Optimizing ideal ion propulsion systems depending on the nature of the propellant

Grigore CICAN*[,1,a], Ionut-Florian POPA[2,b]

*Corresponding author
*[,1]"POLITEHNICA" University of Bucharest, Faculty of Aerospace Engineering,
Gh. Polizu Street 1-5, 011061, Bucharest, Romania,
grigore.cican@upb.ro
[2]National Research and Development Institute for Gas Turbines COMOTI,
220 D Iuliu Maniu Bd., sector 6, cod 061126, OP76, CP174, Bucharest, Romania,
ionut.popa@comoti.ro

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Abstract: *From all accounts the ion thrusters are characterized by the fact that they produce a very high exhaust velocity and specific impulse, sometimes too high for many missions. The exhaust velocity of the ionized particles is a function of the ratio between electrical charge and mass. The obvious solution is the use of ions with low electrical charge – mass ratio, but many of these substances have a corrosive effect on the acceleration grids, they are toxic and hard to store on board the spacecraft. Currently the most used propellant for the ionic propulsion systems is xenon gas having many advantages, but it is expensive when compared to other propellants. The current paper aims to make an optimization study of ideal ion thrusters depending on the nature of the propellant using for studying a significant number of substances. It will study the variation of the performances: force, specific impulse, efficiency, etc for the same power available on board, for the same accelerating voltage and the same ionic current.*

Key Words: *ionization, propellant, exhaust velocity, optimization*

1. INTRODUCTION

Since old times, humankind desired to explore the cosmic space. This fact ensured the development of spacecraft, starting with the first ones used to explore the Moon, communication satellites and space probes meant to explore the planets of the Solar System and other secrets of the Universe. However, classic chemical rockets are impractical when it comes to such applications due to the fact that they need large amounts of propellants to finish an interplanetary or intergalactic travel which can take years. Thus, the development of new propulsion systems is required.

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[a] Lecturer PhD. Eng.
[b] BMs. Eng.

One of the best alternatives for such applications is the electric propulsion, based on the acceleration of an ionized gas using electricity. This type of propulsion was considered somehow atypical due to the fact that it wasn’t used for the applications foreseen by the visionaries of this technology, namely the human exploration of other planets [1].

The performance of the ion propulsion systems is influenced by various elements. One of these elements is the nature of the propellant. As stated by [2], the ideal propellant is easy to ionize and has a high mass/ionization energy ratio. Also, the propellant should not affect or erode the metallic structure of the thrusters in order to ensure a long life span.

The first engine designs used caesium due to its high vapour pressure and ease of ionization, but caesium is difficult to store because its reactivity is rather hard to isolate. The first demonstration of this propulsion technology in space took place in 1964, following to the launch of the “Space Electric Rocket Test – 1” [3]. The spacecraft was equipped with two types of thrusters using different propellants. One of the thrusters was based on electronic bombardment using mercury electrons (Kaufman ion thrusters), running for about half an hour. Unfortunately, the second ion thrusters, based on caesium ions, never functioned because of a short circuit. The developments achieved in the previous mission were used for the “Space Electric Rocket Test – 2” which also demonstrated the functionality of the ion thrusters using mercury, this time for thousands of hours.

However, mercury is toxic, expensive and tends to contaminate the spacecraft, reason why in the 1980 time frame it was decided to replace mercury with xenon because xenon was less contaminating the spacecraft surfaces, has a reasonably high atomic number, is inert and causes low corrosion [4]. It was used for the first time in the beginning of the ‘70s for satellite propulsion and later for missions such as Deep Space 1, SMART-1 and Dawn.

At this time xenon is the most common propellant used for ion thrusters due to its ability to ionize at relatively low voltages and its reliable storage properties. However, it’s rather hard to produce and also expensive due to the fabrication process.

In this paper, only the elements of the propulsion system will be optimized, without involving optimization criteria which imply parameters defining the rocket, as presented in reference [5]. The scope of this work is to present the optimization of the ion propulsion system as a function of the propellant’s nature for the same value of the electric power and of the accelerating voltage.

