Performance Evaluation of a Novel Inductive Atmosphere-Breathing EP System

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Abstract

Challenging space mission scenarios include those in low altitude orbits, where the atmosphere creates significant drag to the S/C and forces their orbit to an early decay. An atmosphere-breathing electric propulsion system (ABEP) ingests the residual atmosphere through an intake and uses it as propellant for an electric thruster that compensates the drag. Theoretically applicable to any planet with atmosphere, the system might allow to orbit for an unlimited period without carrying propellant on-board. IRS has several decades of heritage on the development of inductively heated plasma generators (IPG). Such devices are electrodeless, therefore issues of potential electrode erosion are eliminated. This paper deals with the complete refurbishment of a facility that was previously used for RIT testing, for the use of IPG6-S, a small scale IPG with an input power up to 3.5 kW. This facility allows more reliable test conditions. First operational and performance tests of IPG6-S have been performed. IPG6-S serves as test bed for the development of an inductive plasma thruster (IPT) for ABEP application. A newly designed water-cooled de Laval nozzle has been built and applied to IPG6-S. The nozzle is modular, it has the possibility of having various configurations so to assess its performance in terms of plasma acceleration and thrust production. Within this paper plasma plume energy has been measured by means of a cavity calorimeter and correlated to current, power, and pressure in the injector head.

Nomenclature

I = anode current
p = pressure
P = real part of the input power
V = screen grid voltage

I.Introduction

Missions in LEO can open a new range of opportunities for weather forecasting, oceanic currents, polar ice caps, fires, agriculture monitoring, and civil surveillance services. Recently ESA mission GOCE has ended, providing detailed information of Earth's geomagnetic field by orbiting as low as 229 km [1] continuously using RIT as EP for drag compensation. Missions at low altitudes have limited lifetime due to aerodynamic drag, caused by momentum exchange between the residual atmosphere particles and the S/C, requiring a propulsion system that compensates the drag. Such low altitudes would allow simpler and smaller platforms, meaning lower costs, as well as ensuring self de-orbiting at the end of the mission [2]. For such missions, the maximum mission lifetime of a S/C is a mission design driver that depends on the thrust that the propulsion system can provide, and for how long. These two are dependent on the propulsion system efficiency, on the amount of propellant carried on board, and on the generated of drag.

II. Atmosphere-Breathing Electric Propulsion

Atmosphere-Breathing Electric Propulsion System (ABEP) is a promising strategy for efficient drag compensation in orbit, enabling longer mission lifetime in VLEO and reducing propellant mass requirement. An ABEP system provides thrust to the spacecraft by collecting the residual atmosphere at low altitude using a specially designed intake, and utilizing it as propellant for an electric thruster. The concept is to extend the spacecraft’s lifetime by eliminating the need to carry propellant on-board. Providing a virtually unlimited amount of propellant, the lifetime-limiting factor is no longer the amount of propellant carried on-board, but the durability of the other satellite's subsystems. Eliminating the need of carry propellant into orbit brings the benefit of reduced launch mass, as long as the ABEP system’s mass is less than that of a conventional EP system (including the propellant). As part of the DISCOVERER (DISruptive teChnOlogies for

VERy low Earth oRbit platforms) project, funded through the European Commission's Horizon 2020 program, the development of an ABEP system concept is envisaged to allow for a new low-altitude platform paradigm to yield increased Earth observation capabilities. For this purpose, technology derived from inductively-heated plasma generators was selected as potential candidate for such an ABEP system. Previous numerical research led to an understanding of intakes to gather the atmospheric mass flow at high velocities, and, therefore, a more accurate estimation of the possible input parameters to a thruster head [3], [4], [5]. To develop a pertinent and efficient inductive thruster head, more experimental work is necessary to understand the characteristics of inductive plasma generator technology with aforementioned input parameters, and the effects of nozzles on the plasma flow properties. In this study. In this paper, a new refurbished facility for IPG6-S is presented. A nozzle has been developed to assess performances of an inductive plasma thruster (IPT)-based ABEP system using IPG6-S and first ignitions performed. IPT are electrodeless devices based on inductively heated plasma generators (IPG), therefore eliminating the performance degradation issue typical of RIT and HET when using aggressive propellants, allowing a wide range of propellant to be used and, moreover, removing the need of a neutralizer. The concepts is shown within Fig. 1.

