First Experiments Towards an Atmosphere-Breathing PPT

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Pulsed plasma thruster (PPT) technology had been proposed as a possible candidate for atmosphere-breathing electric propulsion, and in this study the first experiments towards an engineering model of an atmosphere-breathing PPT are described and discussed. To conduct the transition from solid to gaseous propellant, a new feeding system was developed and assembled, and successfully tested in low-energy PPT to demonstrate the operativeness of the LabVIEW-supported setup. For continuing experiments, a higher-energy PPT is considered and the design is explained as well as the upgrade necessary for the thrust balance to cope with the new heavier and more powerful thruster. Finally, some considerations about the entire atmosphere-breathing design and conclusions are added.

Nomenclature

I = discharge current
t = time

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I. Introduction

Recent years saw an increased interest in pushing the frontiers of electric propulsion application in space in many directions: higher power[1], miniaturization[2], deep space[3], lower Earth orbits[4,5], and so on. The latter is attributed to the fact that most satellites without propulsion would quickly lose altitude due to the residual atmosphere's drag in orbits below 200-300 km of altitude. As the propellant consumption of a long-term operation would be staggeringly high, few missions are considered to remain in these low orbits and can do so only by enormous effort put in both the satellite design and the propulsion development as happened with ESA's GOCE mission[6,7]. However, even for a mission that well designed, the estimated lifetime of 20 months was only extendable due to the unforeseen weak solar impact and happened in 260 km of altitude. The scientific interest is higher for lower orbits down to 100 km of altitude as the gradients in the atmospheric properties are yet to be investigated, and the closer proximity to the Earth's surface would allow for a better observation of natural and man-made processes.

A common approach to overcome the issue of the high propellant consumption is the usage of the residual atmospheric gases as propellant in any of the many kinds of electric propulsion. In fact, the idea to do so dates back many years[8], but it was only until recently that practical work could be undertaken to verify whether the vision could become true. Although electrostatic propulsion, in the form of ion thrusters and Hall effect thrusters, were successfully operated with atmosphere-like propellants, the performance naturally dropped, but it also revealed that the power consumption increased as ionization became more energy-consuming[5]. Additionally, erosion due to the atmospheric oxygen was suspected to cause a design challenge for electrostatic propulsion. Consequently, we proposed to use either pulsed plasma thruster technology or inductively heated thruster technology as an alternative as performance drop and erosion issues seem to be of a lesser concern[5,9].

To verify the usefulness of the PPT proposal, the thruster test-bed was modified to enable feeding of gaseous propellant to the PPT, and first operational tests on air as propellant are described. As the current thruster operates at too low a discharge energy to be sufficiently efficient and to make changes in the thrust performance observable, this study also reports on the changes made to the thruster head, and the necessary changes on the thrust balance to measure the higher-energy PPT. Concluding, a plan for the near-term evaluation is included.

II. Experimental

A. Propellant Feeding

A first step to verify whether PPT technology can be used for air-breathing (or more general: atmosphere-breathing) propulsion purposes is to adapt the commonly solid-propellant thruster to a gas-fed system. While there have been several tests on gas-fed PPTs in the past, extensively at Princeton University[10], most experimental work was focused on the use of argon as propellant. A closer test to air as propellant was conducted by General Dynamics in the 1960s on nitrogen[11], but it is needless to say that PPT technology has evolved in the past decades, and performance values are likely to be different. Further, as there was no oxygen involved in the study, the effects on electrode erosion are yet unclear.

Therefore, for this study, a propellant feeding system for air was designed as is shown in Figure 1, where the propellant is fed from outside the vacuum chamber into the thruster and regulated in pressure by two valves and a sub-tank. The valves are controlled by LabVIEW to allow for a concurrent ignition of the thruster whenever the valve is opened. For ground testing, the "injection" time, i.e., the time when solenoid valve #2 is opened was set significantly longer compared to the ignition time to guarantee an ignition during presence of gaseous propellant. Valves with opening times in the order to the discharge time are a challenge, and it is expected that a multitude of ignitions during an injection is the option to be favored to reduce losses of propellant and to increase the pressure for injection.

