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Advanced Mesh Grid Geometries for EAD Thrusters: An Experimental Approach

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Abstract. This work presents an experimental study of ion thrusters for atmospheric flight, with a focus on the research for an optimal configuration of the collectors. Based on a recent study that demonstrated the advantages of EHD grids as a replacement for classical airfoil shaped ion collectors, test campaigns were carried out with the aim of finding configurations that would further improve their performance in terms of thrust density and thrust-to-power ratio. The main topic of the work is the investigation on the benefits of using a double level of grid collectors, representing the proof of concept for the final examined configuration, which involves the use of metal blade collectors, replacing the classic wires. This latest development could in fact be the ideal solution for practical applications, given the constructional and operational advantages.

Introduction

Ion propulsion is a novel technology for atmospheric applications [1,2], it exploits a high voltage difference between the electrodes to ionize the air and accelerate the ions through the resulting electric field, thus creating thrust through the collision with neutral molecules. The simplest form of EAD thrusters employs the corona effect [3] as the ionization source, enabled thanks to the different geometry of the two electrodes. The emitting electrode must have a high electric field in its surroundings to ionize the air, which is achieved by employing physically small conductive objects as emitters. These should possess regions with a small curvature radius where intense electric field gradients can develop, therefore overcoming the breakdown electric field for air and generating ions. Notable examples include wires with a diameter in the range of tens of micrometers, pins, blades, or sawtooth-shaped electrodes. The collecting electrode should instead inhibit ionization in its surrounding region, which is typically obtained using larger objects as collectors, such as plates [4], large diameter cylinders [5] or metallic airfoils [6]. What is necessary for an efficient ion thruster is the asymmetry of the electric field between the electrodes, which may also be achieved employing the same physical objects for emitters and collectors but in a different spatial density and therefore employing the shielding effect, thus enabling the concept of grid collectors, which may employ the same wires as the emitting electrode. As a result of a recent study that demonstrated the great performance advantages of wire grids as a replacement for classical airfoil-shaped ion collectors, previously established as the canonical geometry for atmospheric ion thrusters, comprehensive test campaigns were carried out with the aim of finding configurations that would further improve their performance in terms of thrust density and thrust-to-power ratio, the two main parameters that characterize the performance of an EAD thruster [7], the first representing an index of compactness and the second one of efficiency. This endeavor has been promoted by the need of minimizing the thruster's drag coefficient, which severely limits the maximum operating velocity of an ion thruster [8], defined as the maximum velocity for which an ion thruster generates positive net thrust, a crucial parameter for any future practical application of this technology, such as airships [9]. Two possible configurations are here presented to limit the aerodynamic drag generated by a single-level mesh grid collector. A first solution would be using a double level of collectors with the second row in the wake of the first one, therefore reducing the overall drag coefficient. This approach represents the electrical analogue as proof of concept for the final examined configuration, which involves the use of metal blade collectors, replacing the classical wires. This latest development aims to become the ideal solution for practical applications, given the construction and operational advantages paired with the performance improvements of the novel grid collectors, extended to higher velocities. The main geometrical parameter of interest is the grid density, which, for a single-level grid collectors corresponds to the aerodynamic blockage ratio of the grid itself. Previous studies have indicated that a minimum grid density is necessary for the thruster to function efficiently, after which a plateau for all main performance parameters is found, albeit with an increasing drag created by the collectors, which mainly hampers performance in non-zero velocity conditions. The effective grid density of double-level collectors was found to be the sum of its two constitutive levels, thereby allowing a lower blockage ratio and drag for the same grid density and performance, thus becoming promising for practical applications. Blade collectors would be a further aerodynamic improvement, as they substitute the cylindrical wires with ultra-thin metal strips. An overall three-fold thrust increase compared to the baseline configuration found in literature is possible with these types of collectors.

