 2, consists of a 80 cm diameter by 120 cm length vacuum chamber equipped with two turbo molecular pumps, with total pumping speed of 4600 l/s (for N_2), pumped by a 250 m^3/h roots pump and an 80 m^3/h rotary pump, ensuring running tests a base pressure of 3 $\times 10^{-6}$ Pa with no gas load and in the range of 2 to 5 $\times 10^{-4}$ Pa depending on the propellant gas mass flow rate.

B. Cylindrical Langmuir probe

The Langmuir probe is used as a basic resource to obtain the basic diagnostic of plasma parameters in the plume of the HC, namely: the electron plasma density n_e, electron temperature T_e and floating potential and plasma potential, ϕ_f and ϕ_p, respectively. The output of the Langmuir probe system generates I-V curves (Figure 3) by using a data acquisition system that controls a programmable bipolar power supply to generate a triangular voltage ramp (from negative to positive voltages) and post process the data in terms of plasma parameters. The code for processing the probe signal data was developed by ITA (Brazilian Technological Institute of Aeronautics) [4] in LabViewTM platform and it was updated for HC characterization [5]. The following physical and numerical approaches are used to calculate the plasma parameters in the different regions of the characteristic curve: Orbital Motion Limited Theory – OML, Classic Langmuir procedure, Exponential fitting, and Druyvesteyn procedure [4].

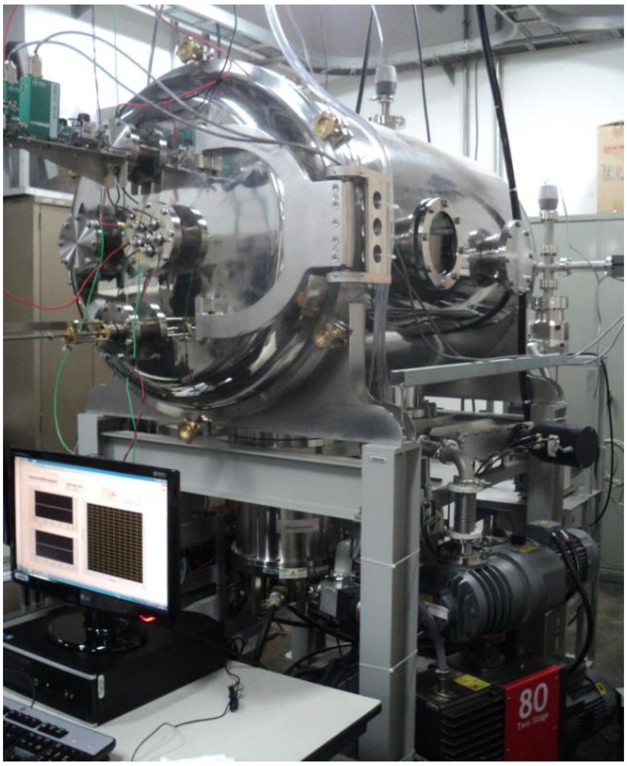

Figure 2. Vacuum chamber

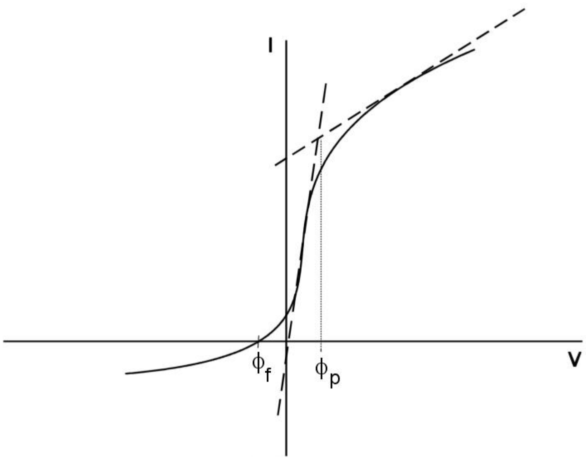

Figure 3. Typical I-V probe curves for cylindrical probe.

The cylindrical Langmuir probe consists of a 1 mm diameter and 120 mm length tungsten wire, with an exposed tip of 8 mm to the plasma plume. A 3 mm external diameter and 1.4 mm internal diameter alumina insulator is used to avoid electric current collection by the remaining conductive parts of the probe wire and its electrical connections. A motion leadthrough is used to transmit both rotation and translation movements to the probe stainless steel arm (a 6.35 mm external diameter stainless steel tube). Once the axial measuring position is set by translation movement, the probe is rotated until it is immersed into the plasma plume for I-V curve tracing. Afterwards, data acquisition stops and the probe is immediately moved out of the plume region to avoid the overheating and erosion of the probe tip. An external endstop is used to ensure the probe is always centered on the cathode axis after rotation to immerse it into the plume.