The actual feeding system was set up as is shown in Figure 2, and tested for its operativeness. Measured changes in the tubing pressure and in the chamber pressure indicated a functional system.

For the first operational test of a PPT with air, the existing thruster model[12,13] was modified to enable operation on injected gas by feeding the propellant through the ceramic backplate. The thruster head comprises two capacitors with each 1.5 µF with a maximum voltage of 3 kV, but the nominal voltage is about 2 kV, hence yielding 6 J of discharge energy. To compare the operation on air with conventional operation, Figure 3 shows DSLR images of the discharges when using air, and PTFE respectively.

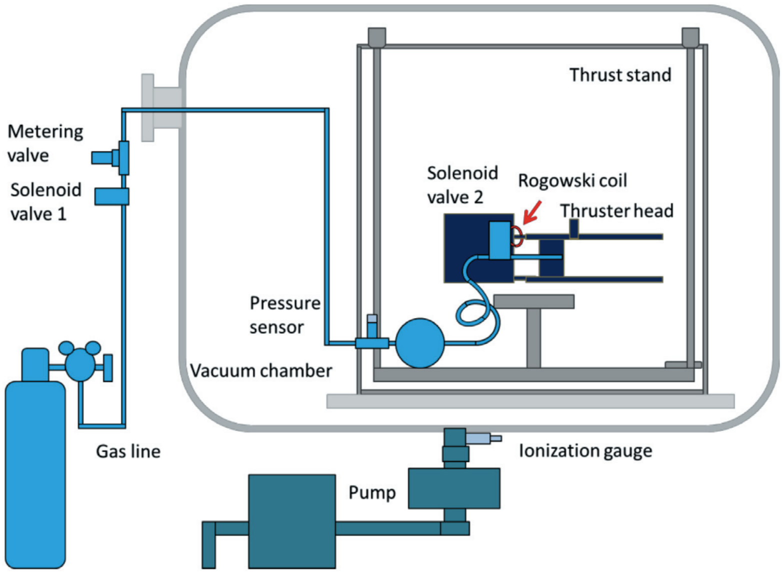
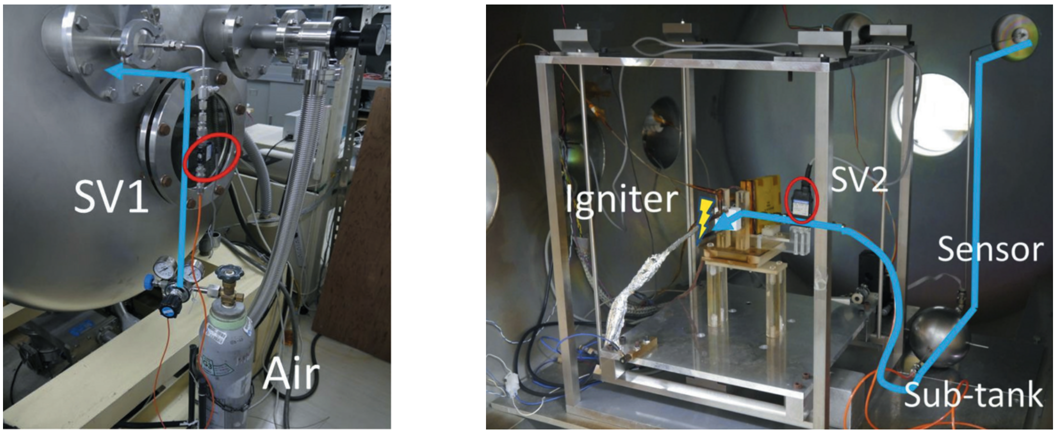


Figure 1. Schematic of the feeding system for gaseous propellant.



