Finite Element Modelling and Performance Optimization of an Ion Thruster depending on the nature of the propellant

Ionuț-Florian POPA
Romanian Research and Development Institute for Gas Turbines COMOTI
Assistant Researcher
220 D Iuliu Maniu Bd., sector 6, cod 061126, OP 76, CP174, Bucharest, Romania
ionut.popa@comoti.ro

Anna-Maria Theodora ANDREESCU
Romanian Research and Development Institute for Gas Turbines COMOTI
Assistant Researcher
theodora.andreescu@comoti.ro

Dan IFRIM
Romanian Research and Development Institute for Gas Turbines COMOTI
Technical Development Engineer
dan.ifrim@comoti.ro

Radu MIHALACHE
Romanian Research and Development Institute for Gas Turbines COMOTI
Scientific Researcher
radu.mihalache@comoti.ro

Dragoș MIHAI
Romanian Research and Development Institute for Gas Turbines COMOTI
Scientific Researcher
dragos.mihai@comoti.ro

Grigore CICAN
"POLITEHNICA" University of Bucharest, Faculty of Aerospace Engineering
Lecturer PhD Eng.
Gh. Polizu Street 1-5, 011061, Bucharest, Romania
grigore.cican@upb.ro

ABSTRACT

The electrostatic propulsion is a class of space propulsion which make use of electrical power and this kind of systems are characterized by high exhaust velocities and specific impulse, enhancing the propulsive performances of thrusters compared to conventional chemical thrusters. Since the ionized particles exhaust velocity is a function of the ration between the electrical charge and their molecular mass, the obvious solution is to use ions with low electrical charge-molecular mass ratio. Currently, the most used propellant for the space propulsion is the Xenon gas, as it has a series of important advantages, but is quite expensive when compared to other propellants. This paper aims to make an optimization of the ideal ion propulsion systems depending on the nature of the propellant, like common used substances in the space propulsion, but also other substances which are potential candidates for this application. A variety of ion thruster performances will be analyzed, such as: force, specific impulse, efficiency for the same power available onboard, the same accelerating voltage, and the same ion current. Also, for the Xenon case a numerical simulation was performed to highlight the behavior and trajectory of the ionized particles and their velocity. The conclusion obtained following the study is that a reasonable ion thruster regarding the dimensions should use an accelerating potential of at least 4000 V and 2 A of ion current.

KEYWORDS: *ion thruster, propellant, optimization, exhaust velocity, numerical simulation*

NOMENCLATURE

De:	exhaust diameter	P:	Power
EP:	Electric Propulsion	RF:	Radio Frequency
ita (η):	thruster's efficiency	SERT:	Space Electric Rocket Test
mf:	mass flow	Ve:	exhaust velocity

1 INTRODUCTION

The evolution of the electric propulsion dates back almost 100 years, period which can be divided into several ages, depending on the progress made in this domain [1]:

- The visionaries' era: 1906 – 1945;
- The pioneers' era: 1946 – 1956;
- The progress era: 1957 – 1979;
- The acceptance era: 1980 – 1992;
- The practice era: 1993 – present.

An aspect worth mentioning is that these eras are not clearly defined by the achievements obtained in each era, but mostly they represent the dominant character of each phase in the development of the EP systems.

EP can be considered quite unconventional, because, compared to other space propulsion technologies, it wasn't used yet for the purpose foreseen by the visionaries, which is human exploration of other planets. This fact is due to technological, space conditions, but also human issues.

A first issue to be considered is that this propulsion technology was put on hold, mainly because the unconventional space propulsion systems were harder to understand and accept at that time. This problem was overcome in 1991 in an attempt to minimize the space programs costs, but also because the Soviet Union managed at that time to send in the deep space the first EP spacecraft [2]. Until that, the first demonstration of EP working in space was achieved by NASA onboard SERT 1 and 2 spacecraft. SERT-1 was launched in 1964, being featured with an ion thruster which functioned about 31 minutes, while SERT-2, launched in 1970, was featured with two ion thrusters which functioned 5, respectively 3 months [3][4].

Another problem, and maybe the most important, is the lack of high electrical energy sources in space. A solution can be the development of a nuclear source, but its development is conditioned by financial, political and national safety reasons, as well as the need of screening the nuclear source is space and the need of putting that source into the orbit, requiring a lot of thrust force because of the high mass. The first nuclear source used in space, approximately 5 keV, was a fission reactor onboard the Cosmos spacecraft [5].

Despite all of these issues, more than 200 satellites on Earth orbit, as well as some spacecraft out of the Earth gravitational influence are currently using EP [1].