2. THE RUNNING PRINCIPLE OF THE ELECTRIC PROPULSION SYSTEMS

The running principle of electrical propulsion systems consists of making the gas molecules or, in general the particles which have to be ejected, sensitive to the action of an electric field and to send them the desired energy using this field. The known method for making a conductor from a gas is its ionization, case in which the gas becomes sensitive to the action of an electric or magnetic field. If we ionize a gas in a given chamber we obtain negative and positive charges. In a ionic rocket, first the negatives charges are separated from the positives ones and the ions obtained are accelerated in a particle accelerator.

An electrostatic propulsion, regardless of type, consists of the same series of basic ingredients, a propellant source, several forms of electric power, an ionizing chamber, an accelerator region, and the means of neutralizing the exhaust. While Coulomb accelerators require a net charge density of one polarity, the exhaust beam must be neutralized to avoid a space-charge build-up outside of the craft which could easily cancel the operation of the thruster.

The main components of an ion thruster are described below:

a) Ion Sources:

As proven in different space missions, the most reliable propellants for electrostatic thrusters are cesium, mercury or noble gases such as argon, krypton and the most used propellant for such applications, xenon. There are known many methods to ionize a propellant, but the most promising ones are the bombardment discharge surface, the cesium-tungsten surface contact ionization source and the RF (Radio Frequency) discharge source.

The bombardment method implies the use of a cylindrical discharge chamber containing a cathode which releases electrons, a surrounding anode shell and a magnetic field which constraints the electrons from hitting the chamber wall while increasing the chance of collision between an electron and neutral atom, thus occurring the ionization process. One important particularity of this device is the existence of a hollow cathode wherein is sustained a secondary discharge that facilitates electron emission from the interior walls of the cathode cavity.

The magnetic field surrounding the interior of the chamber is provided by three ring magnets, configured such way to ensure an optimized discharge for ionization and ion extraction processes. The magnitude of this field is adjusted in accordance with the differential voltage between the anode and the cathode in order to maximize the ionization efficiency and discharge stability, while minimizing the production of doubly charged ions which tend to erode the acceleration grids.

Typical values for xenon and mercury propellant range around 0.25 T and 30 V, respectively, but other chamber configurations and field values used have proven to be successful.

b) Accelerator Grids:

Almost all types of ion thrusted use a system of acceleration grids designed to achieve a certain exhaust velocity. The process implies the extraction and acceleration of the positive ions downstream due to the electric potential applied between the grids, while minimizing electron impingement.

Most of the bombardment thruster's type use a double grid configuration to improve the mechanical and thermal stability of the propulsion system. The upstream grid has a higher positive potential than needed to increase the ion extraction process and also the space-charge limited current density. The second grid reduces the speed of the ions to the desired value. A third grid can be introduced, acting as a shield in front of the electrons that tend to get back in the ionization chamber, eroding the grids and the ion source.

Thus, the third grid increases the operational lifetime of the ion thruster, but adds complexity to the overall system.

The holes in the grid are designed in order to ensure a minimum impingement of ions, while focusing the ion stream intro an array of beamlets.

c) Neutralizers:

In order to avoid the increase of the negative charge around the spacecraft, the ion thruster is usually equipped with a hollow cathode which releases a flux of electrons in order to neutralize the ion beam exiting the thruster.

3. MATHEMATICAL MODEL FOR IDEAL ION THRUSTER

The evacuation speed at which the particles arrive is determined in a particle accelerator.

We analysed the direct particle accelerator because it is the most used particle accelerator. This particle accelerator is described in reference [6].

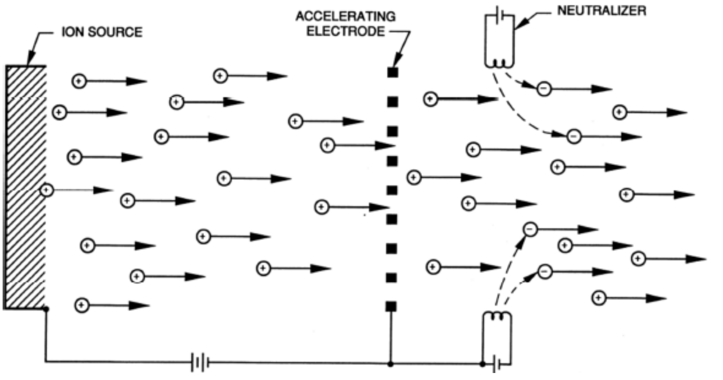

Fig. 1 The schematic diagram of the ion thruster.

