Hollow Cathodes for 100-kW MPD Thrusters

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Abstract: Multiple-channel hollow cathodes are of crucial importance for MPD thrusters. While single-channel cathodes are still suitable for 10-kW class discharges, at higher powers the multiple-channel configuration seems at present the only option for limiting the electrode erosion and the power losses in the cathode region. Unfortunately multiple-channel cathodes are difficult and costly to manufacture and as for single-channel ones the investigation of the internal plasma is very difficult. Hence, the availability of a numerical model as reliable design tool, allowing to limit the number of required tests would be very important. Whereas for single-channel cathodes some sophisticated models already exist in literature, reliable and numerically affordable multi-channel cathodes modeling is difficult to achieve. After a brief review of main efforts and results at Alta and RIAME-MAI on hollow cathodes development during the past years, a new multiple-channel hollow cathode model is presented and the results in terms of plasma parameters, voltage drop and cathode temperature are shown for a 100-kW, argon-fed MPD thruster.

Nomenclature

L = cathode lenght
r = cathode radius
t = cathode thickness
ScH = Single-channel Hollow (cathode)
McH = Multiple-channel Hollow (cathode)

I. Introduction

FUNDAMENTAL but critical components of plasma and ion devices, hollow cathodes have both functions of electron source for plasma generation and plume neutralization. The state of the art of MPD thruster design points to hollow cathodes in single or in multiple channel configuration, as the rod configuration was given up since the 90's. In fact experimental MPDT prototypes using rod cathodes showed erosion rate values too high with respect

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to the limit of 0.1 ng/C (depleted mass per unit charge) that can be reasonably assumed for MPD propulsion applications[1]. The attention is focused on the high working temperature: in the hollow cathode configurations a larger electrode surface is interested by the discharge current leading to lower temperature values. Furthermore ionization process taking place in the active zone of the channel is more efficient, allowing less electron emission request, implying a lower surface temperature. Other important beneficial aspects of discharges burning with hollow cathodes are lower voltage drops and less plasma contamination than with rod cathodes. The practice in MPD thruster operations showed that single channel hollow cathodes achieved the best performance for discharge powers up to 10 kW, while at higher powers till megawatt levels the use of multichannel hollow cathodes is basically mandatory.

Being part of Hall and ion thrusters, ScH cathodes have been extensively studied for many years; on the contrary McH cathodes are by far less known, except for MPD thrusters specialists. Moreover they are complex to manufacture and rather expensive. Finally the experimental investigation is very difficult because of the little dimensions of the channels and as a consequence most measurements limit to cathode external temperature. For all these reasons few experimental works exist on McH cathodes[2, 3]. On the other hand, also the numerical modeling can be a challenging task, due to the intrinsic principle of operation of a McH cathode, where plasma conditions and surface temperatures of the different channels vary consistently with their radial position. Nevertheless, one can envisage that the development of McH cathode models is of great interest.

For many years ALTA and RIAME-MAI, both independently or in collaboration, have carried out a deep research on hollow cathodes; McH cathode models have been developed at both centers. After a brief review in section II and III of the work at Alta and RIAME-MAI respectively, section IV deals with the numerical results of the RIAME-MAI model for a cathode operating in a 100-kW class, argon-fed MPD thruster.

II. Review of hollow cathode models at ALTA

ALTA developed analytical models both for single channel and multichannel configurations[4,5].

A. ScH cathode model

The model is numerically complex and describes phenomena taking place inside the channel when stationary working conditions are reached, i.e. normal mode or spot mode regime. At the base there are several hypothesis that simplify the search for a solution of the equation system. First of all the model is one-dimensional, that means radial gradients are neglected with respect to the axial ones (that is possible because $t<<r<<L$). Inside the channel the electric field is considered axial in the plasma and radial in the wall sheath. The gas flow is considered to be laminar, viscous and subsonic, with a sonic condition at the outlet section. The plasma is assumed to be a perfect mixture of perfect gases: electrons, positive ions and neutrals. Ions and neutrals are considered at the same temperature, equal to the wall temperature, as a consequence of the heat exchange by conduction between the surface of the cathode and the gas. The electron gas is considered to be at equilibrium at a higher temperature. The model considers only interactions between emitted primary electrons and heavy particles during the ionization process.