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. 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 an ionic rocket, first the negative 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 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 [6]:

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 constraint the electrons from hitting the chamber wall while increasing the chance of collision between an electron and neutral atom, thus occurring the ionization process.
The magnetic field surrounding the interior of the chamber is provided by ring magnets, configured such way to ensure an optimized discharge for ionization and ion extraction processes, while minimizing the production of doubly charged ions which tend to erode the acceleration grids.

b) Accelerator Grids:

Almost all types of ion thrusters 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 THE IDEAL ION THRUSTER

In the optimization, a direct particle accelerator was considered, as it is the most used type for the space propulsion. A description of the particle accelerated shown in Fig. 1 is presented in reference [7].

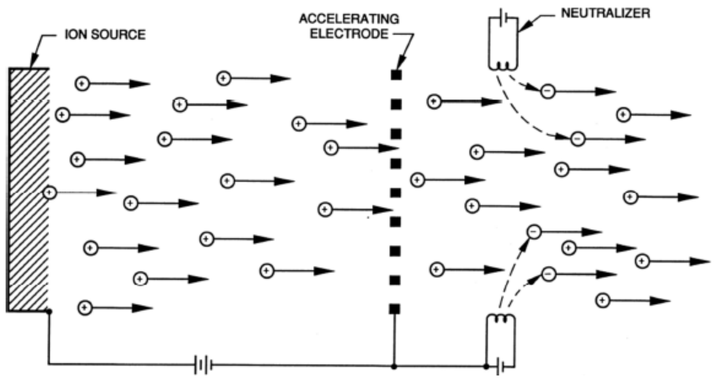

Figure 1: The schematic diagram of the ion thruster

The mathematical model used for calculating the performances of the ion thruster is presented in reference [8]. The fact that the ionic thruster is presumed to be an ideal one requires some simplifying assumptions like: the whole quantity of propellant is ionized, thus the neutral particles won't be taken into account; the propulsion force is fully axial; and the entire gas quantity is ionized in its first state of ionization which will be specified in the next paragraph.

4 PROPERTIES OF THE PROPELLANT CONSIDERED FOR THE OPTIMIZATION

The most used gases for EP are Argon, Krypton and Xenon, given their inertness. The last is the most used for such propulsion systems, as it has low ionization energy and high molecular mass compared to other gases.
Table 1 [9] presents several gases to be considered as propellants in the optimization process, both usual gases and other gases which can may be successfully used in EP.

Table 1: Ionization potential and molecular mass for various gases

Gas	Ionization potential P_{ion} (eV)	Atomic mass M (kg/kmol)
Cesium	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 THE ANALYTICAL OPTIMISATION

For the ion thruster, the following information was considered for the mathematical model:

- The working fluid is represented by each gas mentioned in Table 1;
- The distance between the acceleration grids is *d=2,5 mm*;
- The diameter of each hole drilled in the grid *D=2 mm*;
- The electric power ensured by the power source is P_e*=10 Kw*.

The following figures present the results of the analytic optimization as charts [6].

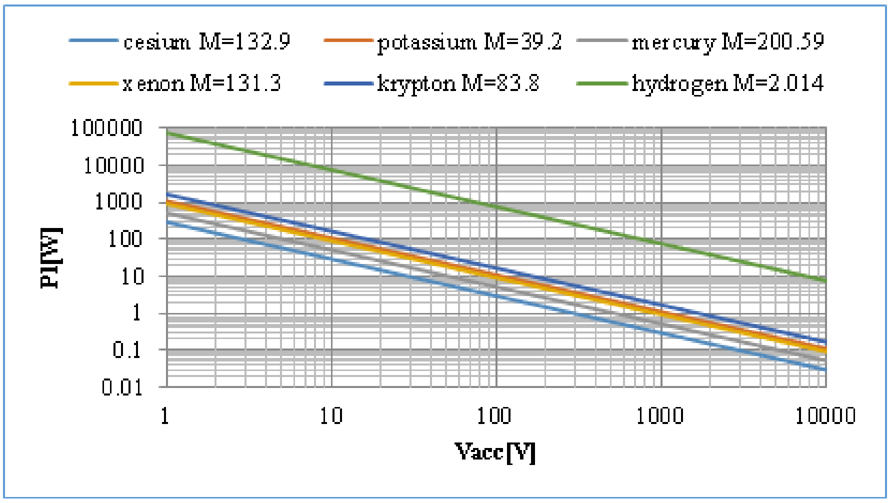

Figure 2: The necessary power for ionization as a function of the acceleration voltage

In Fig. 2 it can be observed that for an electric power of 10 kW, the ionization power necessary for hydrogen is greater than the available power on the spacecraft.