According to reference [7] we will present the calculation method for the ionic engine. For starters it will be analyzed the situation of an ion which has the load q and mass m located in an electric field $\vec{E}$, determined by the tension $V_{acc} = V_2 - V_1$ which applies between A anode and C cathode, as it can be seen in the picture below.

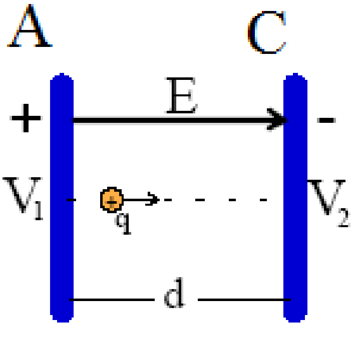

Fig. 2 The schematic diagram of the electric field.

The ion is accelerated until it gets a speed v_e determined by the next equality: the kinetic energy of the electron is equal with the kinetic energy variation of the particle, conditioned by the electric field action.

$$\frac{1}{2} \cdot m \cdot v_e^2 = q \cdot V_{acc} \Rightarrow v_e = \sqrt{\frac{2 \cdot q \cdot V_{acc}}{m}} = 13800 \cdot \sqrt{\frac{V_{acc}}{M}} \tag{1}$$

The expression below is valid if the particle takes off from the ion source with the speed 0, during the acceleration interval being an uniform electric field

$$E = \frac{Vacc}{d} \tag{2}$$

Where d is the distance between the two electrodes.

In order to calculate the propulsion force produced by the ionic engine we used the expression below:

$$P_e = I \cdot V_{acc} \tag{3}$$

$$I = \dot{m} \cdot \left(\frac{e}{m} \right) \tag{4}$$

The propulsion force is defined as:

$$F = \dot{m} \cdot v_e = I \cdot \sqrt{2 \cdot \frac{m}{e} \cdot V_{acc}} \tag{5}$$

We have to determine the intensity of the electric current by defining the current density

$$j = \frac{I}{S} \tag{6}$$

Using the Poisson's equation we obtain:

$$\frac{d^2 V}{dd^2} = \frac{\rho_e}{\varepsilon_0} \tag{7}$$

where d is the distance, ε_0 is the vacuum permeation and ρ_e current density.

Solving the equation below we obtain the current density:

$$j = \frac{4 \cdot \varepsilon_0}{9} \cdot \sqrt{\frac{2 \cdot q}{m}} \cdot \frac{V_{acc}^{\frac{3}{2}}}{d^2} \tag{8}$$

For atomic or molecular ions we obtain:

$$j = \frac{5.44 \cdot 10^{-8} \cdot V_{acc}^{\frac{3}{2}}}{M^{\frac{1}{2}} \cdot d^2} \tag{9}$$

And for circular form holes we have:

$$I = j \cdot S = j \cdot \left(\frac{\pi \cdot D^2}{4} \right) \tag{10}$$

where D is the hole diameter.

$$F = \left(\frac{2}{9} \right) \cdot \pi \cdot \varepsilon_0 \cdot D^2 \cdot \frac{V_{acc}^2}{d^2} = \left(\frac{2}{9} \right) \cdot \pi \cdot \varepsilon_0 \cdot D^2 \cdot E^2 \tag{11}$$

The jet power is:

$$P_j = \frac{\dot{m} \cdot v_e^2}{2} \tag{12}$$

The ionization losses represent the non recoverable ionization energy which is related to the ionization potential of the atom, times the number of coulombs produced per second (see Table 1 and Eq. 3):

$$P_l = P_{ion} \cdot \frac{\dot{m} \cdot e}{M \cdot q} \tag{13}$$

The efficiency of the ion thrusted is calculated using the following expression:

$$\eta = \frac{P_{jet}}{P_{jet} + P_l} \tag{14}$$

4. PROPERTIES OF SEVERAL PROPELLANTS

Argon, Krypton and Xenon are traditionally used in electric propulsion because of their chemical inertness, even only the last one has been extensively used in the actual space environment.

