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Design and Evaluation of Plasma Neutralization Techniques to Produce Hyperthermal Flows Representative of VLEO Conditions

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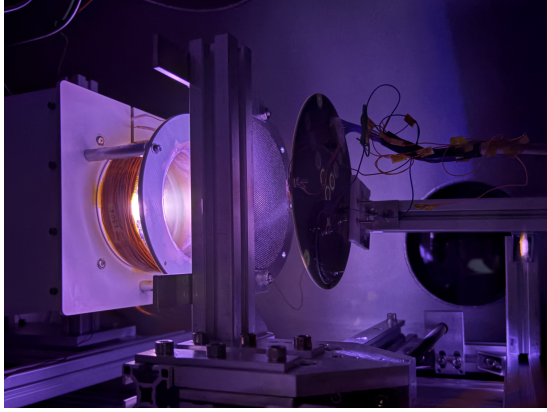
Abstract: The very low Earth orbits (VLEO) offers major advantages over more traditional low Earth orbit (LEO) altitudes in terms of spatial resolution and signal latency. However, operating at these lower altitudes implies interaction with a rarefied atmosphere dominated by atomic oxygen, at orbital velocities of the order of 8 km/s. These interactions lead to aerodynamic drag and material erosion over prolonged periods. Air-breathing electric propulsion (ABEP), is one of the most promising concepts to enable sustained operation in VLEO by collecting the residual atmosphere and using it as propellant to counteract drag forces. To support ABEP development, the von Karman Institute operates the DRAG-ON facility, which produces a fast particle flow representative of VLEO energies. The main limitation of DRAG-ON is that the particle flow is composed of ion species, whereas the orbital environment is essentially neutral. The present work therefore aims to improve the representativeness of DRAG-ON by developing and experimentally validating a practical ion neutralization strategy.

Several neutralization approaches compatible with DRAG-ON constraints are compared, and the perforated plate concept is selected as the most suitable compromise between efficiency, integration simplicity, and preservation of a globally axial flow. To evaluate the performance of this concept, an apparent neutralization efficiency metric is defined from empirical data. A series of experimental campaigns is conducted to map the influence of operating conditions and plate geometry. The results show that perforated plates can strongly reduce the transmitted ion current and achieve high apparent neutralization efficiencies, with clear trends indicating improved performance for higher aspect ratio plates. However, measurements also reveal an unexpected increase in ion energy downstream of the plate, suggesting an additional acceleration mechanism likely linked to plasma potential effects. Finally, a novel polyimide erosion experiment is performed as an indirect neutral diagnostic, providing evidence of a significant neutral contribution downstream of the neutralizer.

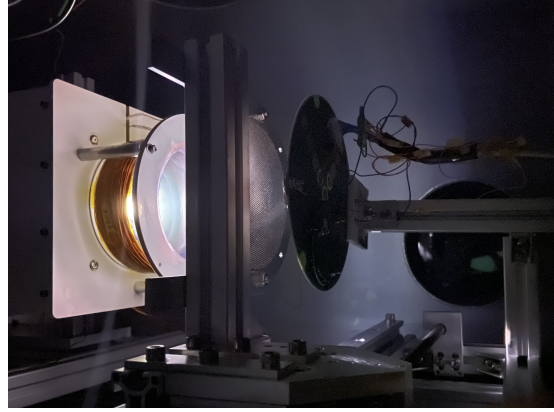
Overall, this work demonstrates that perforated plate neutralization is a promising solution to reduce the ionic fraction of the DRAG-ON particle flow. At the same time, it highlights the need for further investigation of the underlying physics and for improved neutral diagnostics to fully quantify the neutral flux properties. These developments are necessary steps toward achieving a truly VLEO-representative ground facility for ABEP intake testing and material degradation studies.

Keywords: Very low Earth orbit (VLEO) – Air-breathing electric propulsion (ABEP) – Rarefied plasma flow – Atomic oxygen (AO) – Ion neutralization – Polyimide erosion

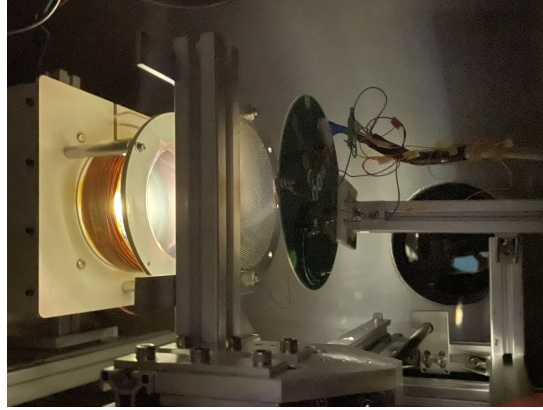
Representative illustrations:



(a) 10 sccm Ar .

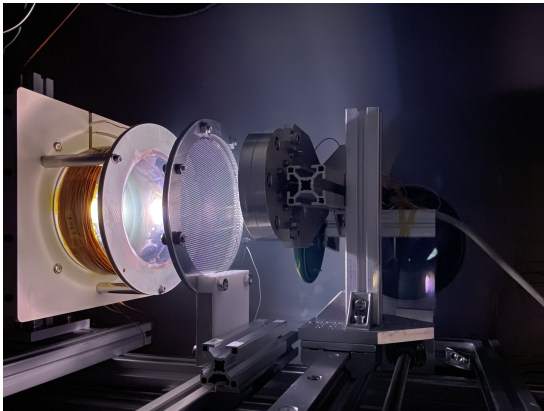


(b) 10 sccm O_2 , 3 sccm Ar .