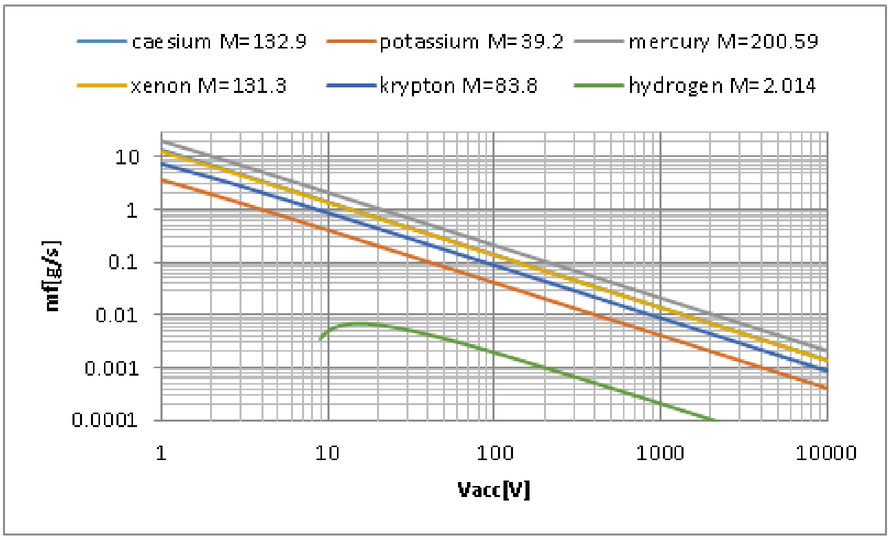

Figure 3: The propellant flow which can be ionized as a function of the accelerating voltage

Fig. 3 presents the same anomaly for hydrogen as discussed earlier. Also, it can be seen that the propellant having the highest molecular mass has the highest ionized flow.

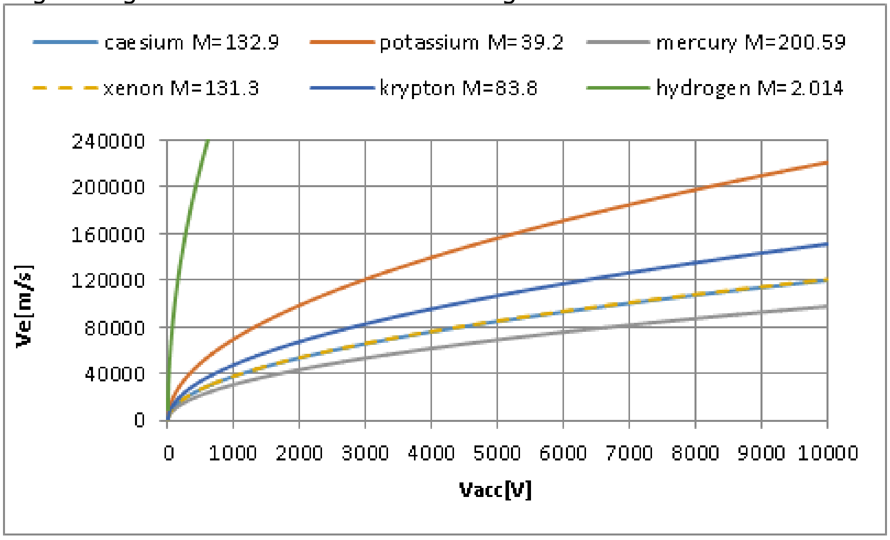

Figure 4: The exhaust speed as a function of the accelerating voltage

In Fig. 4 the variation curves of the exhaust speed are directly proportional with the accelerating voltage and the molecular mass of the propellant. For the same accelerating voltage, the hydrogen has the highest exhaust speed as it also has the lowest molecular mass.