The motivation is mainly based on the lower Xenon ionization energy (see Table 1) [8] and the higher mass respect to the other gases.

Table 1. Ionization potential for various gases

Gas	Ionization potential P_{ion} (eV)	Atomic mass **M** (kg/kmol)
Caesium	3,9	132,9
Potassium	4,3	39,2
Mercury	10,4	200,59
Xenon	12,08	131,30
Krypton	14,0	83,80
Hydrogen	15,4	2,014

5. RESULTS OF OPTIMIZATION

The following information is known about the ionic engine:

The working fluid is each gas presented in Table 1, the distance between the acceleration grids *d*=2.5mm, the diameter of each hole of the grid D=2mm, the electric power provided by the power source $Pe = 10kW$.

The fact that the propulsion system is an ideal one presumes the following simplifying assumptions: the whole quantity of propellant is ionized, so neutral propellant particles which are not part of the propulsion beam won't be taken into account; the ion beam is not splay, so the propulsion force is fully axial; the entire gas is ionized only in its first state of ionization for which the ionization potentials presented in Table 1 apply.

In order to obtain the results, the following calculus process was conducted:

Knowing the electrical power provided by the power source (solar arrays), the acceleration voltage was varied between 1 and 1000V, obtaining the ion current intensity from expression (3).

After knowing the ion current, the necessary power for ionization can be calculated using expression (13).

The obtained necessary power for ionization was then used to recalculate the ion current, subtracting the ionization power from the electric power, while keeping the initial voltage. The ion current obtained with the expression (4) was used to obtain the propellant flow which can be ionized using the amperage value obtained earlier. Using expression (1), the exhaust speed was calculated for each type of propellant. Also, the propulsion force was calculated using expression (5).

In order to determine the exhaust surface of the propellant, and implicitly the diameter and number of holes with D diameter, expressions (6) and (8) were used.

After variation the parameters, the following results are obtained:

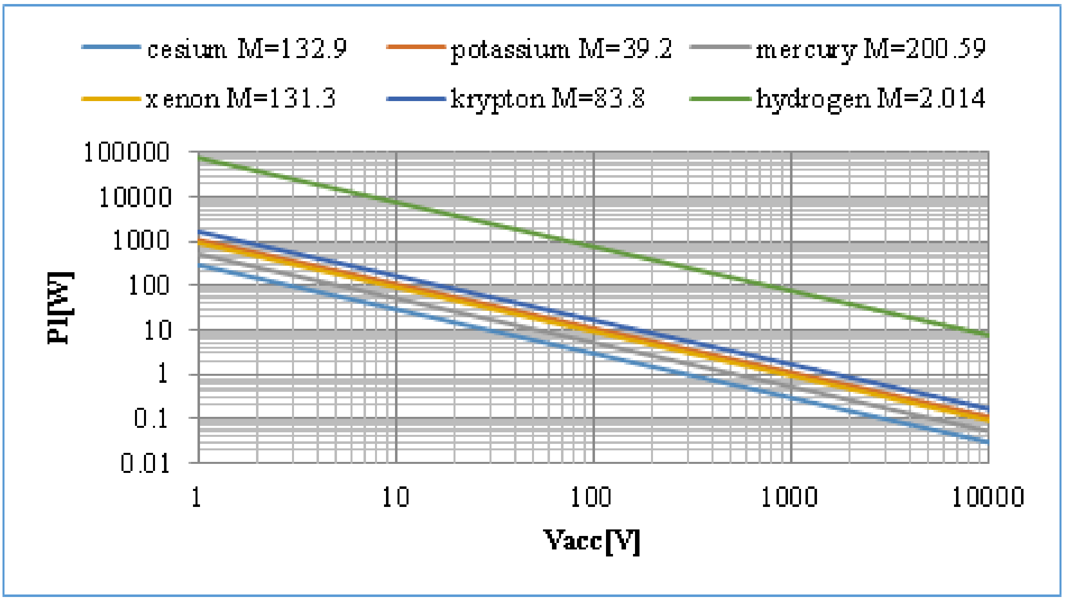

Fig. 3 The necessary power for ionization as a function of the acceleration voltage in logarithmic scale for a better view of the results