Theoretical aspects

In order to facilitate a direct comparison of the performance of the tested configurations with each other and with other types of thrusters, it is possible to introduce dimensionless coefficients, which remove the dependence of the results on the characteristic dimensions and test voltages. The following three coefficients, obtained in a parallel study currently in its publication process [10], will be utilized:

- Thrust density coefficient (C_{TA}).

$$C_{TA} = \frac{T\chi d}{A\epsilon_0 p V_c \Delta V} \tag{1}$$

- Thrust-to-power ratio coefficient (C_{TP}).

$$C_{TP} = \frac{9T\chi\mu_0 V_c}{8P_c p^2 d^2} \tag{2}$$

- Corona current coefficient (C_c)

$$C_c = \frac{I_c}{\frac{9}{8}\epsilon_0\mu_0\frac{V_c\Delta V}{d^3}} \tag{3}$$

In order to provide a description of the behavior of EAD grid thrusters, it is necessary to introduce parameters that are specific to these systems, related to the geometry of the configurations under consideration. In particular, since both the distance between the wires and their diameter may vary between tests, the grid density parameter ρ_c has been introduced, following the same definition as in [11]. For tests involving double-level collectors, the calculation of ρ_c is derived as the sum of the contributions of the individual grids ρ_{c1} and ρ_{c2}, which are separated by a distance *h*, regardless of the orientation of the wires at the two levels, such that:

$$\rho_c = \rho_{c1} + \rho_{c2} \tag{4}$$

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It has to be pointed out that, in the case of the double-level configuration, the parameter ρ_c defined above has a strictly electrical significance and does not reflect the total blockage ratio of the two collector grids. Previous experimental campaigns have demonstrated that ρ_e and ρ_c are the geometric parameters that most influence the performance of grid ion thrusters. The subsequent results will present the evolution of the dimensionless performance parameters of the thruster as ρ_e and ρ_c vary. For blade collectors the mesh density parameter is again equivalent to the blockage ratio, such that:

$$\rho_c = \frac{t}{S_b} \quad (5)$$

Where t is the blades thickness, here fixed at 0.1 mm and S_b is the spacing between the parallel blades.

Experimental setup

Different custom setups have been designed and built to accommodate the three different configurations (Fig. 1 shows the double-level collectors setup as an example) to be compared in this work, all retaining the same Power Supply Unit (PSU) and nominal geometrical parameters such as frontal area and inter-electrodes gap d (defined as the distance between the emitters plane and the closest point of the collectors, thus being applicable for all configurations). The setup is then mounted on a high precision scale to read the thrust produced T, obtained subtracting the different loads on the balance with the thruster powered on and off. At the same time the corona voltage V_c and corona current I_c are acquired through a voltage divider in parallel with the thruster and a shunt resistor in series with the collector on the ground return path respectively. More details about the setup may be found in [11], which shares the same equipment and measurement techniques.

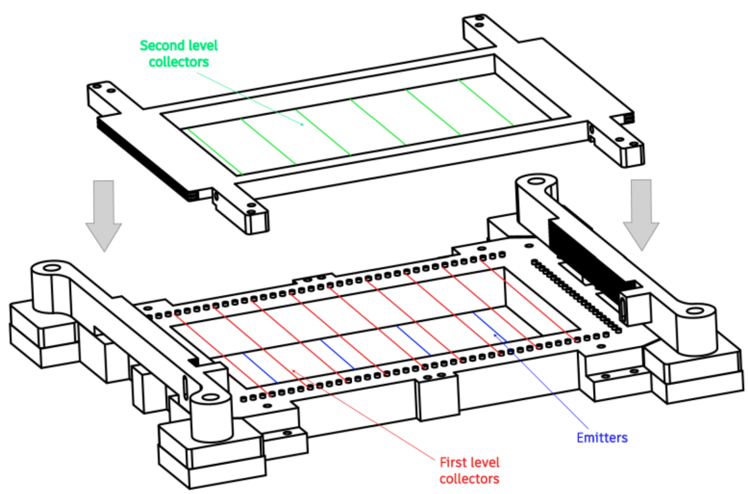

Figure 1: Double-level collectors setup.