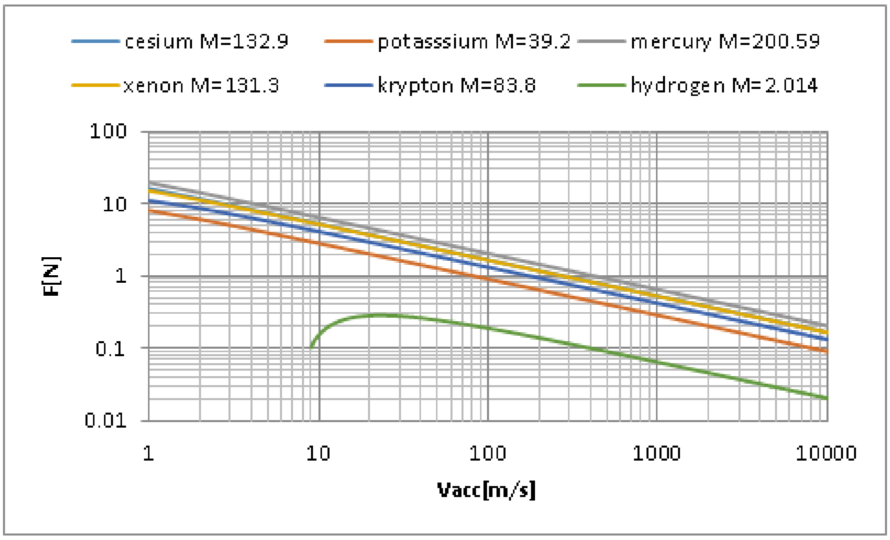

Figure 5: The propulsion force as a function of the accelerating voltage

Fig. 5 highlights the variation of the propulsion force decreasing as the accelerating potential increases. As a consequence, an ideal ion thruster presumes using low accelerating voltages and very high ion currents in order to obtain large thrust forces. However, according to reference [10], the entire system has also a large diameter, being more voluminous.

In Fig. 6 the ion thruster's efficiency is presented, including the losses linked to the propellant ionization. One can see that for low acceleration voltages, the efficiency is also low, increasing towards 1 at high acceleration voltages. In the case of the hydrogen, the efficiency has the smallest value.

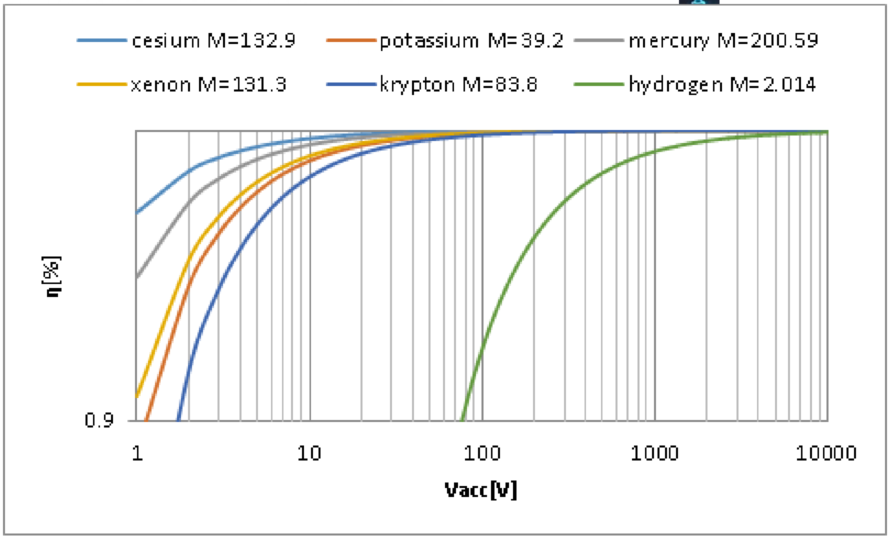

Figure 6: The efficiency of the ion thrusters as a function of the accelerating voltage

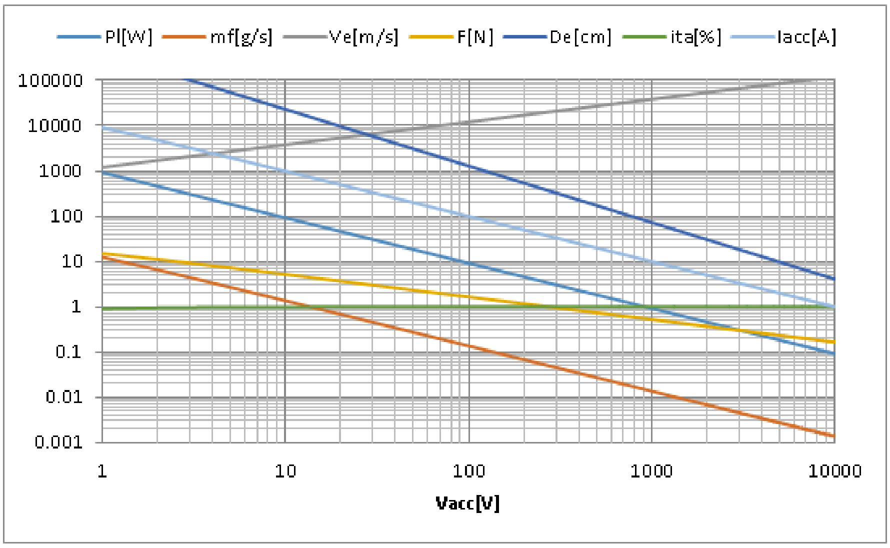

Figure 7: The main performances for an ion thruster using Xenon as propellant

Finally, in Fig. 7 the main parameters of interest for an ion thruster using Xenon gas as a propellant are presented. According to the results, a dimensionally reasonable ion thruster shall use an accelerating voltage of 4000 V and 2 A as the ion current intensity.