The system developed is made of five, 1st order differential equations and one equation of the 2nd order. It is not a Cauchy problem because boundary conditions are defined on both sides of the integration domain. For this reason the system is divided into two subsystems solved alternatively using the variables calculated by the first subsystem as inputs for the solution of the second system and vice-versa. The solution provides plasma parameters (electron and ion temperature, density and plasma potential), cathode temperature and electron and ion current densities distributions along the channel axis as a function of cathode geometry and materials properties, propellant characteristics, mass flow rate and plasma potential drop at cathode outlet. It is worth to note that the model has not the length of the plasma column as an input parameter; this is rather an output of the model: final profiles of plasma parameters and cathode wall temperature reveal how far upstream the plasma has penetrated inside the cathode.

The results are quite accurate in describing plasma physical properties, and agree well with experimental data reported in literature.

B. McH cathode model

In the past a multichannel model has been developed for a particular geometrical configuration consisting in a multichannel cathode made of 7 equal cylindrical tubes regularly disposed in a main tube (*macaroni-packet*). The model allows to change diameter and thickness of internal tubes, calculating the parameters of the main cylinder as a consequence. The problem symmetry allows to study an angular sector of $\pi/6$, as can be seen in Fig.1. The main hypothesis at the base of the model are the same of the single channel model. Plasma parameters inside each channel are only dependent on the x-coordinate along the axis and at each section the model considers one plasma node for

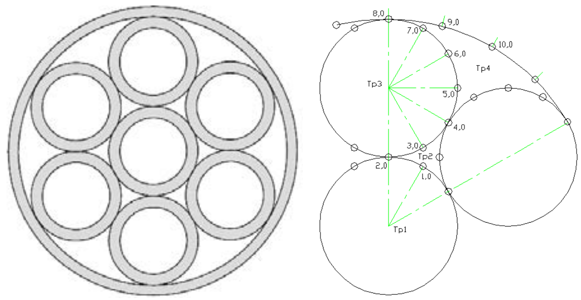


Fig. 1 Schematic of the McH cathode geometry (on the left, thickness walls not in scale) and nodes considered by the model (on the right).

each of the 4 channels (Tp1, Tp2, Tp3, Tp4 in Fig.1) and a total of 10 nodes in order to account for temperature gradient along the circumference of each tube.

There are two main differences between the two models. The first one is about the temperature of ions and neutrals, that now is calculated as average value of temperatures in the nodes of the corresponding channel wall, while the second difference concerns the mass flow rate distribution, that now is taken according to Ref. 2, in order to account for the different conductances among the channels.

The model is strongly complex by a numerical point of view, but the first results are encouraging. Temperatures profiles obtained with this model seems to be consistent with data available in literature. Fig.2 shows temperatures profiles of the wall of the main tube and for the plasma point Tp1. These results are obtained with a multichannel hollow cathode with main tube radius of 2.06 mm, length of 68.5 mm, argon flow rate of 1.2 mg/s and discharge current of 2.3 A.

Temperature profile grows up from the external tube to the internal one, because of the main cooling effect that is due to surface radiation. The same figure reports the wall temperature of a ScH cathode with the same external diameter and wall thickness of McH cathode and operating at the same conditions. ScH cathode temperature is higher than the other ones, and its peak position is more inside the cathode, that implies an internal plasma column longer and a potential drop greater than the values obtained with the McH cathode.

