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Operational Envelope of an EAD Thruster Under Varying Pressure and Humidity

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Abstract. A wire-to-grid electroaerodynamic (EAD) thruster is experimentally investigated under varying environmental conditions. Experiments are conducted in a low-pressure chamber to assess the influence of ambient pressure p and relative humidity RH on device performance. The key performance metrics considered are corona current i_c, the thrust density T/A, and the thrust-to-power ratio T/P. Experimental results indicate that decreasing pressure negatively affects all performance indicators while reducing the ignition threshold. Additionally, both current consumption and ignition voltage exhibit a parabolic dependence on relative humidity.

1. Introduction

Electroaerodynamic (EAD) thrusters are emerging as a promising technology for aerospace applications, particularly for lighter-than-air (LTA) vehicles such as airships [1]. These air-breathing devices offer several advantages, including zero emissions, low acoustic noise and the absence of moving parts. Although various EAD thruster concepts exist, they all rely on a common operating principle: two electrodes supplied with a high DC voltage generate a sufficiently asymmetric electric field such that air is ionized at the emitter and drifts toward the collector. The resulting interaction between ions and neutral molecules produces an ionic wind and generates thrust [2]. The performance of EAD thrusters is influenced by environmental conditions such as temperature, pressure and humidity, which can significantly alter their operational characteristics [3,4,5]. In this work, the performance of a gridded EAD thruster developed at Politecnico di Milano within the framework of the EU-funded I-PROP project is experimentally investigated as a function of two environmental variables, namely ambient pressure p and humidity.

2. Experimental Setup

The experimental campaign was conducted in a grounded cylindrical steel chamber capable of sustaining pressures down to a few pascals. The desired pressure level was achieved using a single-stage rotary vane pump connected to a lateral port. The corona voltage was monitored using a voltage divider connected in parallel with the thruster, while the corona current i_c was measured using a contactless probe. Thrust was measured with a load cell and humidity was determined from the output of a dew-point temperature sensor. The water vapor content inside the chamber was reduced using silica gel and increased through controlled water evaporation.

Low-voltage connections (load cell, dew-point sensor, and ground lines) were routed through a feedthrough and EMI-shielded to prevent signal degradation. The voltage supplied by the 0–30 kV DC power supply was delivered to the thruster through a dedicated high-voltage feedthrough. A ballast resistor with resistance $R_b = 1\ \mathrm{M\Omega}$ was connected in series for safety purposes.

Analog outputs were acquired using a data acquisition system at a sampling frequency $f_s = 25$ kHz over an observation time $T_{obs} = 2$ s, and subsequently processed in Python. A schematic of the setup is presented in Figure 1. Further details about the instrumentation can be found in [6].

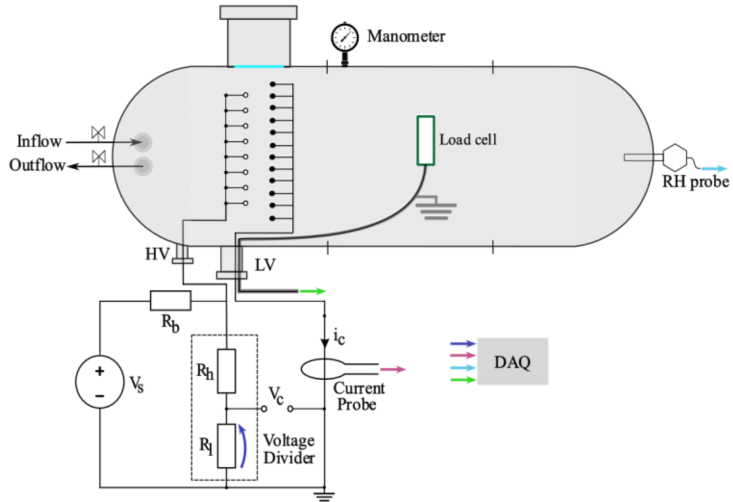

Figure 1 — Schematic diagram of the test facility. Colored arrows indicate acquired signals.

A dedicated test rig was designed to house the wire-to-grid thruster inside the chamber. The adopted thruster configuration replicates the one presented in [6]. The load cell was installed vertically and connected to the test rig through a single-point attachment, while its base was secured to a grounded iron platform. A counterbalancing arm was added to offset the cantilever moment and prevent overload. A schematic view of the complete test rig is shown in Figure 2.