6 NUMERICAL SIMULATION OF AN ION THRUSTER OPERATING WITH XENON

For the numerical simulation of the thruster it was considered to use COMSOL Multiphysics, a complex simulation tool which can solve various physics problems from almost all domains. The characteristics of the ion thruster are listed below:

- **The ionization chamber** was considered to be made of AISI304, non-magnetic in order to minimize the influence of the magnetic field over it, having 150 mm length and 240 mm in diameter [11];
- **Magnetic rings** made of Neodymium [11];
- **Acceleration grids** made of Molybdenum, known to withstand corrosion [12].

Fig. 8 presents the 3D model created based on the information above.

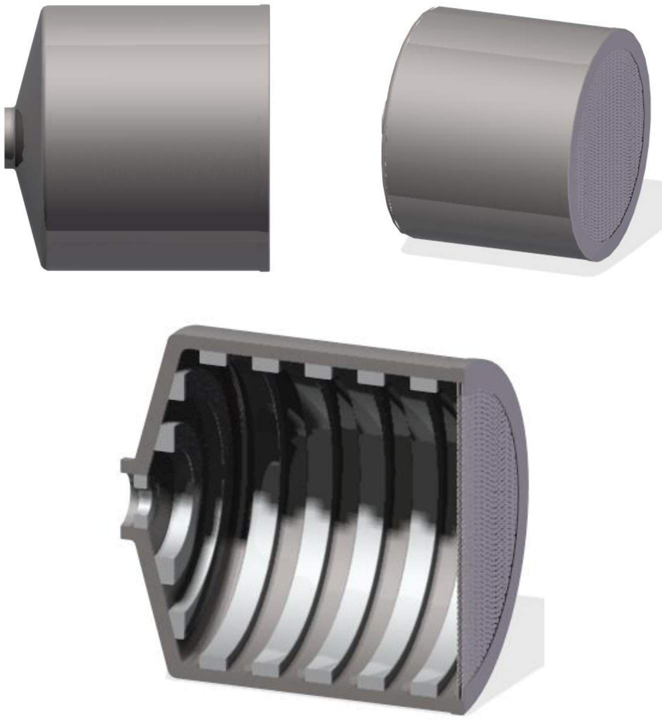

Figure 8: 3D model of the ion thruster

The following problems were considered to be solved following the numerical simulation:

- **Magnetic field problem**, used to define the magnetic rings inside the ionization chamber;
- **Electric field problem**, used to define the acceleration potential between the grids;
- **Electrostatic problem**, used to define the interaction between the two fields mentioned before;
- **Charged particle trajectory problem**, used to define the model of the accelerated particle, its mass and charge.

Fig. 9 presents the magnetic field created inside the ionization chamber. As it can be seen, it has a reduced influence over the walls, due to the used material. Also, the magnet rings layout ensures a uniform magnetic field, which must ensure a confinement of the ion beam.

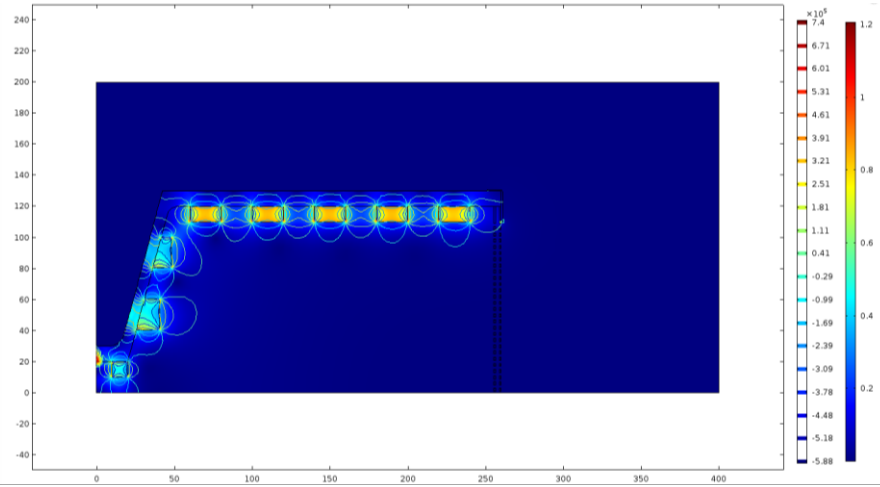

Figure 9: Magnetic flux density [T] and the magnetic field lines [A/m] in the ionization chamber

The next plot shows the electric potential created between the acceleration grids, 5000 V on the first grid and -1000 V on the second, meaning 4000 V of acceleration voltage. Fig. 10 shows the interaction between the two opposite voltages applied on the grids.

