Physics of Electric Propulsion

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INTRODUCTION

Electric propulsion (EP). [1], [2] is a technology widely employed for maneuvering spacecraft on orbit. The defining characteristic of these devices is their use of external electrical power—typically in the form of solar—to accelerate and expel propellant to high speed (> 10 km/s). This process is often facilitated by converting a neutral propellant into an ionized state and then employing a combination of electric and magnetic fields to direct it. Common examples of EP include gridded ion engines, Hall effect thrusters, arc/resistojets, magnetoplasmadynamic thrusters, electrosprays, pulsed inductive concepts, and magnetic nozzles. The capability to achieve high exhaust speed in EP translates to higher specific impulse (> 1000 s) than conventional chemical rockets, which in turn enables higher propellant efficiency. Indeed, select EP devices can perform comparable in-space maneuvers to more traditional chemical rockets with an order of magnitude less propellant. This yields substantial savings in launch mass and cost. On the other hand, the gains in fuel economy for EP systems is presently traded against lower thrust due to limitations in the available input power on orbit. This in turn leads to less acceleration than chemical rockets. EP maneuvers thus can require days or months of continuous thrusting.

Despite the penalty in transit time, the advantages in lower propellant mass requirements have led to a growing use of EP technology for in-space applications. While earlier missions were limited to station-keeping, increasingly EP systems have been employed for drag make-up in low-Earth orbit, orbit raising and transfer, and deep space exploration [3]. There are currently thousands of operational systems in orbit with thousands of more launches planned in the near term.

The operational success of EP has led to new initiatives to further explore the potential of this technology. For example, next-generation missions for robotic exploration will require longer lifetime, improved stability, and greater throttleabilty. Non-conventional propellants (in lieu of the more conventional noble gases) such as metals, liquids, and complex molecules are also attractive for applications ranging from air-breathing EP engines in the upper atmosphere to *in situ* resource utilization. In parallel, the increasing use of small satellites is fueling a need for EP technology at lower power levels than systems currently flown. There are also calls to develop EP devices with orders of magnitude higher power than the state of the art to provide the higher thrust levels necessary for crewed exploration. Relatedly, increasing the power and required throughput of EP systems invites new questions about how representative ground-based tests are of on-orbit behavior.

Research into the fundamental physics of EP devices is critical to addressing many of these outstanding challenges to advancing the start of the art in this field. Indeed, EP devices are highly complex systems, governed by processes that span orders of magnitude in time and lengthscales (c.f.[4]) As a consequence, although there are EP systems that are operationally flown, several questions about their operation remain—particularly when these systems are extended to new operating regimes. Similarly, while there are less mature EP technologies that offer potentially transformative capabilities, aspects of their behavior remain poorly understood and characterized.

This special issue, which focuses on the physics of EP, is timely in light of the growing number of applications of this technology coupled with several emerging challenges for the field. The topics addressed in this collection illustrate not only the broad range of research areas of interest but also the increasing sophistication of numerical and experimental tools being brought to bear on these problems. In this introductory note, we briefly highlight the common themes from this collection.

Physics of Hall effect thrusters

The Hall effect thruster is the mostly widely flown form of EP. This device consists of an annular geometry in which crossed electric and magnetic fields accelerate a partially magnetized plasma to high speeds. These devices offer a combination of high specific impulse (1000-3000 s) with moderate thrust density. It is in part due to their heritage and potential for extensibility to new operating regimes of interest (e.g., new powers and lifetimes), that these thrusters have been the subject of a wide range of past and ongoing investigations. The articles in this collection highlight several outstanding physics-based questions related to these devices. Key topics include the nature and impact of large scale ionization-driven plasma oscillations [6]–[11], onset of self-organized, gradient-driven modes [12], microinstabilities and their impact on particle transport [13]–[15], evaluation of lifetime and the processes that govern lifetime [15]–[17], operation on alternative propellants [18], [19], methods for improving testing fidelity [20], the role of variations in magnetic field configuration and thruster geometry on performance [21]–[24], and development of novel diagnostics tools to assess the plasma state [10], [25], [26].

Physics of hollow cathodes

The hollow cathode is the most commonly employed electron source for two widely known types of EP, Hall effect thrusters and gridded ion engines. These cathodes are typically characterized by a central bore lined with an internal thermionically emitting surface. A working gas passes through this tube where it is ionized and then expelled downstream. While the hollow cathode has been in use for over a half century, there remain several open questions related to both the internal physics as well as the downstream plume. Among these, the articles in this special collection address the evolving chemistry of the thermionic inserts [28], [29], models for the internal plasma physics in the central bore [30], the presence of microinstabilities in the cathode plume [31], the existence of non-classical electron transport and the factors that impact this transport [32], [33], the role of test facility configuration on operation [34], and the implementation of novel diagnostic methods to characterize the internal and external plasma processes in these devices [35], [36].

Physics of electrospray thrusters

While electrospray thrusters conceptually are one of the oldest types of EP devices, this technology has been the focus of renewed and extensive research in the past fifteen years. Unlike plasma-based forms for EP, these devices are characterized by microscale emitters typically in the form of cones, pyramids, or ridges, that support a conducting liquid propellant. An electric field is applied to these emitters with sufficient strength to extract charged particles directly from the liquid. These are then accelerated to high speed through electrostatic force. The range of topics covered in this special collection are broadly representative of the key physics-based and engineering challenges in the advancement of electrospray thruster technology. For example, developing physics-based, end-to-end models that encompass the current emission of a single emitter as well as the evolution of the downstream charge plume is particularly challenging given the several orders of magnitude in lengthscale involved with each stage [37]–[40]. Similarly, there are potential issues with testing these devices with high fidelity as there is evidence to suggest the test environment can impact thruster operation [41], [42]. The distribution of the downstream plume is also critical for lifetime assessment and spacecraft integration [43].

Other topics in EP

Several contributions in the special issue focus on research into the physics of less mature or novel EP technologies that may offer highly enabling capabilities. Topics include an analysis of the efficiency [44] and thermal properties [45] of the magnetoplasmadynamic thruster, a type of electromagnetic accelerator that supports operation at extremely high power density; numerical and experimental analyses of novel concepts for plasma acceleration that may provide improvements in thrust density, specific impulse, or lifetime [46]–[50]; and experimental and numerical treatments of electrodeless concepts based on radio frequency waves that enable longer lifetime as well as operation on alternative propellants [51]–[56]. In addition to examining the physics of novel concepts for propulsion, several contributions in this issue outline novel diagnostic methods for characterizing the plasma properties in a wide range of EP devices [10], [25], [26], [31], [35], [36], [57]. Key considerations include the capability to measure these properties non-invasively and to achieve higher instrument resolution for energy and charge states.

CONCLUSIONS

In closing, electric propulsion is a highly enabling technology for the commercialization and exploration of space. Research into the physics of EP devices in turn has a critical role in furthering the capabilities of these systems. This special collection highlights several ongoing efforts to address key outstanding questions related to the physics of both established EP devices as well as novel concepts. Given the broad range of plasma conditions addressed by the articles in this issue, it is our hope that this collection will serve not only as a resource for members of the EP community but also will be of interest to researchers in the wider field of low-temperature plasma physics.

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