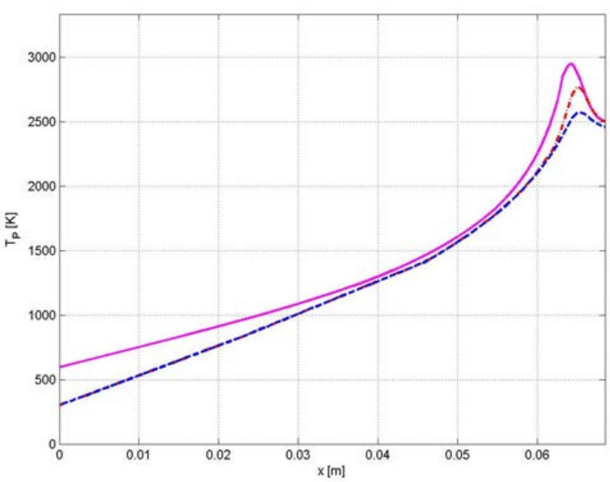


Fig. 2 Temperature profile for the ScH cathode (solid) and for the McH cathode (dash-dash: main tube wall, dash-dot: innermost plasma channel) operating at the same conditions.

III. Review of hollow cathode models at RIAME-MAI

The research on hollow cathodes at RIAME-MAI started in the 90's, when the study of arc-jet devices showed that high performance was achieved using this technology. The complex studies in this field provided a lot of experimental data directly from the tests and the development of an analytical model of ScH cathode[6].

As ALTA model, that of RIAME-MAI is one-dimension, stationary model of the cathode active zone. The gas flow is considered to be at the speed of sound at the outlet section. The plasma is assumed to be a mixture of perfect gases: electrons, positive ions and neutrals. Ions and neutrals are considered at wall temperature, while the electron gas is at equilibrium at a higher temperature. The presence of products of erosion inside the flow does not modify the dynamics of electrons. Ion recombination is considered only inside the hollow channel.

Also for the RIAME-MAI model, the solution scheme bases on two sub-models, solved alternatively and iteratively. However in the RIAME-MAI model some differential equations are transformed in integral ones, then the corresponding boundary conditions become implicit. This was found to facilitate the convergence of the system to a real solution.

An additional model describes the erosion process of the cathode, by means of the processes of sputtering, evaporation, sticking and reflection of cathode material atoms and ions recycling through the plasma. It takes also in consideration the mixture of products of erosion inside plasma.

The distribution of wall temperature, pressure, electron temperature, ionization degree and drop of potential at cathode were calculated and compared to experimental data: the wall temperature fits well experimental data, and its dependence on cathode material is well appreciable.

More recently RIAME-MAI is developing a McH cathode model, based on the previous one, which, on the contrary of Alta McH cathode model is in principle suitable for simulating cathodes with any number of channels. The mass flow rate and discharge current is however equally distributed among the channels, while the cathode temperature gradient in the cross section is calculated by a special algorithm.

IV. 100-kW MPDT cathode design

The RIAME-MAI model was used to calculate argon plasma state and cathode temperature for a multichannel hollow cathode operating in a 100-kW class MPD thruster.

Previous tests on applied-field MPD thruster, operating with argon in pulsed, quasi-stationary devices suggest a discharge current between 1.0 and 1.5 kA at a mass flow rate in the 6 ÷ 40 mg/s range.

In a very preliminary design phase, the existence diagram by Delcroix[7] for the normal regime of operation of a ScH cathode has been used after some adaptation to the McH configuration, for determining the number of the required channels and the cathode overall dimension. It turns out that the cathode is constituted by an external tube, 46-mm in internal diameter, stuffed with 126 rods, 3-mm in diameter. Fig. 3 represents the schematic of such a cathode; the material of the tube and rods is tungsten.

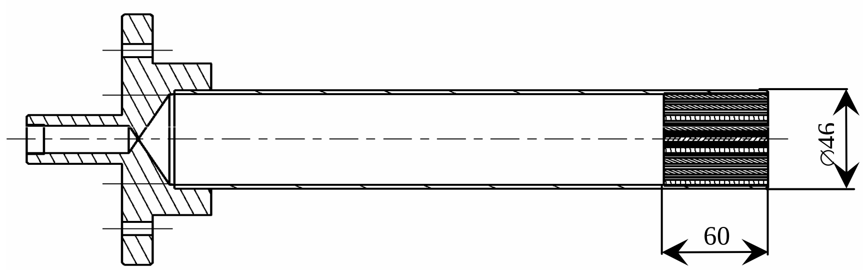


Fig. 3 Schematic representation of the multichannel hollow cathode.