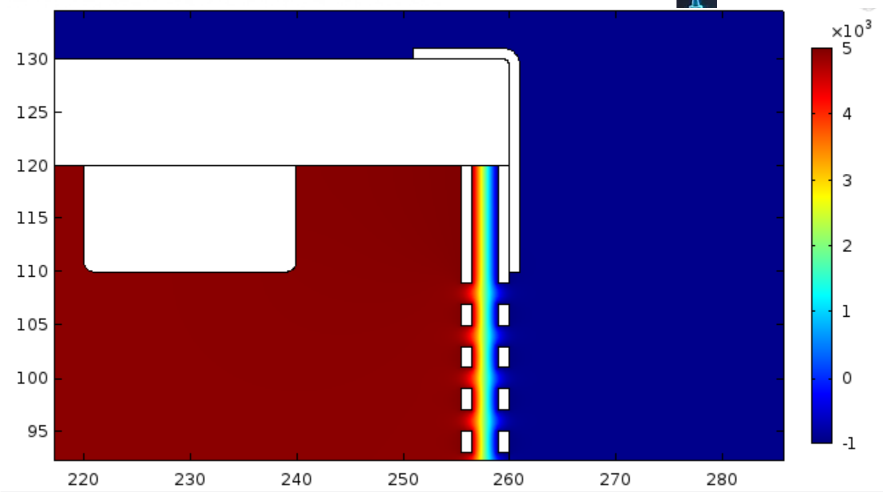

Figure 10: Electric potential applied between the two acceleration grids [V]

The movement of the particles inside the ionization chamber is determined by the interaction between the electrical and magnetic fields defined in the simulation model, and finally, by passing through the acceleration grids. As specified before, the particle model has the molecular mass of the Xenon, and positive charge associated with the positive ion.
The following figures present the movement of the particles inside the ionization chamber for a time period between 0 and 1,2x10^{-3} seconds, the time step being t_{step} = 10^{-5} seconds. The legend on the right shows the particles speed in m/s.

