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PROGRESS IN ELECTRIC PROPULSION NUMERICAL SIMULATION

Electric propulsion has been developed since the early 1960s, and its use onboard satellites, orbiting platforms, and interplanetary probes have increased significantly in the 21st century. The need for a detailed understanding of the working physics and a more accurate assessment of performance to create innovative designs has stimulated the development of several numerical simulation codes. The choice of method for modelling a specific thruster should be dictated by the physical characteristics of the flow in the device, and by the level of accuracy required from the simulation. There are various conditions in different types of thrusters. This means that different methods and computer codes must be developed for each of the different thrusters. The successful development of physically accurate numerical methods for simulating gas and plasma flows in electric propulsion thrusters can significantly improve the design process of these devices. In recent years, numerical simulations have increasingly benefited the basic understanding and engineering optimization of electric thrusters. This is due to several concurrent contributions: the evolution of computer hardware that has allowed the representation of multidimensional geometries and multiscale phenomena; implementation of sophisticated new algorithms and numerical diagnostic tools; and availability of new collisional and surface interaction data. There are two main directions for future work to continue to improve the numerical modelling of electric thrusters. First, the numerical methods themselves must be improved in terms of their physical accuracy and computational speed. The second main direction for improvement in the simulations involves more accurate determination of physical parameters that are required by the numerical formulations. This paper outlines efforts to develop models of various electrical propulsion concepts, from the first attempts in the early 90s to the latest sophisticated multidimensional simulations.

Keywords: *electric propulsion; plasma thrusters; numerical methods; numerical simulation.*

Introduction

Electric propulsion (EP) has have been developed since the early 1960s, and its use onboard satellites, orbiting platforms, and interplanetary probes has increased significantly in the 21st century. The need for a detailed understanding of the working physics and a more accurate assessment of performance to create innovative designs has stimulated the development of a large number of numerical simulation codes.

European Space Agency (ESA) and Electric Propulsion Innovation & Competitiveness (EPIC) have prepared a table with a list of Electric Propulsion thrusters flown or ordered for information, outreach and education purposes. A list of these thrusters can be seen in Fig. 1.

Although studied, developed and tested for several decades, certain EPS (Electric Propulsion System) had not been readily employed in the early times of space missions mainly due to the unavailability of sufficient electrical power on board the spacecraft. Since the new century, the constantly increasing levels of electrical power on new developed spacecraft allows EP to be a very realistic and serious alternative to chemical propulsion, and the use of this technology for different type of missions is already a common practice internationally (in Europe i.e: Artemis, SMART-1, GOCE, AlphaSat, Bepi Colombo, SmallGeo, NEOSat, Electra) [1].

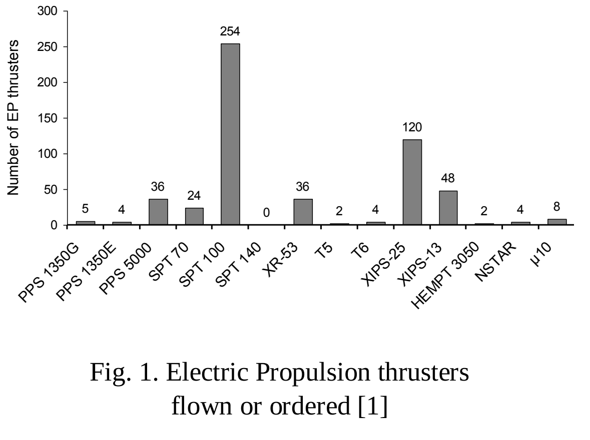

Fig. 1. Electric Propulsion thrusters flown or ordered [1]

In recent years, numerical simulations have increasingly benefited the basic understanding and engineering optimization of electric thrusters. This is due to several concurrent contributions: the evolution of computer hardware that has allowed the representation of multi-dimensional geometries and multi-scale phenomena; implementation of sophisticated new algorithms and numerical diagnostic tools; and the availability of new collisional and surface interaction data. This paper outlines efforts to develop models of various electrical propulsion concepts, from the first attempts in the early 90s to the latest sophisticated multidimensional simulations.