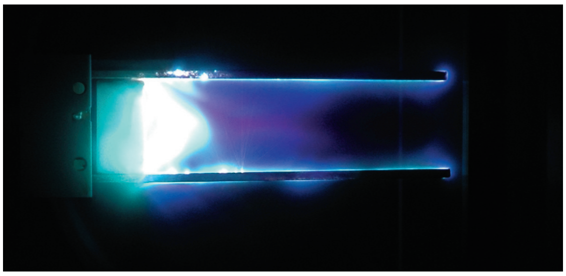
(a) Outer part

(b) Inner part

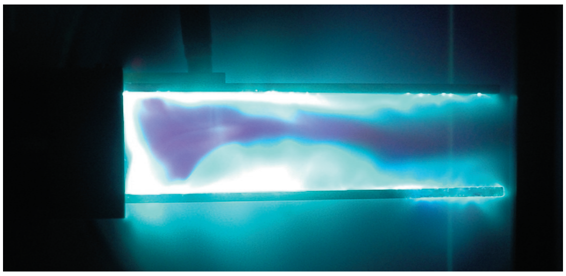
Figure 2. Experimental setup of gaseous propellant feeding.

From the images, one can conclude that the discharge is altered by the presence of gas, a fact that is supported when looking at the current profiles of the air-breathing PPT for the case of an ignition-only discharge (VAT-like) and the case of a concurrent ignition and injection of air propellant as plotted in Figure 4.

The profiles indicate that the presence of the air propellant affects resistance and inductance of the circuit, and, thus, the gas participates in the discharge process. Note that no increased erosion as a result of present oxygen was observed on the electrodes after a few thousand discharges. It became clear during the design and operation process that a higher discharge energy would be desirable to benefit more from the electromagnetic acceleration, and to exclude further the possibility of a vacuum discharge as the main driving mechanism.



(a) Operation with PTFE



(b) Operation with air

Figure 3. Images of discharges with different propellants.

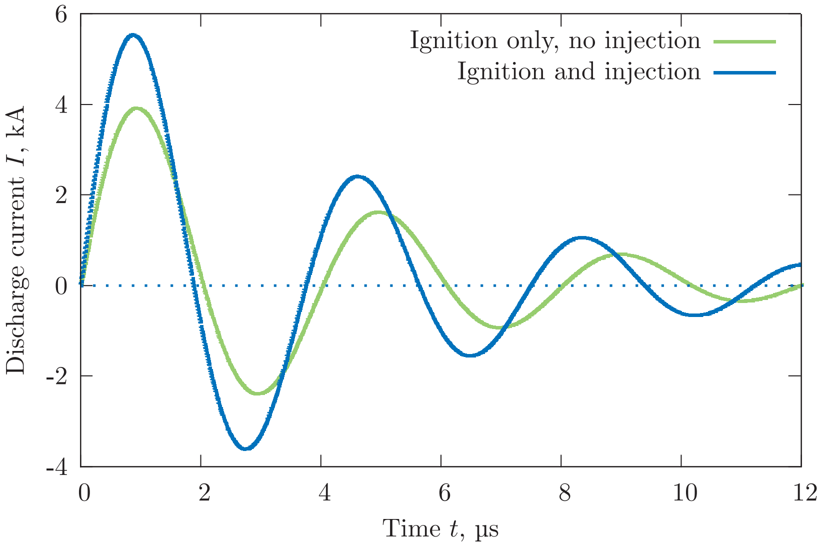


Figure 4. Current profiles of PPT discharge with and without injection of propellant (U = 2100 V).

B. Thruster Head

As mentioned in the previous section, the current standard PPT is a low-energy thruster with about 6 J of discharge energy[12]. Additionally, the inductance and resistance are not yet well balanced to offer a damped oscillation of the discharge (see Figure 4), usually seen as a criterion for eventual thrust performance[14,15]. In the current model, this can be mostly attributed to the capacitors, which have a high internal inductance.