The curves traced by the Langmuir probe need to be adjusted due to noise generated during data collection. Afterwards, the curves are analyzes in LabView^{TM} platform to obtain the main plasma parameters for each axial distance between the probe and the keeper plate. Finally, the results are plotted for each parameter as a function of the axial distance between the probe and the keeper plate.

C. Experimental setup

The experimental setup is mounted on the door of the vacuum chamber, as shown in Figure 4 and Figure 5, It consists of a HC, cylindrical anode (110 mm diameter, 40 mm length and 3 mm thickness stainless steel) located at 94 mm from the keeper in the case of the first experiment, and a cylindrical Langmuir probe. The probe can be moved along the cathode axis to measure the plasma parameters (in cathode plasma plume), placing it at different distances (d_p) from the keeper.

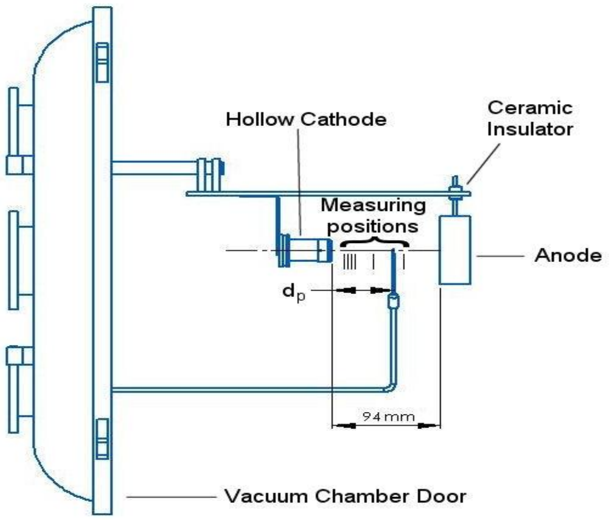

Figure 4. Hollow cathode assembled on the vacuum chamber door. dp: distance from cylindrical probe to keeper.

One of the varied parameters in the experiment is the distance between the anode and the cathode, where three different distances will be investigated. Others varied parameters in the experiment are the mass flow rate and the keeper current. The aim is to obtain the best configuration, according to plasma plume parameters of typical HCs for ion thrusters.

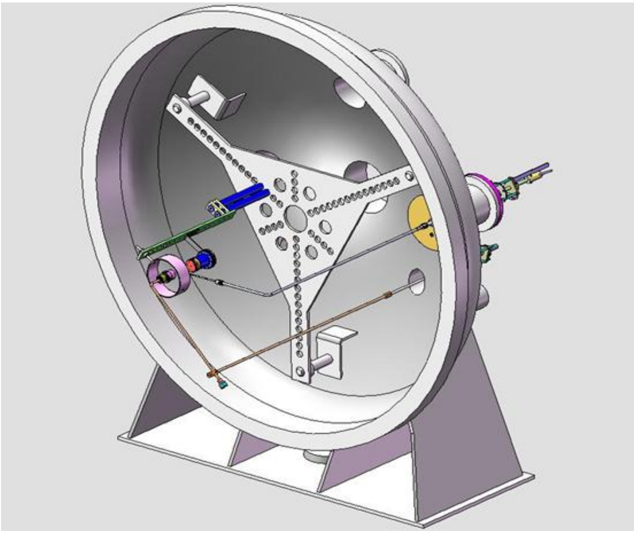

Figure 5. Internal equipment setup

IV. PRELIMINARY RESULTS

The expected results in this study are curves for each plasma parameter in the plume generated by the HC with respect to probe to keeper plate axial distance. The aim is the comparison, understanding and characterization of the HC.

Early experiments were carried out with the chamber pumped down to base pressure of 3×10^{-6} Pa and the cathode temperature raised to about 800 ^{o}C by increasing the heater current up to 7 A in 1A/min steps. The discharge ignition took place with the keeper at 200 V relative to the cathode and argon mass flow rate was a set to the desired value (typically in range of 2 to 4 sccm). Once a steady electric discharge between the HC and the keeper was reached the heater was turned off and the keeper current was adjusted to 2 A, resulting in a keeper voltage in the range of 24 V to 30 V. At this point the measurements can then be carried out by either biasing the anode with a ground potential (0V) or by biasing the anode with a voltage of 200 V. In the latter case currents in the 500 mA to 700 mA range were recorded. The values of both keeper voltage and anode currents depend on the cathode operating parameters.