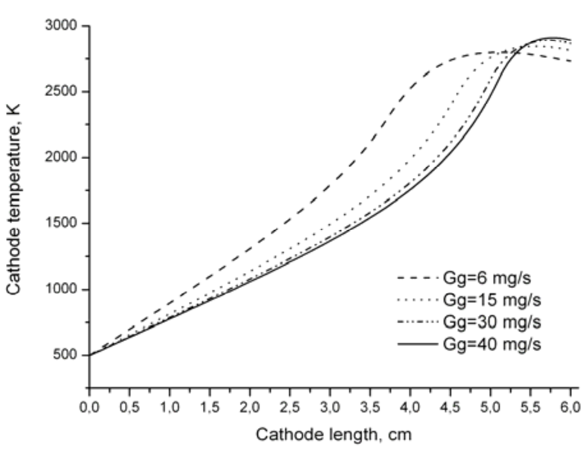


Fig. 4 Temperature distribution of the central channel for different argon flow rates at the discharge current of 1.5kA.

Next figures show parameters calculated by the model.

In Fig.4 the wall temperature is plotted for different argon flow rates and with the boundary temperature of 500K. It can be seen the shift of the maximum value of the temperature as soon as the argon flow rate increases.

Fig.5 reports the temperatures for different channels inside the cathode compared to the external cylinder. It is clear the difference in temperature of the inner channels respect to the external one: layers between 1 and 5 have almost the same temperature, while the external wall has a lower temperatures because of the external radiating surface.

Fig.6 shows the voltage distribution in the active area of the hollow cathode for different argon flow rates.

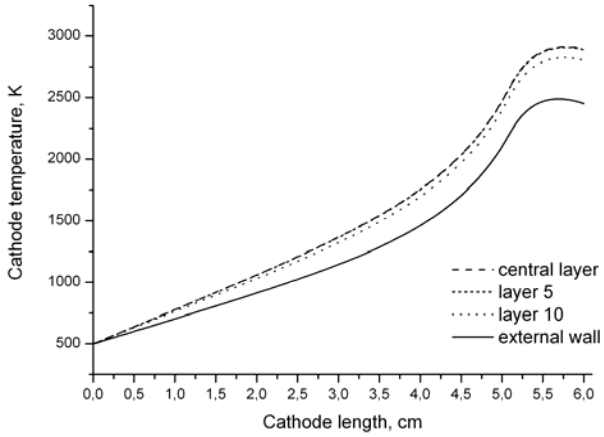


Fig. 5 Temperature distribution for different channel layers at the discharge current of 1.5kA and argon flow rate at 40mg/s.

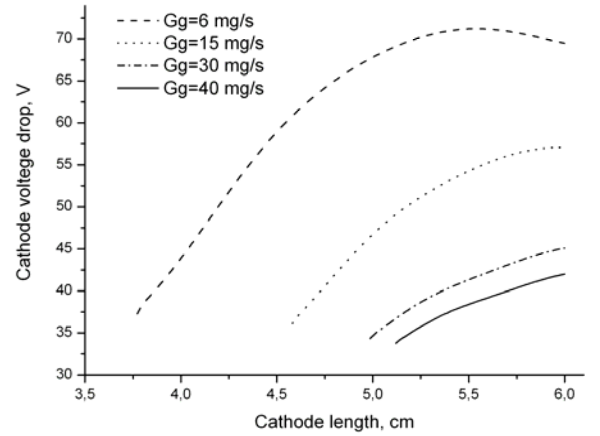


Fig. 6 Discharge voltage distribution at the discharge current of 1.5kA.