For an optimization of the circuit, a new block capacitor was acquired with a capacitance of 15 µF and a rated voltage of 2.5 kV, thus offering up to 47 J of discharge energy, which is in the same order of magnitude as ADD SIMP-LEX (68 J)[16]. However, the capacitor comes in a 1.4 kg sealed block that is more compact and lighter than the capacitors used in ADD SIMP-LEX, while the equivalent series inductance is at about

20 nH with 5 mΩ of equivalent series resistance at 100 kHz of discharge frequency. The low inductance and the high energy rating will allow for a current profile that suits better a PPT discharge with an improved electromagnetic acceleration.

The new PPT design also incorporates the electrode geometry design changes previously found to easily improve the performance outcome of an electromagnetic PPT[17], whereas the igniter and injection system is maintained from the previous model. The total thruster design is shown in Figure 5.

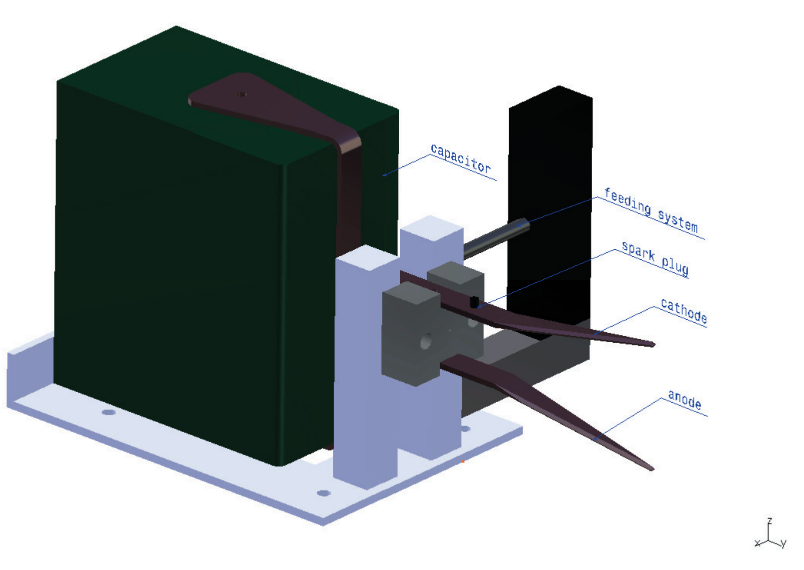


Figure 5. 3D model of the new thruster head.

With the higher discharge energy and the increased thruster weight, the previously used thrust balance could not be used accurately anymore, and an upgrade was sought after, which is discussed in the subsequent section.

C. Thrust Balance

For previous researches on PPT at the University of Tokyo, a torsional balance was used that measured the thrust impulse of low-energy PPT accurately[18]. With an increasing bank energy and an increasing weight of the PPT, as will be for the new thruster head, an improved thrust impulse balance is considered. This would also enable measurements for the parallel project on ADD SIMP-LEX[16] and liquid-fed PPT[19].

The new thrust balance design is based on a design previously used to build the thrust balance for the Hall thruster developments[20]. That is, a moving platform is suspended on knife-edge mounts allowing for a low-friction movement. The thruster is located on that platform, and the movement is recorded by a LVDT and processed by LabVIEW to obtain the amplitude of the oscillation. A model of the balance is shown in Figure 6 whereas the real structure can be seen in Figure 2(b).

For the calibration of the movement against a force impulse, an electromagnetic calibration system is used. The principle is similar to other systems of such kind[21] with modifications to fit into our system, and to be operated by LabVIEW. The setup is shown in Figure 7 and comprises a neodymium magnet extended by an iron yoke, and a copper rod to convey the EMF induced by a current pulse. The EMF then causes an impact on the measurement surface of a force transducer and the correlation between the force and the oscillation of the balance platform yields the calibration factor. Eventually, a calibration curve can be derived by modifying the current pulse to yield various forces–a process that might be able to be automatized by LabVIEW prior to actual experiments.