Results

In this section the three configurations, namely the original grid collector thruster and the two novel configurations here presented (double-level grid collectors and blade collectors) are compared employing the different performance coefficients at varying grid density levels (ρ_c, defined specifically for each configuration). All the configurations show the typical behavior of mesh grid thrusters, showing a low performance and high power consumption at low grid densities and then improving and finally reaching a plateau at higher grid densities, representing the region where the thruster works as intended with no reverse corona forming, ionization happening exclusively at the emitters and the collectors functioning as an equipotential plate. The generated thrust actually decreases at very high mesh densities due to the increasing aerodynamic drag generated by the increasingly more numerous collectors. The regression line of all the points inside the plateau of a given configuration are representative of the drag coefficient of that configuration, with the double-level collectors (especially when the second level is exactly in the wake of the first one) and the blade collectors showing a lower drag coefficient compared to the original single-level grid thruster, thus being better suited for high-velocity applications, while retaining the same or even slightly superior static performance. In particular, Fig. 2 shows how the thrust coefficient varies for the different configurations, comparing the novel geometries at different distances h for the double-level collectors setup and different blade chords c for the blade collectors with the classic single-level grid collector design found in [11], displayed at varying emitter densities ρ_e. It has been confirmed that all configurations require a minimum mesh density in order to achieve optimum performance levels, this being confirmed also for the other performance indicators, as in Fig. 3 for the thrust-to-power coefficient and in Fig. 4 for the corona current coefficient, reiterating the presence of adverse reverse corona effects at insufficient grid densities. Outliers in the double-level collectors setup are relative to configurations with increasing drag, i.e. when the second level does not lie in the wake of the first one.

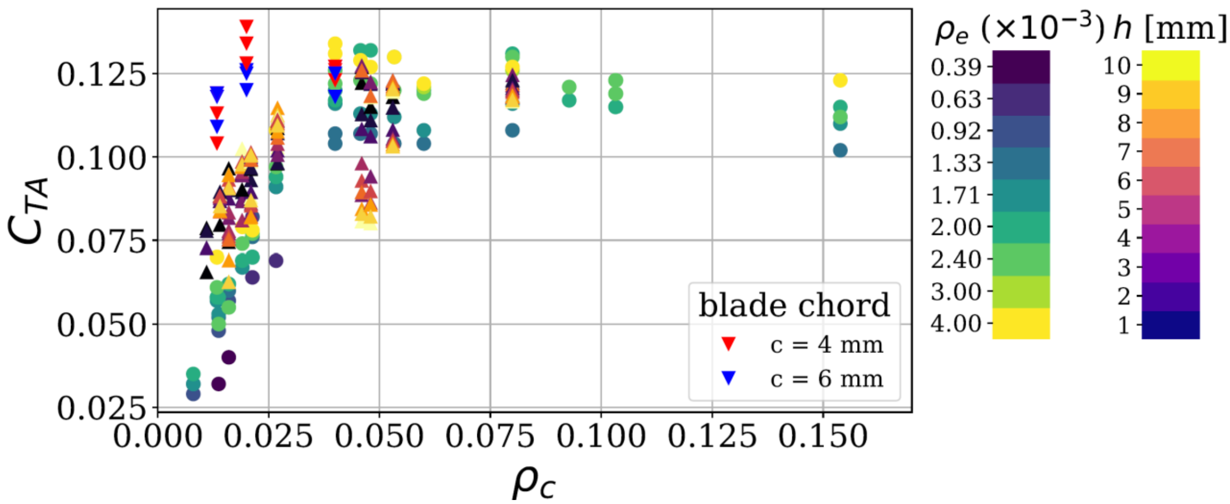

Figure 2: C_{TA} for different configurations at varying grid density (ρ_c).