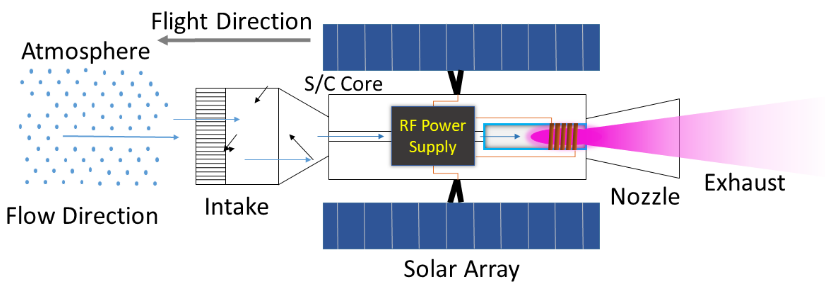

Fig. 1 ABEP Concept

IRS has gathered several decades of experience in the development, operation, characterization and qualification of various plasma sources. Among them are steady state self-field and applied field magnetoplasmadynamic (MPD) sources, thermal arcjet devices, IPG and hybrid plasma systems [9], [10], [11]. These plasma systems are in application for aerothermodynamics testing, heat shield material characterization [9], [10], [11], [12], [13], [14], electric space propulsion [15], [16], [17], [18], [19], [20], [21] and terrestrial plasma technology (i.e. technology transfer) [22], [23], [24]. IPG have originally been developed to cope with chemically aggressive working gases for the IRS plasma wind tunnel PWK3. The electrodeless design enables additionally a pure plasma which engages the potential for aerothermochemical investigations in the field of heat shield material catalysis [14], [13], [25], nitridation and oxidation [26], [27] and, in addition, the behaviour of both plasma sources for plasma wind tunnels and electric propulsion and respective flow conditions [30]. Moreover, the high power inductively heated plasma sources developed at IRS were respectively characterized and modeled to provide increased understanding and an experimental database [13], [15], [29]. On basis of both system and mission analyses and the IPG-heritage, IPG6-S has been tested as IPT candidate in the context of ABEP [3], [4], [5], [33], [34].

III. IPG6-S

IPG6-S is a small-size inductively-heated plasma generator (IPG) available at IRS. IPG6-S has a coil wrapped around a quartz tube, the discharge channel, that is fed by RF AC current. It operates in a way similar to a transformer where the primary winding is the coil and the secondary is the gas inside the discharge channel. The current flowing in the coil induces an oscillating magnetic and electric field in the discharge channel which accelerate ions and electrons of the gas, plasma forms and a chain reaction establishes. IPG6-S, see Fig. 2, is water cooled, the discharge channel has an outer diameter of 40mm, a length of 180 mm, and the coil has 5.5 turns. A twin facility, IPG6-B, is installed at Baylor University, Waco, Texas, USA.

Fig. 2 IPG6-S

IV. Nozzle

IPG6-S is a plasma generator and is not optimized for propulsive purposes. Within the DISCOVERER project, an inductive plasma thruster (IPT) has to be developed. The device has to be passively cooled, scaled in size, optimized for ABEP requirements in a power range between 0.5 and 5.5 kW. A modular nozzle has been designed and built for IPG6-S, to estimate its performance and provide a test-bed for the future IPT. The nozzle is made of brass and is water cooled, designed such that its components can be easily substituted to obtain a variety of configurations: de Laval nozzle, convergent nozzle only, or no nozzle. The convergent section and the divergent section can be substituted for different sizes and angles. The current first design has a throat diameter of 20 mm and the divergent section with a final diameter of 40 mm. The nozzle assembly is shown within Fig. 3.

External nozzle structure | Convergent section | Convergent-only | De Laval

Fig. 3 Modular Nozzle Assembly

V. Refurbished Facility

Large part of last year's work was the refurbishment of a vacuum tank used for RIT testing at IRS, and prepare it for IPG6-S operation. The refurbishment was needed to obtain more reliable testing conditions. The previous test facility had a vacuum tank of 1 m^3 providing background pressures of 30 Pa highly dependent on the injected mass flow (e.g. 50 Pa for 20 mg/s N_2). The current test facility for IPG6-S is now a 12 m^3 (2 m diameter, 4 m length) vacuum tank, see Fig. 4. The main vacuum facility provides background pressure of ~ 1 Pa, while a system of 50 000 l/min oil diffusion pumps can bring the background pressure further down to 10^{-5} Pa. First tests of IPG6-S have been performed with the main vacuum pumps during first middle of September 2017. The facility has now also a better open-loop water cooling system that provides fresh water at constant temperature, currently around 14°C. Water is pumped by two water pumps on two different loops. The first one is dedicated to the power supply only, while the second cools, separately, coil, calorimeter, nozzle, and the generator itself (including the injector head). The system is provided with Pt100 for water temperature measurements. Gas supply system currently provides O_2 and N_2 which can be operated singularly or mixed, the option for Ar is ready and an external gas bottle (CO_2, CH_4) can be connected as well. The power supply provides maximum input power $P_{max} = 20$ kW, maximum anode current of 4.5 A, maximum anode voltage of 8.5 kV, and a nominal frequency of f = 4 MHz dependent on the IPG impedance. The control is on the screen grid voltage, that determines how much current can flow to the IPG. Anode current, screen grid voltage, and real part of the input power, are the three values that are analogically displayed by respective indicators at the power supply. Plume plasma energy is measured by a cavity calorimeter mounted inside the tank, at a distance of 1 cm from the nozzle exit. A Pt100 has been mounted inside the tank as close as possible to the calorimeter on the outflow water, to provide most reliable measurements.