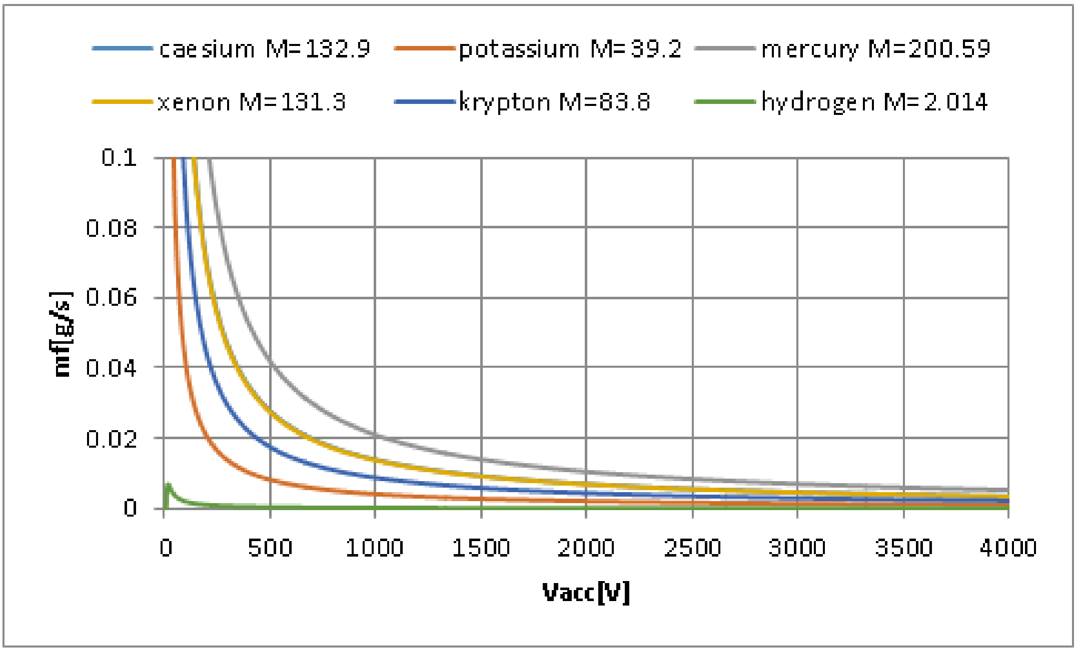

Fig. 4 The propellant flow which can be ionized as a function of the acceleration voltage

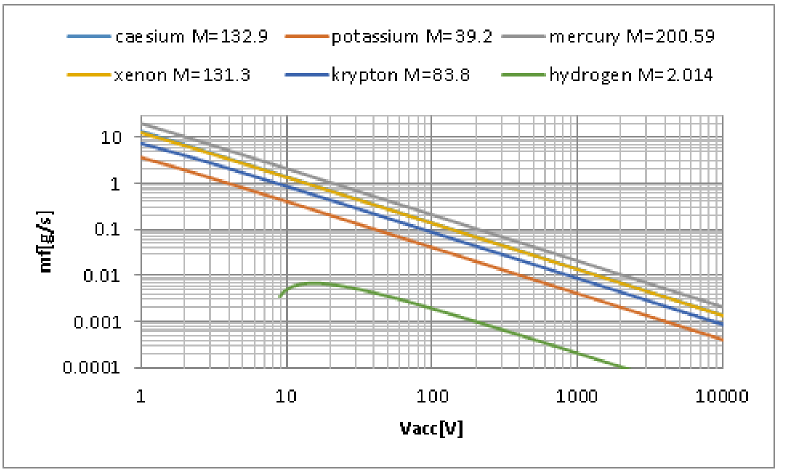

Fig. 5 The propellant flow which can be ionized as a function of the acceleration voltage in logarithmic scale for a better view of the results