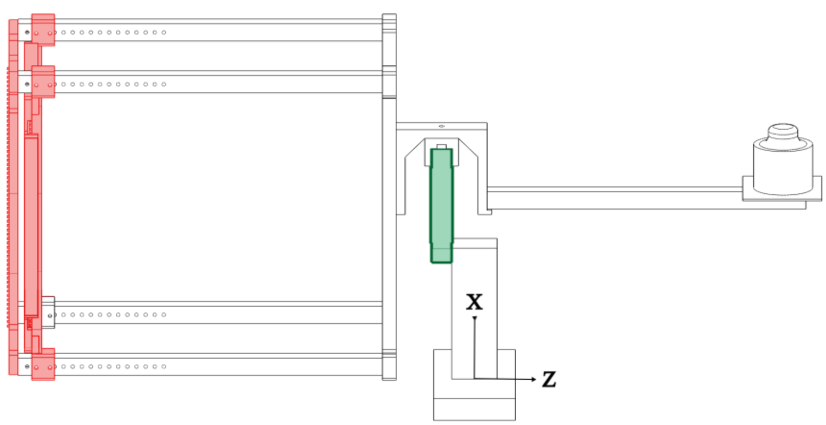

Figure 2 — Complete test rig: the EAD thruster is highlighted in red, while the load cell is depicted in green.

The tested pressure levels ranged from 101 kPa down to 20 kPa. Absolute humidity values between 5 and 20 g/m^3 were achieved, corresponding to relative humidity levels of approximately 20–80%. Temperature could not be actively controlled during the campaign but was continuously monitored and showed no significant variation; it was therefore treated as constant. Thrust, voltage

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and current measurements were obtained as the difference between the thruster-on and thruster-off signals. Multiple acquisitions were averaged to obtain the final measurement values. Measurement uncertainty was propagated using the root-sum-square method.

3. Results

The outcomes of the experimental campaign are reported in three parts: the ignition voltage V_{ign}, which sets the lower limit of the thruster's electrical envelope, is addressed first; second, the influence of the tested variables on the corona current $i_c$is examined; finally, the performance is evaluated through the thrust density T/A, which is an index of thruster compactness, and the thrust-to-power ratio T/P, representative of efficiency.

Ignition Voltage

The ignition voltage is found to be a monotonic function of pressure, as shown in Figure 3. Experimental data are interpolated using a model function resembling Peek's law.

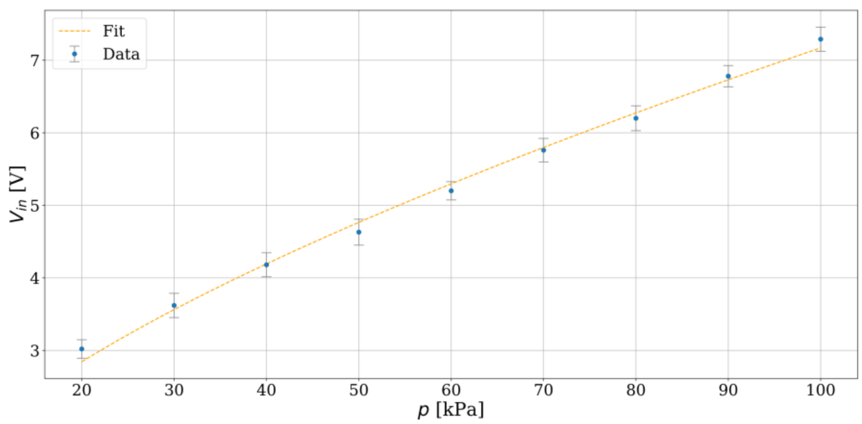

Figure 3 — V_{ign} as a function of pressure p.

The effect of humidity on the ignition voltage is shown in Figure 4. Experimental data are well fitted by a parabolic trend, in agreement with previous findings reported in the literature [7].