Problem definitions

The use of EP on satellites for commercial, defense, and space science missions has been increasing in recent decades, from the first successful operation in 1964 aboard the Zond-2 spacecraft to the present day [2]. There are many reviews devoted to various aspects of the development, design and testing of various types of electric propulsion thrusters, as well as their application for various missions. They began to be published in the mid-60s [3] of the last century and up to the present [4-8].

The difficulty of experimentally characterizing plasmas and the operative in-space conditions of plasma thrusters make simulations a real game changer in this advanced technology/researchfield. In this respect, the rapid growth of high-performance computing and the scale of modern architecture supercomputers has made it possible to solve more and more complex and computationally costly tasks. With the use of different numerical approaches, typically based on kinetic, fluid hybrid or hybrid plasma models, a large number of applications can be covered: thruster physics and performance estimation, plasma thruster plume interaction with the spacecraft, etc. [9].

According [10], the technology of electric thrusters can be subdivided into three categories:

- Electrothermal propulsion: the electric energy is used to heat the propellant that is expanded through a nozzle.
- Electrostatic propulsion: the electric energy is used to accelerate propellant ions.
- Electromagnetic propulsion: the electromagnetic forces permit the acceleration of a propellant plasma.

Fig.2 shows the classification of electric propulsion systems.

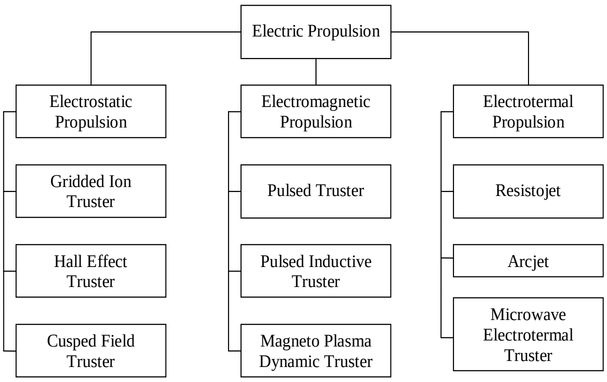

Fig. 2. Classification of electric propulsion systems

The review [11] shows that there are a number of aspects that illustrate that there are still many unresolved issues in the field of EP. For example, EP systems are only partially scalable. Typically, the efficiency decreases significantly with smaller size so that new concepts may have to be used in the long run, when miniaturizing EP systems further. Currently, most of the new concepts are still at a low level of technological maturity. Therefore, modeling of EP systems is an important tool for understanding the underlying physical processes, on the one hand, and for accelerating development processes, on the other hand.

The choice of method for modelling a specific thruster should be dictated by the physical characteristics of the flow in the device, and by the level of accuracy required from the simulation. There is a wide range of conditions in different types of thrusters. This means that different methods and computer codes must be developed for each of the different thrusters [4]. This work is devoted to the analysis and classification of methods and approaches to modeling electric propulsion thrusters.

Methods and Approaches

Plasma thrusters can be classified in terms of the gas ionization process, the basic conversion mechanism for the kinetic energy gained by the ions, the main acceleration mechanism of the plasma, or the modeling needs. Electric propulsion thrusters (with the exception of electro-thermal thrusters) fall within the electrostatic and electromagnetic categories. Thrusters belonging to the former can be modeled by retaining only Poisson’s equation, while the second category requires including the full set (or a subset) of Maxwell’s equations.

Computer simulations of plasmas can be based either on kinetic or on fluid descriptions. Fluid simulations use a magnetohydrodynamic(MHD) equation, with assumed transport coefficients characterizing macroscopic quantities such as density and temperature. In contrast, the kinetic description is more detailed because each species, i.e., ions, electrons, and neutrals in the plasma, is treated as a collection of particles with individual positions and velocities in the presence of an external electromagnetic field. Since the pioneering work [12], involving few thousand of particles only at that time, the kinetic codes have evolved and modern codes can treat now 10^6–10^{12} particles using powerful computers.