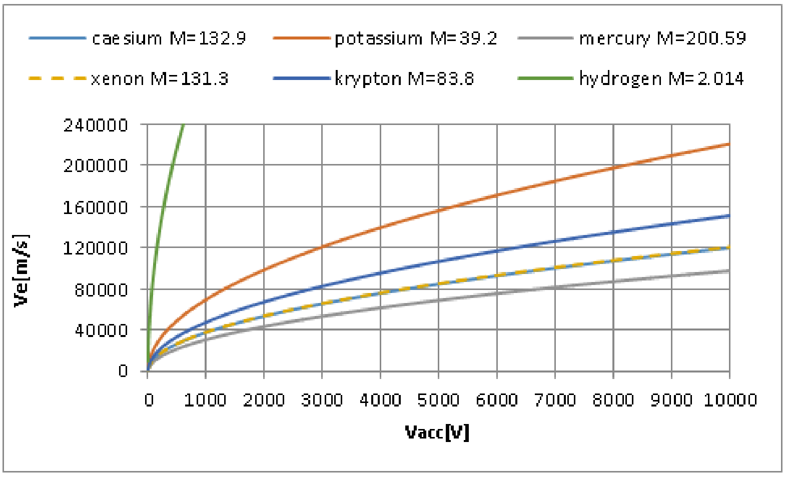

Fig. 6 The exhaust speed as a function of the accelerating voltage

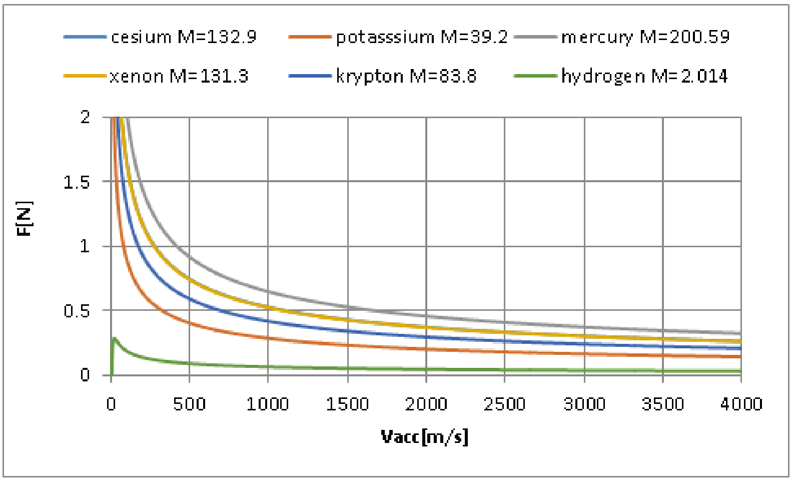

Fig. 7 The propulsion force as a function of the accelerating voltage

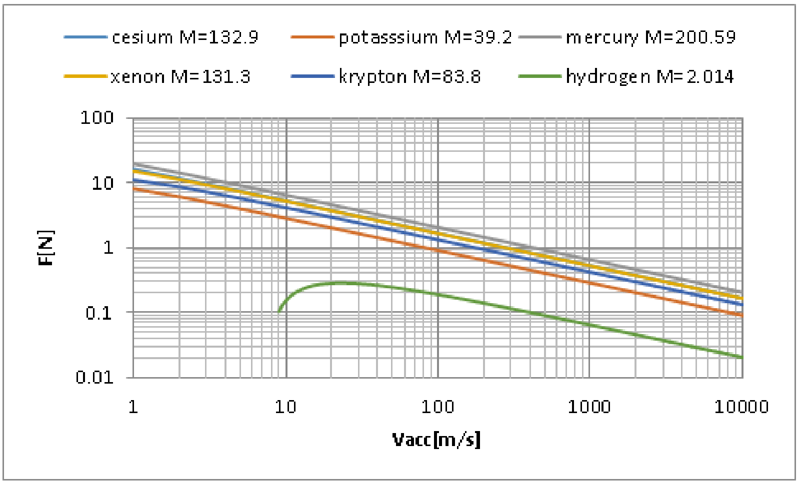

Fig. 8 The propulsion force as a function of the accelerating voltage in logarithmic scale for a better view of the results