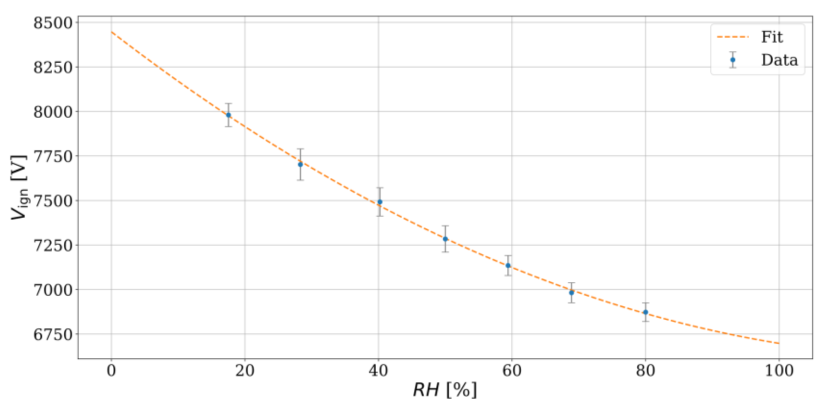

Figure 4 — V_{ign} as a function of humidity.

Corona Current

The corona current increases as pressure decreases, as highlighted in Figure 5, due to the dependence of ion mobility on pressure [8]. The corona current exhibits a parabolic dependence on humidity, as shown in Figure 6 for three different voltage levels. This behavior is attributed to the combined effects of variations in both ignition voltage and ion mobility.

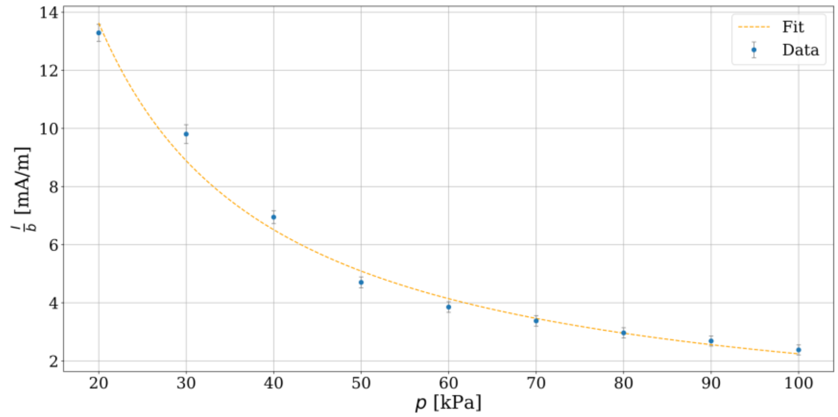

Figure 5 — Corona current i_c as a function of pressure p.

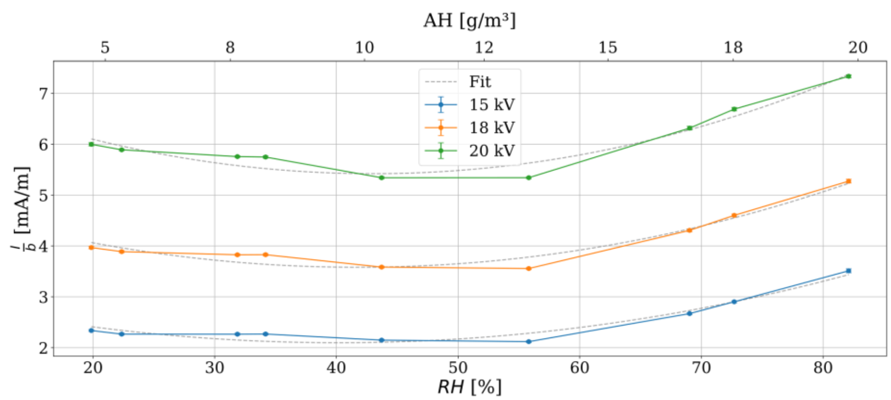

Figure 6 — Corona current i_c as a function of relative humidity RH and absolute humidity AH.

Thrust Density and Thrust-to-Power Ratio

Thrust density exhibits a linear dependence on pressure as shown in Figure 7, resulting from the dependence of the collision frequency νon the gas density ρ. As the gas becomes rarefied, the probability of ionizing collisions decreases, despite the greater ion availability associated with lower ignition voltages, which drives a reduction in space charge density. In other words, although ionization is easier to initiate at lower pressures, the number of effective ionizing collisions decreases, thereby reducing the momentum transfer which is the main mechanism of thrust generation. The corona current, as well as the corona power P, decreases proportionally to $1/p$; the combination of this dependence with the scaling of the generated thrust explains the behavior of T/P, which tends to zero as $p \rightarrow 0$, as shown in Figure 8. This is expected, since fewer neutral particles are available at lower pressure levels, resulting in null thrust production regardless of the consumed power. The dependence of thrust density and thrust-to-power ratio on humidity does not exhibit any significant variation, as the measurements acquired at different humidity levels fall within the uncertainty bands.