Kinetic simulation has proved very successful for solving problems in which particle distributions deviate from a Maxwellian distribution due to stochastic heating, wave-particle resonances, or trapping. Another commonly used approach is the hybrid model in which some species, typically ions, are described using a kinetic approach and others (electrons) are described using a fluid approach [13].

In some cases, for example, in inductively coupled plasmas at low pressures, when the electron mean free path is comparable to the lateral dimensions of the discharge vessel, kinetic effects come into play, and the electron distribution function may become substantially non-Maxwellian. Therefore, it becomes necessary to develop an entirely particle-based simulation tool for the understanding of plasma properties in such situations, e.g., those of a propellant plasma inside the discharge vessel of ion thrusters [14].

The PIC method is based on calculating the trajectories of the particles inside the plasma. Thereby, one discretizes the underlying partial differential equations in time Δt and space Δx. On the latter grid, the electromagnetic fields are evaluated, whereas the particles themselves can have any position in space. A single computational cycle, i.e., time step, of the PIC algorithm comprises the following routines: a particle mover, interpolation of charge and current source terms on the grid, computation of the fields on grid points, and, finally, interpolation of the fields from the grid to the particle locations. Two important conditions needed to be satisfied regarding time step and grid size are

$$\Delta t < 2\omega_{pe}^{-1},$$
$$\Delta x < 3.4\lambda_D, \qquad (1)$$

where ω_{pe}, λ_D is the plasma frequency and Debye length [15]. The PIC model resolves the dynamics of the particles by following the algorithms chematically shown in Fig. 3.

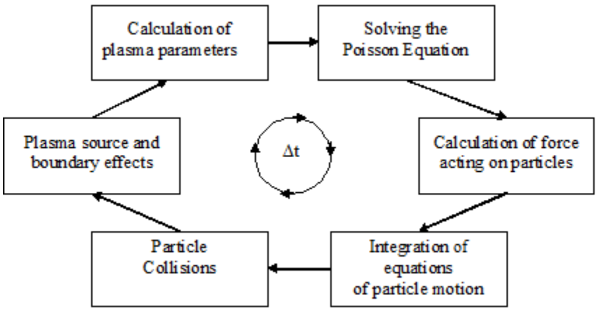

Fig. 3. Schematic diagram of the PIC cycle

Monte Carlo collision (MCC) methods have been developed to simulate binary collisions, e.g., elastic collisions between charged and neutral particles. In the widely used binary collision model, particles are grouped according to their cell locations and then paired randomly, and finally, they collide [16].

By including the MCC method in the code, one can account for important aspects inside the plasma such as the production of new ions and electrons, energy losses, and heating mechanisms. The interaction of the ions with electromagnetic forces and with the neutral gas can be described with the direct simulation Monte Carlo (DSMC) method for interparticle collisions. The DSMC technique is a stochastic particlebased method for the simulation of rarified gas flow problems [17]. Fig.4 shows the ranges of characteristic plasma parameters where MHD, hybrid, and PIC modeling are used.

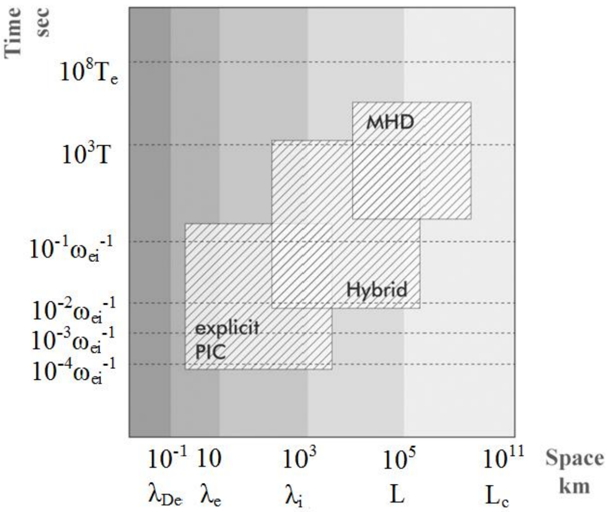

Fig. 4. Scope of application different model [11]

Recently received implementation of the PIC method with Monte Carlo Collisions and direct simulation Monte Carlo (PIC-DSMC) in the open-source numerical toolbox OpenFOAM (Open-source Field Operation And Manipulation) [18]. By this the newly implemented solvers picFoam [19] and pdFOAM [20] gains access to OpenFOAM’s powerful tool sets and an easy to set up simulation case structure.