At small argon flow rate (about 6mg/s) cathode voltage drop is high, as confirmed by experimental data, and an unstable discharge can be observed, leading to cathode melting[8]. Flow rates at about 30 – 40 mg/s seem to be more appropriate.

Fig.7 shows plasma pressure at different argon flow rates, while in Fig.8 a comparison between plasma pressure and electron pressure is presented.

In Fig.9 the ionization degree for different argon mass flow rates is reported. Plasma ionization coefficient does not exceed 10%.

Electron temperature is showed in Fig.10 at different argon flow rates. Note that at the cathode end, electron temperature rises quickly, reaching the level of about 10eV for argon flow rates of about 6 mg/s. It seems that exactly for this zone of the hollow cathode the model of processes needs additional consideration and investigations.

Fig.11 and Fig.12 respectively show the electron concentration and the ion fraction of the discharge current in the active zone of the channel, still at 1.5 kA discharge current.

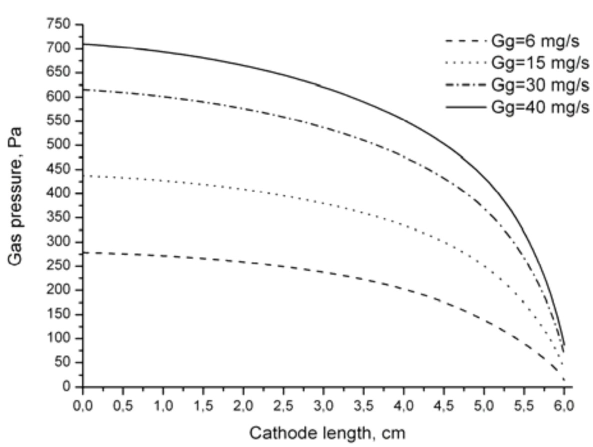


Fig. 7 Argon pressure distribution for different flow rates at the discharge current of 1.5kA.

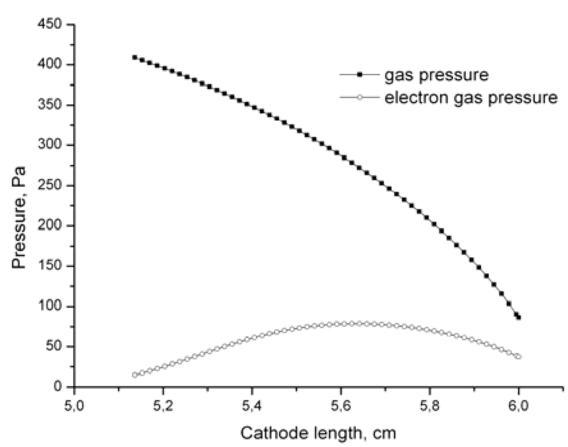
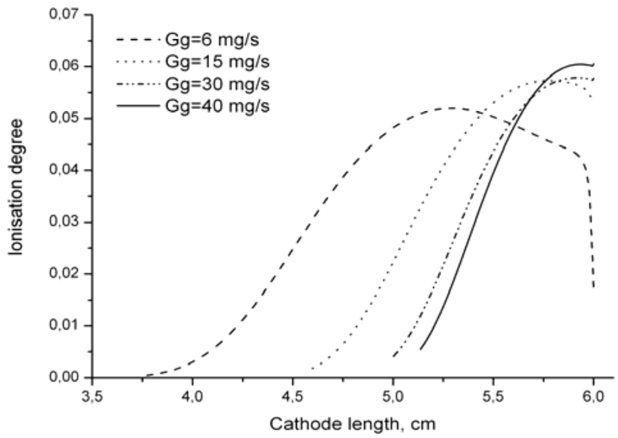


Fig. 8 Partially ionized gas and electron gas pressure in the active zone at the discharge current of 1.5kA.