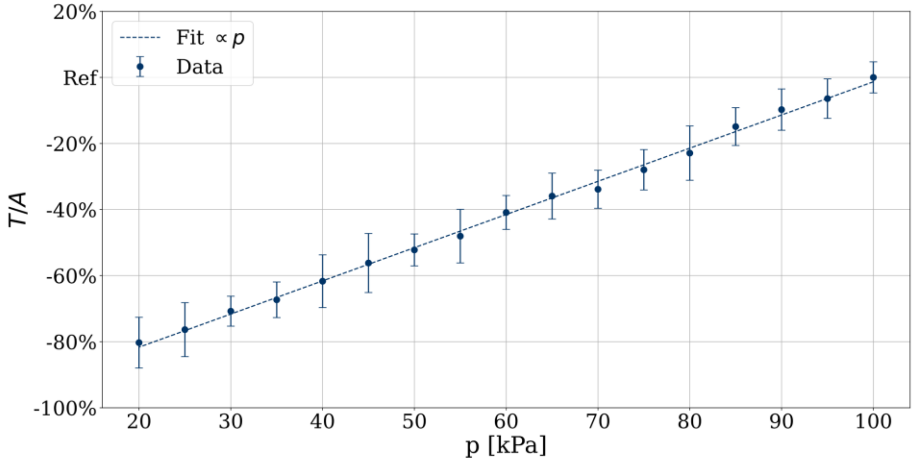

Figure 7 — Thrust density T/A as a function of pressure p.

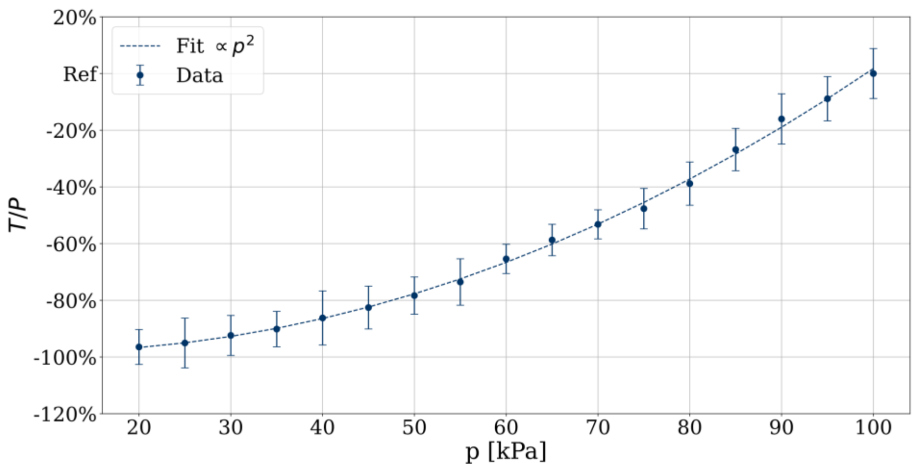

Figure 8 — Thrust-to-power ratio T/P as a function of pressure p.

4. Conclusions

This study experimentally investigates the performance of electroaerodynamic thrusters under varying ambient pressure $p$and relative humidity RH. Experiments are conducted in a low-pressure chamber with controlled environmental conditions. Thrust is measured using a load cell, while corona voltage and current are obtained using a voltage divider and a contactless probe, respectively. Results show that the ignition voltage increases with both pressure and relative humidity, with variations reaching up to 25% between dry and saturated air. A reduction in pressure leads to a decrease in thrust density and thrust-to-power ratio proportional to p and p^2, respectively, while the corona current increases inversely with pressure. These trends are primarily driven by changes in ion mobility and space-charge density. Finally, the corona current is found to scale approximately with RH^2, due to the combined effects of humidity-induced variations in both ignition voltage and ion mobility.

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