Visualization of the charged particles movement features in conditions, which are characteristic for the Hall Thruster discharge interval as the technique for the students training in space electric propulsion

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Oghienko(Ogienenko) Sergii*, Setrakova Yana†, Vakulenko Tamara‡, Kulish Olga§
Zhukovsky National Aerospace University “Kharkov Aviation Institute”, Ukraine

Abstract: During students training in electric propulsion of spacecraft, for exploration of features of charged particles dispersion and movement in the Hall thruster (HT) discharge interval the computer program of visualization was used. Such program allows investigating features of electron and ion movement lengthways Larmor trajectories, distributions of the charged particles and integral characteristic - thrust. It was set as a boundary condition: bi-dimensional distribution of magnetic field and a potential of an electric field, permanent distributions of the charged and neutral particles, close to the wall potential drop. The program enables to “turn off” collisions of electron-atom or electron-charged particles, to take or not to take into account an energy exchange at electron collisions that enables to study in details a role of separate processes in plasma of HT.

Nomenclature

\[ B = \text{magnetic induction} \]
\[ E = \text{electric field strength, energy} \]
\[ I = \text{current} \]
\[ M, m = \text{ion and electron mass} \]
\[ n = \text{concentration} \]
\[ P = \text{probability} \]
\[ q = \text{elementary charge} \]
\[ U = \text{discharge voltage} \]
\[ V = \text{velocity} \]
\[ \sigma = \text{cross-section of some process} \]
\[ \varepsilon = \text{electron energy} \]
\[ \varphi = \text{potential of electric field} \]
\[ \lambda = \text{length of electron run way} \]

* Senior Researcher, Department of thrusters and power plant of spacecraft, thrust@d4.khai.edu
† Master, Department of thrusters and power plant of spacecraft, yanaxai@mail.ru
‡ Student, Department of thrusters and power plant of spacecraft, dir@ckbenergo.com
§ Student, Department of thrusters and power plant of spacecraft, cherewnya_@pochta.ru
I. Introduction

Progress in space electric propulsion technologies depends upon professional level of engineers and researchers, who solve scientific and technical problems. For successful preparation of the qualified experts, it is necessary to create conditions, in which students would have got already available knowledge in relatively short term, and on the other hand would have an opportunity to develop the creative potential as the future researchers. Representation of the information as accessible to understanding has the great importance during students training. Especially it concerns to that information, which is base and at the same time - complicated for perception. The problem can be solved by using computer program, which allow to visualize many important features of processes for example in discharge interval of Hall thruster (HT)

II. Mathematical model for detail studying of an electron movement in discharge interval of HT

Main principles of mathematical modeling as bases of the visualization program are the next.

The task was solved based on a Monte-Carlo method. The electron movement trajectory in discharge chamber (DC) is determined by numerical integration of the differential equations system of the charged particle movement with an charge - q, weight - m, in a crossed magnetic field with components $B_x$ and $B_z$ and electric field – $E_x$ and $E_z$ (Fig. 1):

$$
\begin{align*}
    m \cdot V'_y &= -q \cdot B_z \cdot V_x + q \cdot B_x \cdot V_z \\
    m \cdot V'_x &= -q \cdot E_z + q \cdot B_x \cdot V_y \\
    m \cdot V'_z &= -q \cdot B_z \cdot V_y - q \cdot E_z
\end{align*}
$$

Elastic and not-elastic electron collisions are considered: single ionization from the basic level and elastic dispersion on atoms and ion. The collision mechanism is modeled by probability P of an electron run way $\lambda$ before realization of interesting process under the formula

$$
P(\lambda / \lambda_0) = \exp \left( -\frac{\lambda}{\lambda_0} \right),
$$

where $\lambda_0$ - average length of an electron run. Size $\lambda_0$ is defined as $\lambda_0=V_e/\beta n_e$, where $\beta=\langle\sigma V_e\rangle$ - factor of process speed, $\sigma$ - cross-section of process. In a case of coulomb dispersion on ion, the $\lambda_0$ in a range of angles from 0.1 up to 180 degrees is used. Estimate value $\lambda_0$ as

$$
\lambda_0 = \left[ \left( \frac{q^2}{8\pi \varepsilon_0 \varepsilon_e} \right)^2 \cdot \frac{\Lambda \pi \cdot 2 \cdot n_e}{\Theta^2} \right]^{-1},
$$

(according idea1), where: q - an individual charge; $\varepsilon_e$ - the energy determined by the speed $V_e$ of charged particles mutual movement; $\Theta$ - a corner of dispersion; $\varepsilon_0=8.85\times10^{-12}$ – constant, $n_e(x)$ - concentration of electrons. For $\lambda_0$ calculation the data of characteristic primary distribution of plasma parameters lengthways DC are used.

Electron-atom interaction is modelled in view of electron-atom angular scattering characteristic (Fig. 2) depending on kinetic energy $\varepsilon_e$, like

Processes recombination occurs only on surface DC at not-elastic collision of an electron with DC wall. SEE – secondary electron emission yield $\delta$ of surface (properties of acid Al$_2$O$_3$) was determined as
\[
\delta = B \cdot E_p \cdot \left[ \frac{14}{5} \cdot E_g \cdot \exp\left(\frac{E_p}{E_{pm}}\right) \right]^{-1},
\]

where: \(E_p\) - energy of a primary electron; \(B=0.68\) for \(\text{Al}_2\text{O}_3\); \(E_{pm}=512\) eV - energy of a primary electron at which \(\delta=\delta_m\) - it is maximum; \(E_g=9.9\) eV - width of the forbidden zone.

III. Charge particles movement modelling

After beginning of the program, electrons from the cathode start consistently and their movement up to an input in DC or before their absorption by a surface is traced; or electrons from an input in DC start consistently and their movement before absorption by the anode or before absorption by a wall is traced. Features of movement of an electron and ion can be studied in bi-dimensional and three-dimensional space.

As a result of execution of the program characteristics of electrons penetrated in DC (three components of speed and coordinates) are recorded. Then these data are used as entry conditions to study features of electron movement inside DC. “Instant photos” of an electron trajectory – line of white color and for ion trajectory – line of red color are submitted in Fig. 3, 4 for SPT M-25 size type. Red points mark places, where ionization collision of an electron has been performed. The green points - places where there was an elastic electron-atom collision. Dark blue points mark places, where collision of an electron with the charged particle took place. Trajectories of electrons inside DC are shown in Fig. 3. Trajectories in area between the cathode and an input in DC are shown in Fig. 4.

Besides, during execution and after finishing of the program the data are formed: distribution of ion and electron in discharge interval, average electrons energy \(E_{\text{ever}}\), average speed of electron movement along DC axis \(V_{\text{axial}}\) and integral characteristic – thrust for SPT M-70 type on nominal operation mode, like in Fig. 5, 6, 7. The program can be supplemented with other boundary conditions and techniques of data processing.

\[\text{Figure 3. Trajectories of electrons inside discharge chamber of HT.}\]

Color point – place of electron collision. Red points mark places of ionization collision. Green points mark places of elastic electron-atom collision. Dark blue points mark places, where collision of an electron with the charged particle taken place. Red lines – ion trajectories.
IV. Conclusion

Computer program for students training in spacecraft electric propulsion, which allow investigating features of electron and ion movement via visualization of its trajectories in discharge interval of Hall thruster, was development. The program enables to study in details a role of separate processes in plasma of HT by “turn off” some collisions or energy exchange. Due to the program students have got already available knowledge in relatively short term, and on the other hand have an opportunity to develop the creative potential as the future researchers.

References