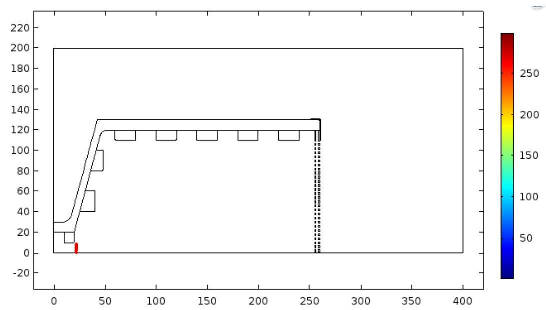

Figure 11: Ion thruster at t=0 s

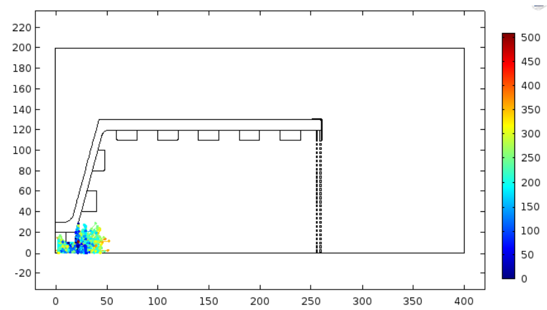

Figure 12: Ion thruster at t=10^{-4} s

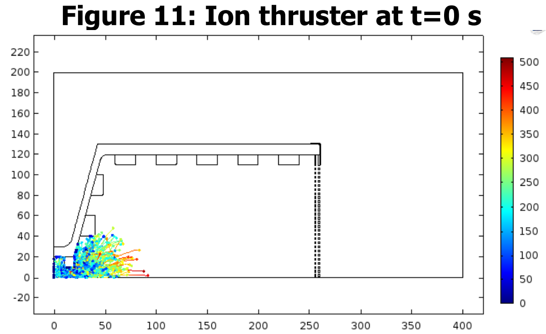

Figure 13: Ion thruster at t=2x10^{-4} s

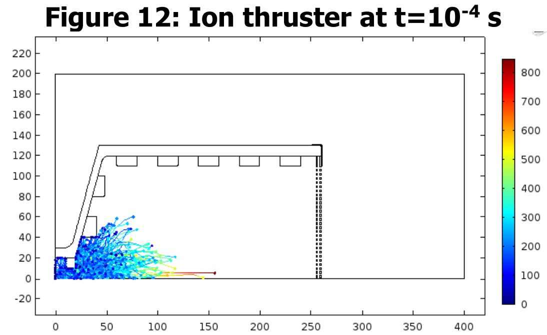

Figure 14: Ion thruster at t=3x10^{-4} s

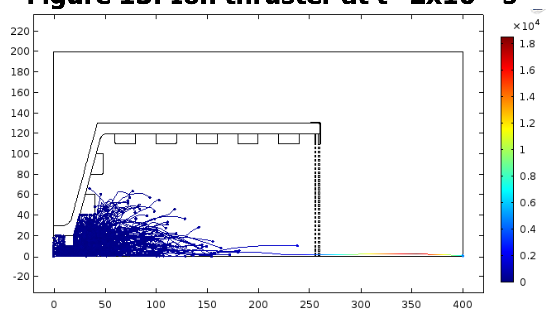

Figure 15: Ion thruster at t=4x10^{-4} s

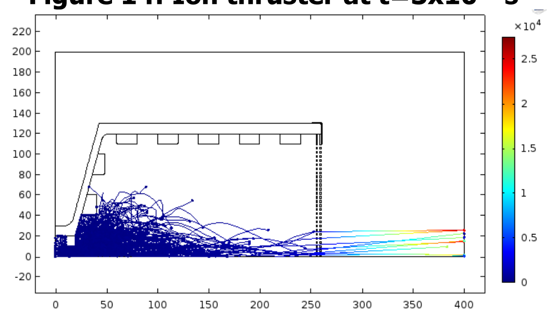

Figure 16: Ion thruster at t=5x10^{-4} s

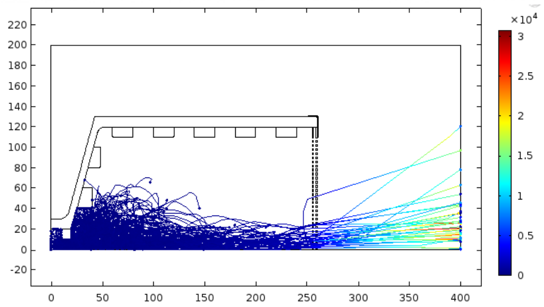

Figure 17: Ion thruster at t=6x10^{-4} s

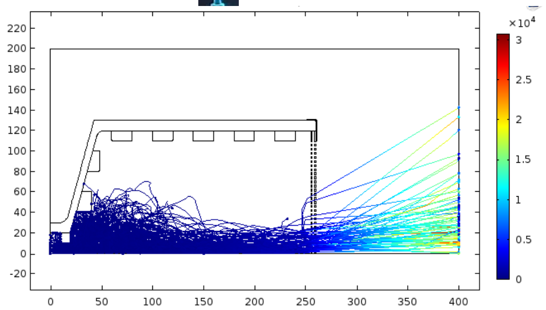

Figure 18: Ion thruster at t=7x10^{-4} s

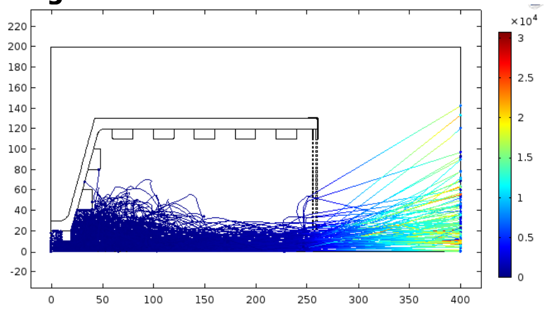

Figure 19: Ion thruster at t=8x10^{-4} s

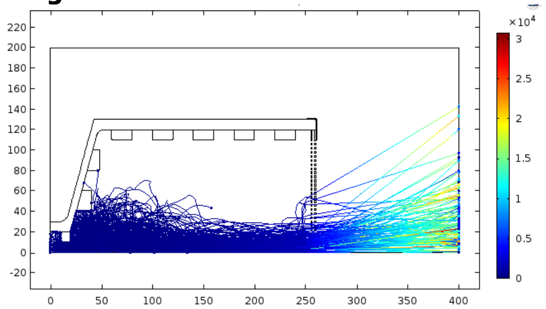

Figure 20: Ion thruster at t=9x10^{-4} s

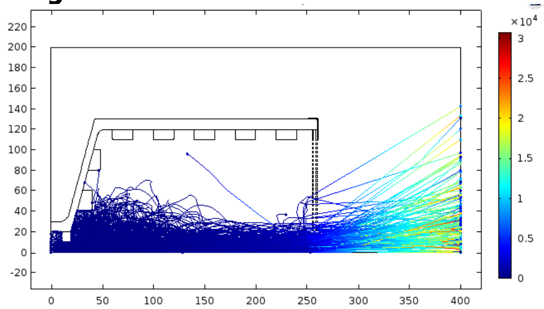

Figure 21: Ion thruster at t=10^{-3} s

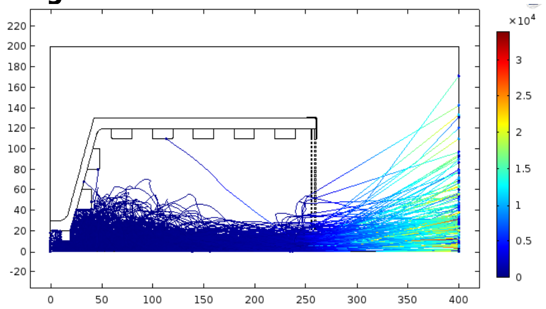

Figure 22: Ion thruster at t=1,1x10^{-3} s

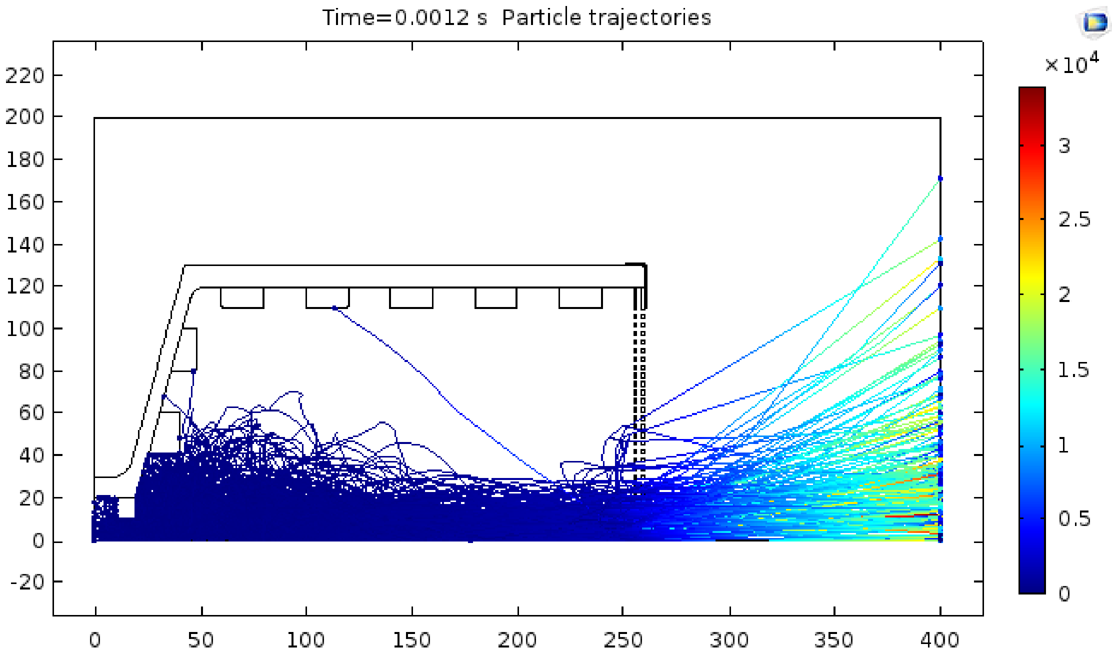

Figure 23: Ion thruster at t=1,2x10^{-3} s

According to the Fig. 11-14, the particles reach speeds up to 600 m/s, before leaving the ionization chamber. After passing through the acceleration grids, their speed increases, reaching 35.000 m/s, a common value for nowadays ion thrusters, fact depicted in Fig. 15-23. Also, contrary to the simplifying assumptions mentioned in paragraph 3, the jet is not fully axial. However, not all the particles go towards the acceleration grids, fact caused by the probabilistic nature of the simulation.

7 CONCLUSIONS