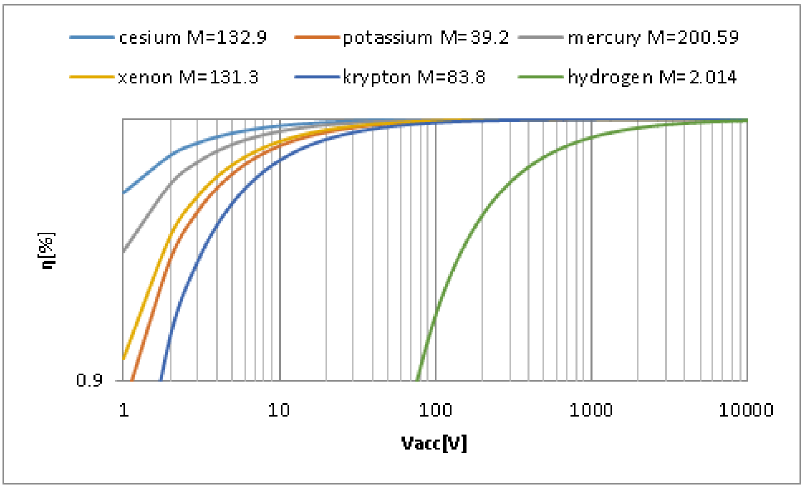

Fig. 9 The efficiency of the ion thrusters as a function of the accelerating voltage

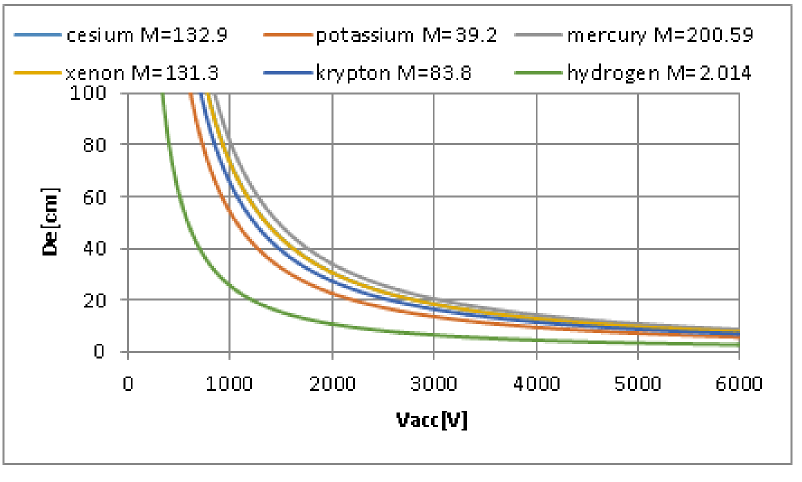

Fig. 10 The diameter of the ion beam exhaust section as a function of the accelerating voltage

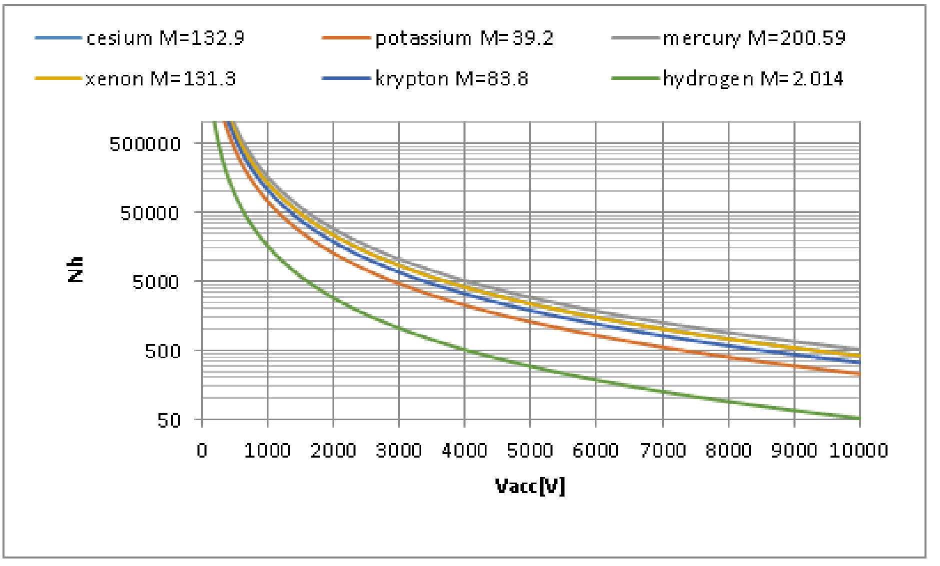

Fig. 11 The number of 2 mm diameter holes on the exhaust surface as a function of the accelerating voltage