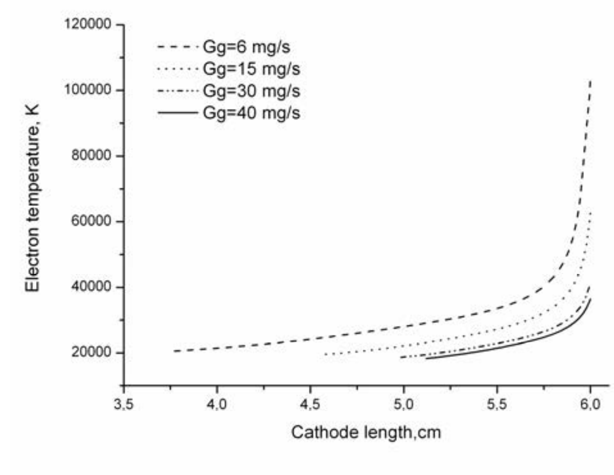
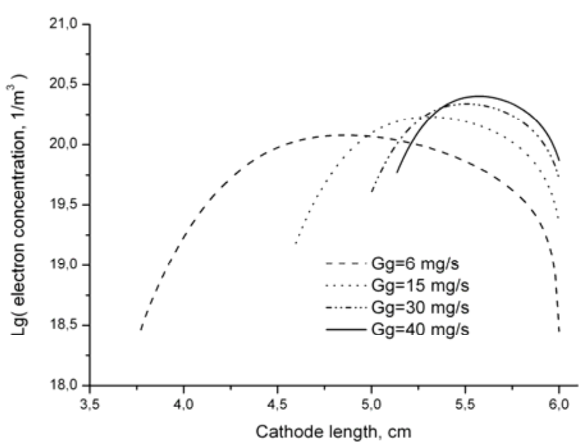


Fig. 9 Ionization degree in the active zone for different flow rates at the discharge current of 1.5kA.

Fig. 10 Electron temperature in the active zone for different flow rates at the discharge current of 1.5kA.



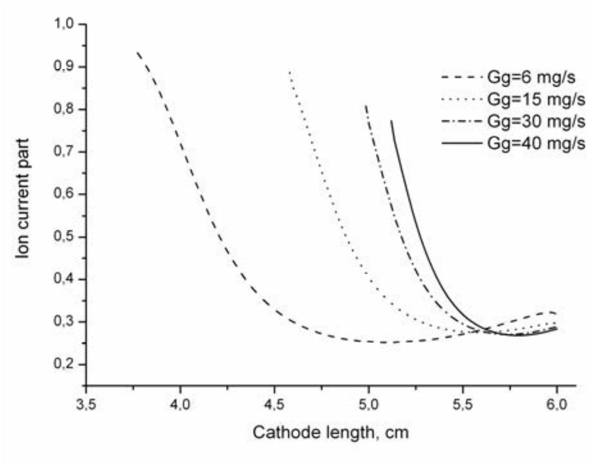


Fig. 11 Electron concentration of plasma in the active zone for different argon flow rates.

Fig. 12 Ion fraction of the discharge current in the active zone for different argon flow rates.

V. Conclusion

The multiple-channel hollow cathode model developed by RIAME-MAI has shown reliable results for the operating conditions explored in past experiments for 100-kW, argon-fed MPD thrusters, with rod cathodes or not optimized hollow cathode configurations. In particular the cathode voltage drop calculated by the model at the higher mass flow rates for 1.5 kA current are compatible with 100-kW power thruster operation. Cathode temperature, voltage drop, gas pressure and plasma parameters have trend with mass flow rates in agreement with what can be expected by hollow cathode theory.

Multiple-channel hollow cathode model is under development at Alta too; the previous model tailored for a precise cathode configuration will be somewhat simplified and adapted for modeling any configuration in terms of number of channels.

In the next months, an experimental activity will be carried out by Alta in the frame of ESA-sponsored TRP project “Technical Assessment for High-Power MPD Systems”, aiming at testing hollow cathodes at 100-A (OM) current levels, for model validation.

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