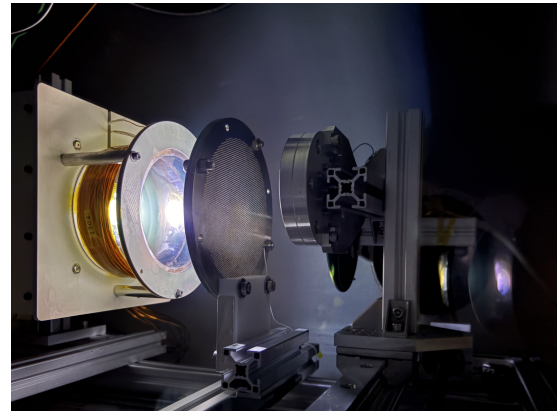


(c) 10 sccm O_2

Figure 1: Pictures of the PFG operating on different gas mixtures and flow rates during a test further described in Chapter 5.



(a) AR0.2 plate.



(b) AR7.5 plate.

Figure 2: Pictures of exposure tests. On each picture, from left to right, there is the PFG, the perforated plate and the samples. The diagnostic plate is mounted on the linear stage next to the sample holder.

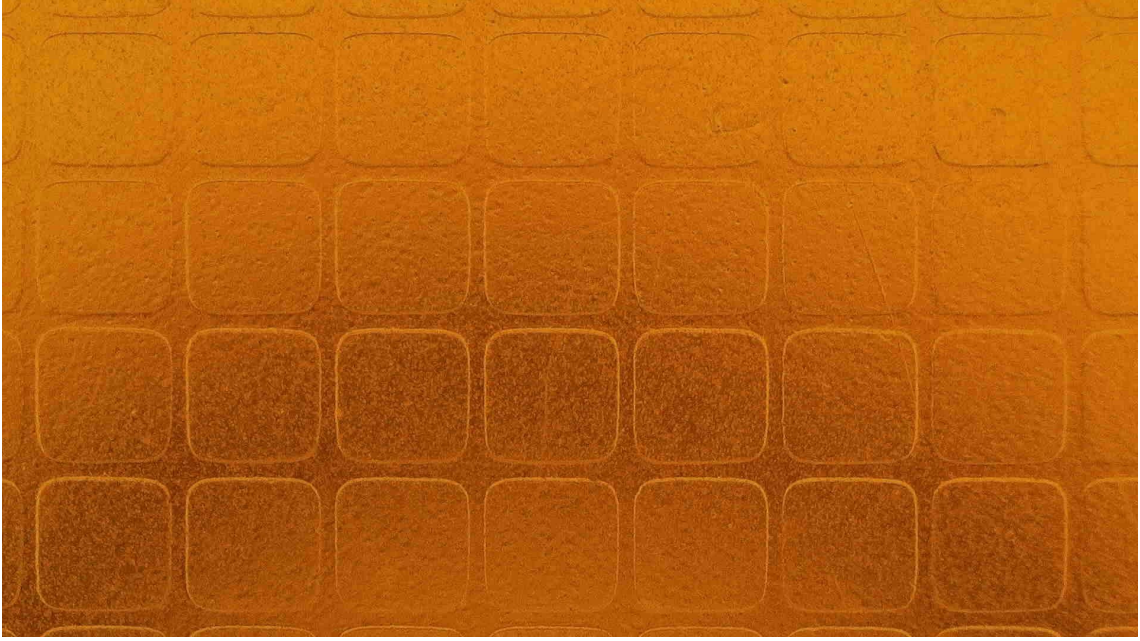


Figure 3: Microscopic view of sample n°7b exposed for 6h to the particle flow with the AR0.2 plate.

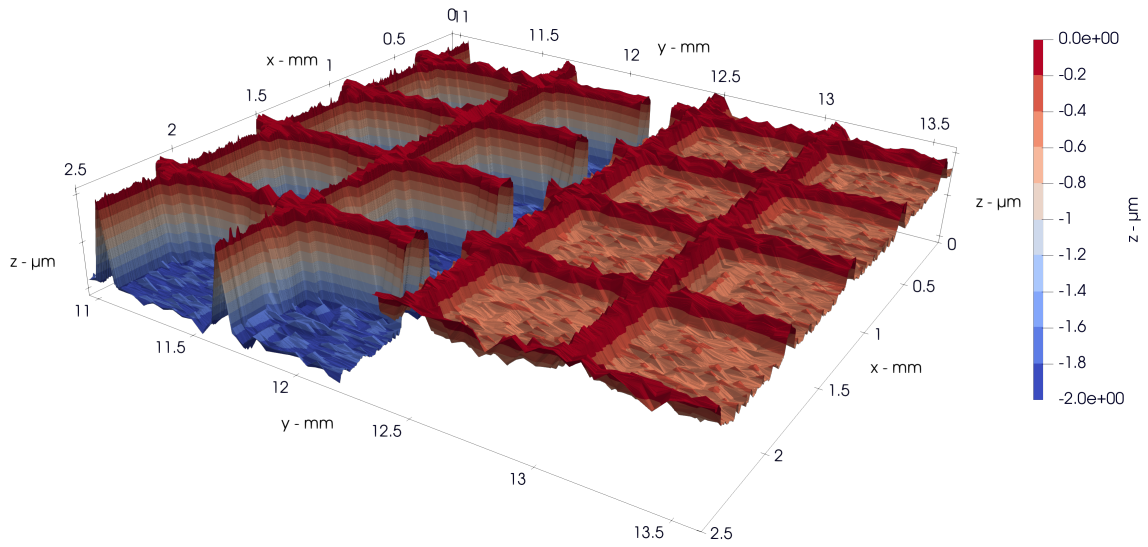


Figure 4: 3D reconstruction of the processed surfaces of sample n°1b of the AR0.2 test (rear left) and sample n°1a of the AR7.5 test (front right). The z-axis is scaled ($\times 200$) for visualization purposes.