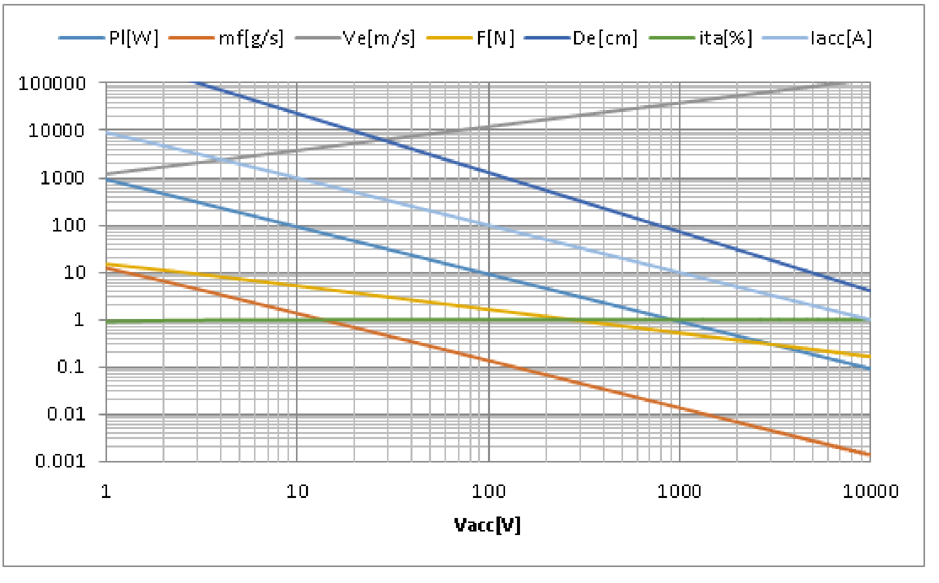

Fig. 12 The main parameters presented earlier for xenon as a function of the accelerating voltage corresponding to an electric power *Pe*=10 kW

6. CONCLUSIONS AND DISCUSSIONS

Following the conducted calculus and obtained plots it can be seen in figure 3 that for an electric power of 10 kW, the ionization power of hydrogen at small values of the accelerating voltage and high values of the amperage has higher values than to entire electric power available from the spacecraft, as it can be observed on the hydrogen curve from the diagram.

In figures 4 and 5 an anomaly can be observed for hydrogen due to the fact discussed earlier. The propellant flow which can be ionized decreases as the voltage increases and the ion current decreases. It can be observed that the propellant having the highest mollecular mass has the highest ionized flow.

In figure 6 the variation curves of the exhaust speed can be observed, as they are directly proportional with the accelerating voltage and the mollecular mass of the propellant. As a consequence of keeping the same accelerating voltage, the hydrogen has the highest exhaust speed due to the fact that it has the lowest molecullar mass.

In figures 7 and 8 it can be observed the variation of the propulsion force which decreases as the accelerating voltage increases. The ideal case presumes having ion thrusters with very low accelerating voltages and very high ion current intensities in order to have large propulsion forces.

Figure 9 shows the variation of the ion thruster efficiency, including the losses linked to the propellant ionization. The efficiency is very low at low voltages and increases tending towards 1 at high values of the accelerating voltage. As it can be observed, the hydrogen has the lowest efficiency.

In figure 10 it can be noticed the variation of the ion beam exhaust diameter, while figure 11 presents the number of 2mm holes which can be executed in the exhaust diameter.

A very important fact which can be observed is that, when working with low accelerating voltages, the propulsion forces are high, but the entire system has a very large diameter, fact also known from literature. According to reference [9], propulsion systems working at low accelerating voltages are much more voluminous.

In figure 12 the main parameters of interest for the ion thruster using xenon as propellant are presented. As it can be observed in the plotted charts, a plausible ion thruster regarding the dimensions should use accelerating potential of at least 4000 V and 2 A.

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