The space propulsion systems based on electric power are a viable alternative to the classic propulsion systems, wherever it is about interplanetary missions or just keeping a satellite on Earth's orbit, mainly because they can ensure a large domain of thrust with a relatively low propellant consumption. Also, due to the use of electric components, their hysteresis tends to be smaller than the one of a propulsion system based on cold/hot gas which needs many valve mechanisms.

The current paper aimed to make an optimization of the ion thruster's performances based on the nature of the propellant. According to the results, the propellant shall be easy to ionize and it shall have a molecular mass enough to ensure high exhaust speeds. Also, a dimensionally reasonable ion thruster shall use an acceleration potential up to 4000 V combined with an ion current of 2 A for the case of the Xenon, which is the most used propellant in this industry, but it shall not be limited only to it, as there are also other substances which can be used as propellant, but they need yet further studies and tests.

The numerical simulation highlighted the behavior of the charged particles inside the ionization chamber when the results of the analytic optimization were introduced in the model. The obtained exhaust velocities were in the range of 30÷40 km/s, which correspond to the exhaust velocities obtained in practice in the space industry.

The results obtained following the conducted study can be used in the near future to develop the first type of this thruster in Romania and, why not, to be validated in a space mission.

However, the problem of ensuring the electrical power onboard still remains, as nowadays the space missions become more and more extended with the purpose to explore the most remote places of our Solar System.

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