Floating potential, plasma potential, electron current, electron density, ion density, electron temperature and Debye length are all plotted using the physical and numerical approaches mentioned in the section III-B. Some comments are made below about selected data collected.

Is observed in the preliminary results that:

- The floating potential (Figure 6), is independent of the procedure used, since it is the point in I-V curve where the electron and ion fluxes are in equilibrium, i.e., where the probe current is zero. It was observed that the floating potential increases when biasing the anode and increases as the Argon mass flow rate increases.
- The Plasma potential (Figure 7) for Langmuir procedure agrees with the values obtained by Martin, R.H., *et al.*,2005 [6], where the anode was placed at 130 mm away from the hollow cathode.
- The electron saturation current and electron density shown in Figure 8 and Figure 9, present a typical distribution for this type of experiment with HCs [7][8].
- The electron density is consistent with values obtained in other experimental studies and theory (about of 10^{13}cm^{-3}) [6][7].
- The ion density (Figure 10) was obtained by using the Orbital motion limited (OML) approach and it was observed that the mean ion density decreased as the distance from the keeper plate increased for all tested cases, as shown in Figure 10. It can be seen that the results are of the same order of magnitude of the electron density and there is no remarkable difference between biased and unbiased anode results and also no remarkable differences for results of the two different mass flow rates used.
- The plasma temperature (Figure 11) increases for distances closer to the anode, and this can be attributed to the charge unbalancing produced by a more effective electron flux accelerated toward the anode.
- When the anode is biased the Debye length starts at lower values compared to the unbiased but it greatly exceeds the unbiased as the axial distance increases, as shown in Figure 12 for the Langmuir method. The electron temperature and the electron density influences the Debye length as seen in Figure 9 and Figure 11, and as predicted theoretically by the expression [1]:

$$\lambda_D = 745\left[T(eV)/n_e\left(cm^{-3}\right)\right]^{1/2}.$$

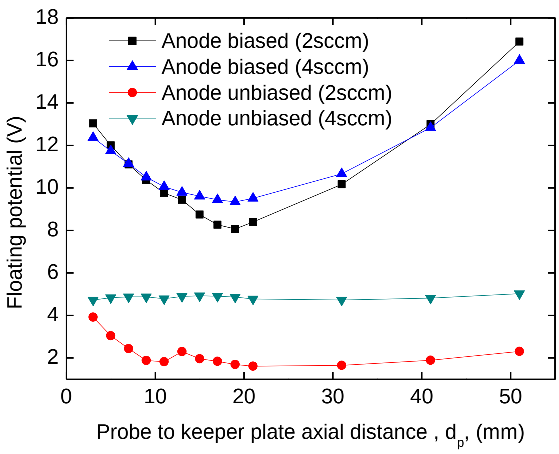

Figure 6. Floating potential

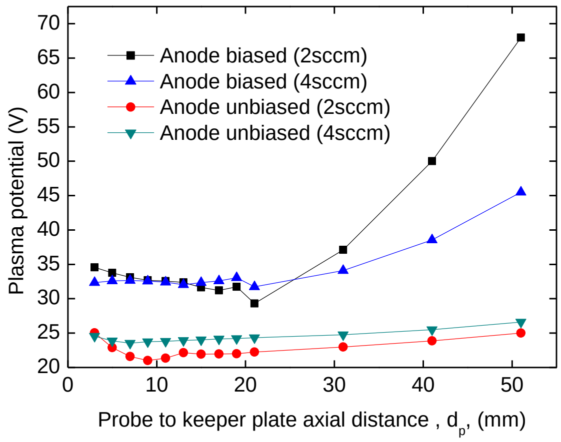

Figure 7. Plasma potential by Langmuir procedure

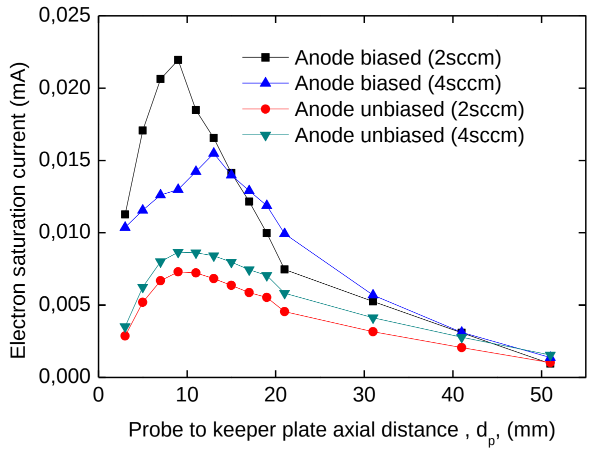

Figure 8. Electron saturation current

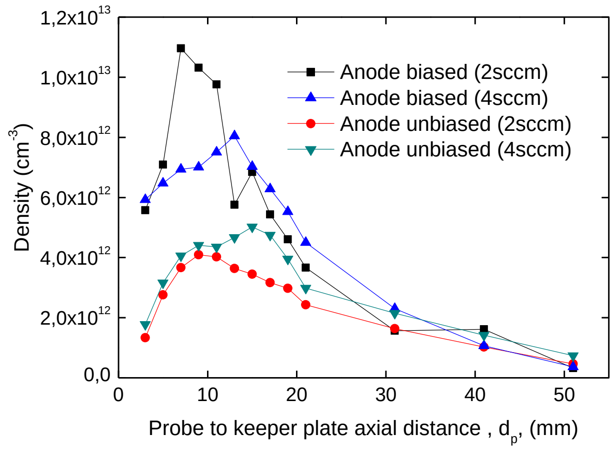

Figure 9. Mean electron density, Langmuir procedure

The preliminary results indicate that the characterization of HC for ion thrusters is well underway.

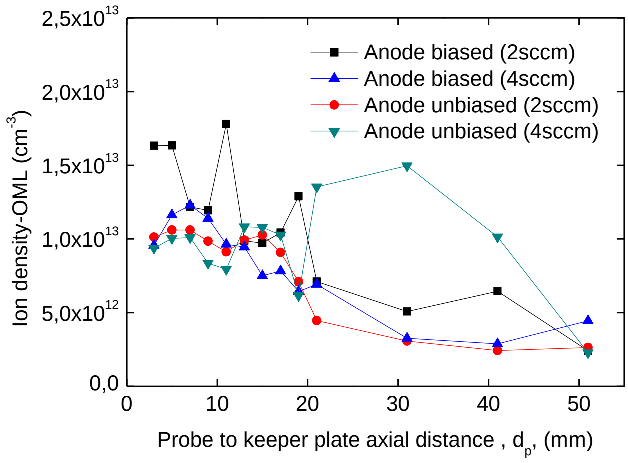

Figure 10. Ion density by orbital motion limited Theory, OML

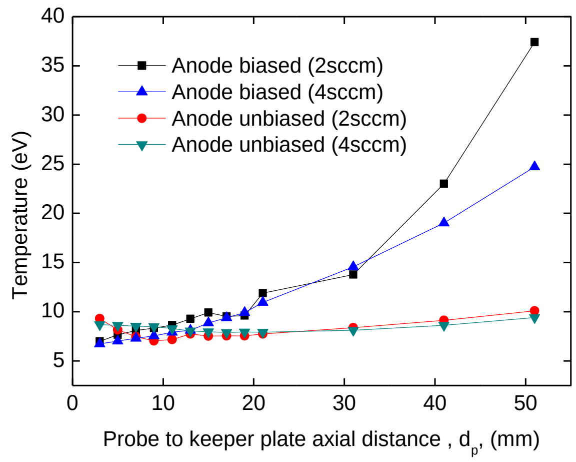

Figure 11. Electron temperature by Langmuir procedure

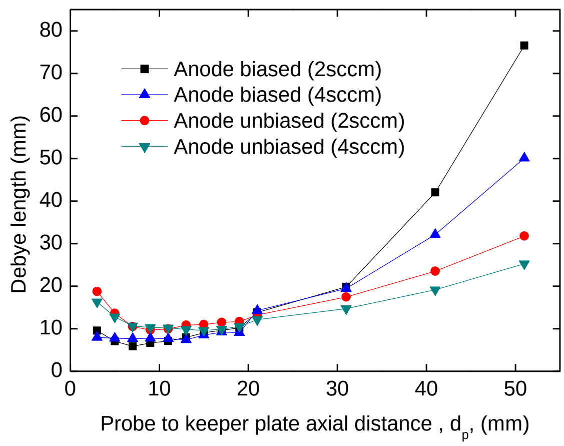

Figure 12. Debye length by Langmuir procedure

It should be pointed out that despite of hollow cathodes being investigated for more than 40 years there is still no definitive mathematical model that describes the plasma parameters in HCs completely and no models describes the several possible configurations and the discharge conditions on HCs. Therefore, experimental studies are absolutely paramount in improving the performance and optimizing HCs for use in electric thrusters [7]. Several experimental studies were carried out with different plasma diagnostic systems by Krishnan, M., *et al*, 1977; Kameyama, I., *et al*, 1993; Martin, R.H., *et al.*,2005; Mikellides, I. G., *et al*, 2005; Goebel, D. M., *et al*, 2005; among others [7][8][9][10][11].

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