Although pdFOAM was developed in 2017, it has not yet been used to analyze the plumes of electric propulsion systems. The work [21] is is the first attempt to use pdFOAM for Hall thruster plume analysis

Similar to other OpenFOAM-based codes, pdFOAM can be applied in numerical simulations associated with both structured and unstructured grids and used in parallel and serial computing. Fig 5 shows the solution algorithm of pdFOAM. The simulated particles are inserted into the domain using the inlet conditions or moved within the domain using the velocity and acceleration conditions of the existing particles (the upper-left box). After updating the cell occupancies with the moved particles, collision partners are selected from each cell. If the collision partners satisfy the collision condition, then the particles collide. Depending on the conditions, the colliding particles may react. After updating the cell occupancies again, the electric charges of the ions are transformed to values at the cell nodes.

Then, using the charges at the cell nodes, the electric field can be solved. Based on the solved electric field, the total electromagnetic forces on each particle are calculated. Using the boundary conditions and the particle conditions, the upper-left box can be revisited as in the first step.

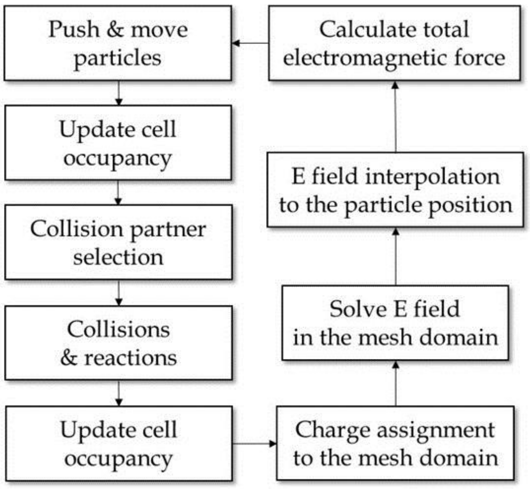

Fig. 5. Solution algorithm of pdFOAM [21]

Results and Discussion

The variety of types of electric propulsion engines, in addition to traditional schemes of Hall effect thruster (HET), gridded ion engine (GIE), including radio frequency (RF) and microwave, helicon and other types, as well as operating modes and conditions for their application, necessitates continuous improvement of existing approaches to modeling processes in plasma thrusters and creating new computer codes.

Obviously, direct kinetic (DK) simulation seems to be the most promising direction in modeling some processes (for example, ion recharging), but from the point of view of computational cost, it is the most expensive, even for 2D models. For example, in [21] it is stated that the simulation results discussed in this work are computed using a total of 24 processors, and the wall time is approximately 3.4 days per 1 ms of computational time. At the same time, the serial PIC simulation takes approximately 14 h to complete 1 ms of simulation time.

Thus, the use of traditional codes in the design of some units and components of the thruster seems to be quite justified and expedient. A typical example is the simulation of plasma inside RF thrusters [11]. The modeling can be divided into electromagnetic field generation, plasma production, multi-species dynamics, and ion extraction. Some software packages exist, which can be used to simulate either of these tasks individually or combined to solve the problem at hand. XPDP1-XOOPIC is a popular PIC open-source code for devices with plasma confined in the planar, cylindrical, or spherical geometry [23]. Accounting for the external circuit and the neutral gas interaction is possible in 2D and 3D. COMSOL is a commercial package that can be used to simulate plasma in a given ion thruster geometry along with the neutral gas flow. Traditionally codes such as IGUN [24], IBSimu [25], and KOBRA3D [26] are used to design ion extraction systems and beamlet formations.