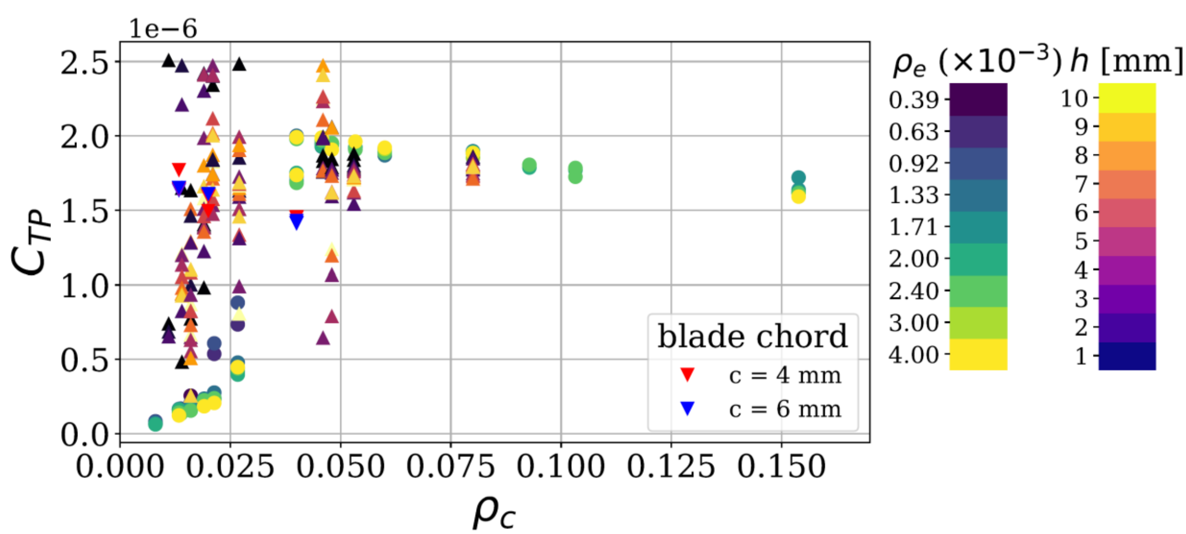

Figure 3: C_{TP} for different configurations at varying grid density (ρ_c).

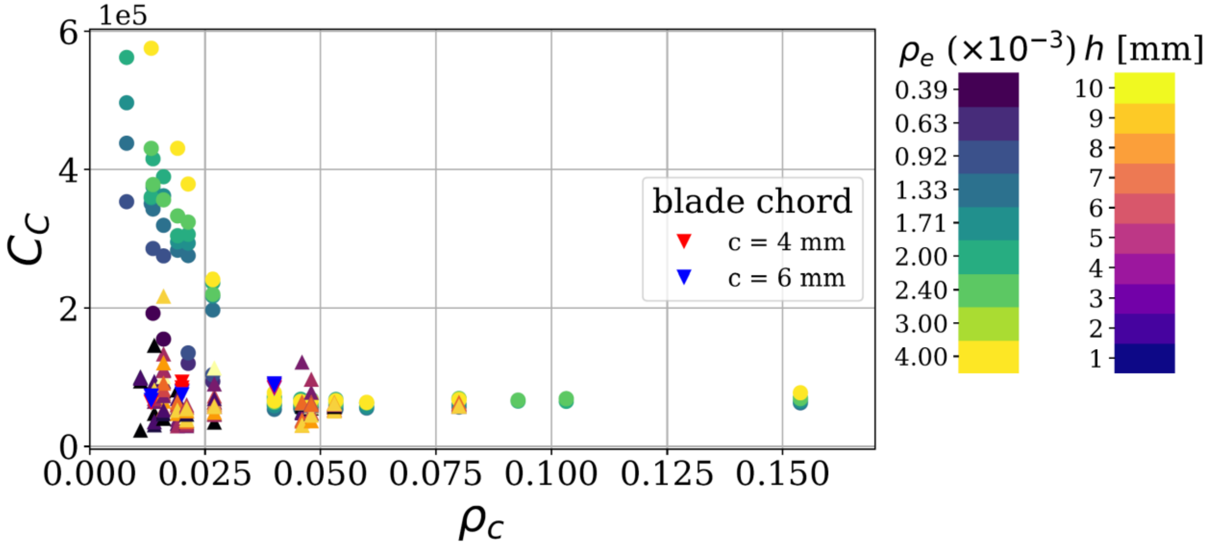

Figure 4: C_c for different configurations at varying grid density (ρ_c).

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