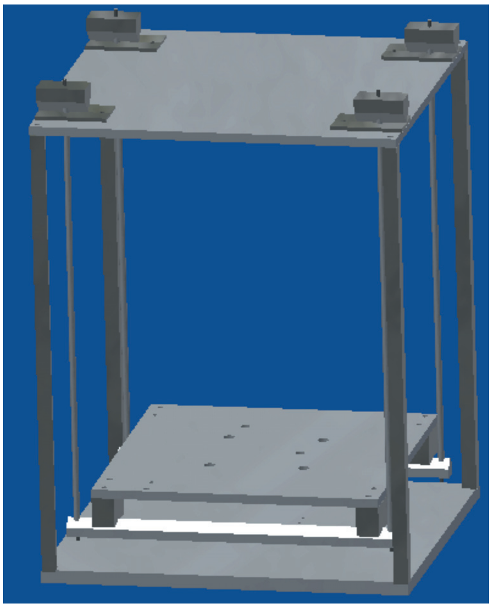


Figure 6. 3D model of the new thrust balance.

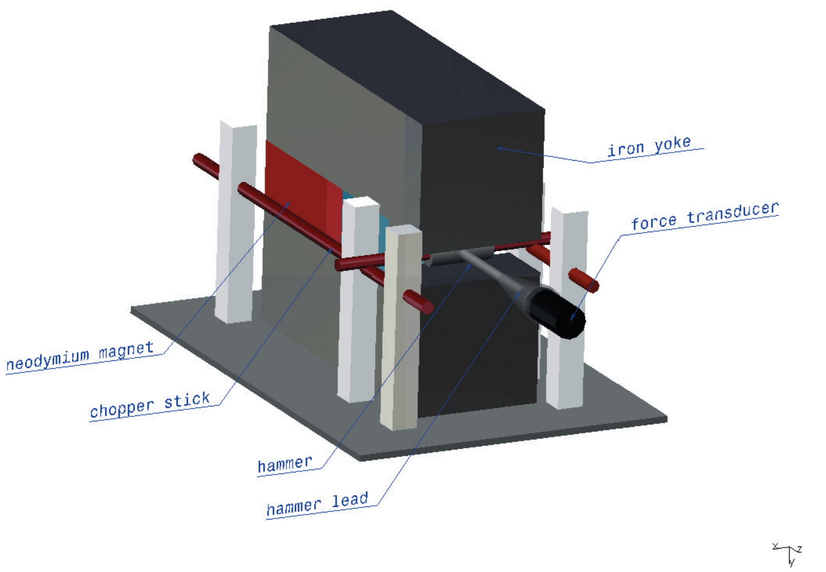


Figure 7. Electromagnetic calibration setup for the improved thrust balance.

D. System Considerations

While the first results for the air-breathing PPT seem promising, only the impulse results will determine how feasible a propulsion system based on PPT technology will be for air-breathing missions. An important aspect to consider is the actual propellant availability. This includes not only the correct feasible mass flow rates for lower Earth orbits and their possible storage capability, but also the composition of the injected gas that might differ by altitude[5] and way of compression.

Regarding the first aspect, several studies to determine the effectiveness of intakes were and are conducted, but all equally showing that collection efficiencies of about 40% are possible[22–24]. However, to validate the feasibility of an intake within a ground-test environment, the air stream intended for collection needs to be produced as well. Such an atmosphere simulator is complex if considering the actual composition and density of the upper atmosphere[25]. The combination of simulating the air stream, collecting the stream, and compressing it for use in the air-breathing PPT is likely to be the bigger challenge for this project, and at this point scheduled for the subsequent work.

III. Conclusion

A pulsed plasma thruster was tested successfully by using injected air as propellant, and the effect on the performance demonstrated. A new thruster was designed for an increased thrust performance, and the thrust balance modified to allow for a proper testing of the new thruster. The performance evaluation is ongoing, and will reveal whether the air-breathing PPT is powerful enough to be a suitable candidate for air-breathing electric propulsion technology. After the thrust performance evaluation, the feeding system shall be modified to allow for an intake use of propellant to demonstrate the feasibility of the propulsion concept.

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