The newly designed dsmcFOAM + software can be used in combination with these packages for the plume simulation of ion thrusters [27].

Conclusions

The successful development of physically accurate numerical methods for simulating the gas and plasma flows in electric propulsion thrusters has the potential to significantly improve the design process of these devices. This goal has been partially realized with numerical simulations playing an increasing role in the design, particularly of ion thrusters and Hall thrusters. In terms of predicting thruster performance, accuracy of the existing numerical methods ranges from within 5% for resisto-jets and ion thrusters, to within 10- 20% for arcjets and Hall thrusters [4].

There are two main directions for future work to continue to improve the numerical modelling of electric thrusters. First, the numerical methods themselves must be improved in terms of their physical accuracy and their computational speed. The second main direction for improvement in the simulations involves the more accurate determination of physical parameters that are required by the numerical formulations. Examples of such information include sputter yields for new grid materials that might be used in gridded ion thrusters, secondary electron coefficients of wall materials used in Hall thrusters, electron mobility and other transport coefficients, and cross sections for new propellant species. These data are most likely to be obtained computationally due to the development of molecular dynamics simulation methods, and the expense and difficulty of performing laboratory experiments to measure such data.

Particle-In-Cell models have proven to be an effective tool for the simulation of plasma thrusters. However, until today, it is not possible touse them for full predictive modelling, since all relevant time and space scales have to be resolved, namely, the electron plasma frequency and Debye length, respectively. This leads to large domain sizes and hence high computational demands. These practical run time limits are a problem and code optimization is necessary.

Contributions of authors: conceptualization, methodology – **Leonid Bazyma;** formulation of tasks, analysis **– Sai Vigness Ramasamy, Leonid Bazyma;** analysis of results, visualization **– Sai Vigness Ramasamy;** writing – original draft preparation **– Sai Vigness Ramasamy**; writing – review and editing **– Leonid Bazyma.**

All the authors have read and agreed to the published version of the manuscript.

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ПРОГРЕС У ЧИСЕЛЬНОМУ МОДЕЛЮВАННІ ЕЛЕКТРОРЕАКТИВНИХ РУШІЇВ

Саі Вігнесс Рамасамі, Л. О. Базима

Електроракетні двигуни були розроблені з початку 1960-х років, і їх використання на борту супутників, орбітальних платформ і міжпланетних зондів значно зросло в 21 столітті. Необхідність детального розуміння робочої фізики та більш точної оцінки продуктивності для створення інноваційних конструкцій стимулювала розробку великої кількості кодів чисельного моделювання. Вибір методу моделювання конкретного двигуна має залежати від фізичних характеристик потоку в пристрої та рівня точності, необхідного від моделювання. Існує широкий діапазон умов для різних типів двигунів. Це означає, що для кожного двигуна необхідно розробити різні методи та комп'ютерні коди. Успішна розробка фізично точних чисельних методів моделювання потоків газу та плазми в електроракетних двигунах має потенціал для значного вдосконалення процесу проектування цих пристроїв. Останніми роками чисельне моделювання дедалі більше сприяло базовому розумінню та інженерній оптимізації електроракетних двигунів. Це пов'язано з декількома одночасними внесками: еволюцією комп'ютерного обладнання, яке дозволило представляти багатовимірні геометрії та багатомасштабні явища; впровадження нових складних алгоритмів і чисельних засобів діагностики; а також доступність нових даних про зіткнення та поверхневу взаємодію. Існують два основних напрямки майбутньої роботи щодо продовження вдосконалення чисельного моделювання електроракетних двигунів. По-перше, самі чисельні методи повинні бути вдосконалені з точки зору їхньої фізичної точності та швидкості обчислень. Другий основний напрямок удосконалення моделювання передбачає більш точне визначення фізичних параметрів, які вимагаються чисельними формулюваннями. У цій статті описано зусилля з розробки моделей різних концепцій електричних силових установок, від перших спроб на початку 90-х до останніх складних багатовимірних симуляцій.

Ключові слова*:* електроракетні двигуни; плазмові двигуни; чисельні методи; чисельне моделювання.

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