Fig. 4 IPG6-S refurbished facility

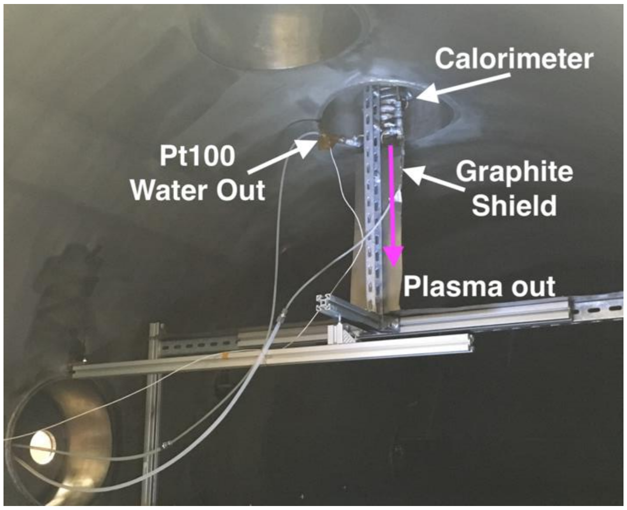

Fig. 5 Calorimeter installation

VI. Preliminary Test Results

First ignition and subsequent tests have been performed using IPG6-S with the de Laval nozzle mounted in the aforementioned configuration. The tests provide first understanding of the refurbished facility and its subsystems, especially the power supply. Tests have been performed with mass flows up to 26.35 mg/s, the maximum with the current configuration of mass flow controllers, and the tank pressure remained stable. The test condition hereby analyzed is a sweep of the current at the power supply for a mixed gas flow of 21.95 mg/s N_2 + 4.40 mg/s O_2 for a total of 26.35 mg/s applied to IPG6-S with the nozzle mounted in the de Laval configuration. The calorimeter power is shown in Fig. 6,7 together with injector pressure, anode current, and real part of the input power. The test procedure is to first increase the screen grid voltage of the power supply until plasma can be seen, this will be set at the ignition point. The screen grid voltage is afterwards increased in 0.1 kV steps, and a steady state condition is determined by looking at the steady state of the pressure of the injector head and of the calorimeter power. Since anode current, screen grid voltage, and real part of the input power have to be visually read from the power supply, test time was noted down for each to compare with the results of the data scan in the post process analysis. In the next months, a system will be implemented to save data from the power supply. Especially an oscilloscope will be used to read voltage and anode current.

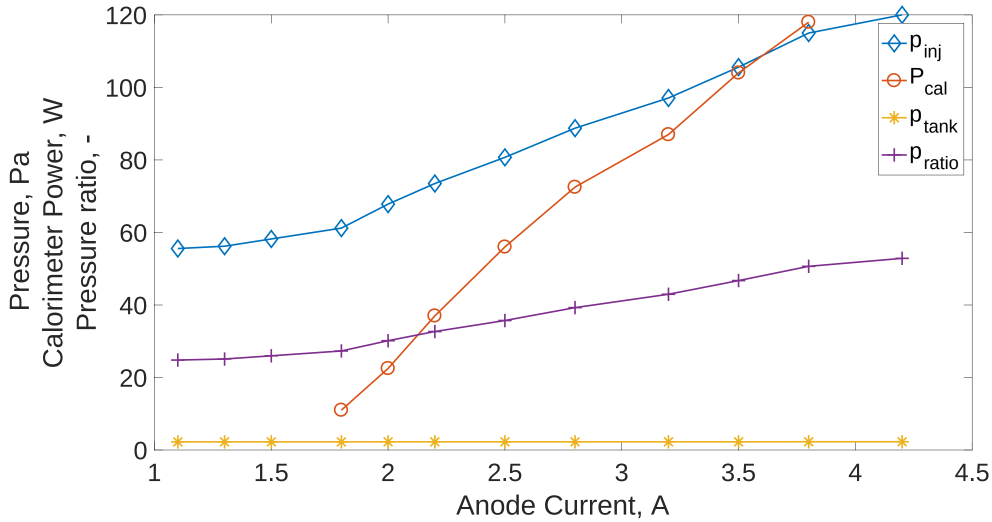

Fig. 6 Calorimeter Power and Pressure Injector Head vs Anode Current

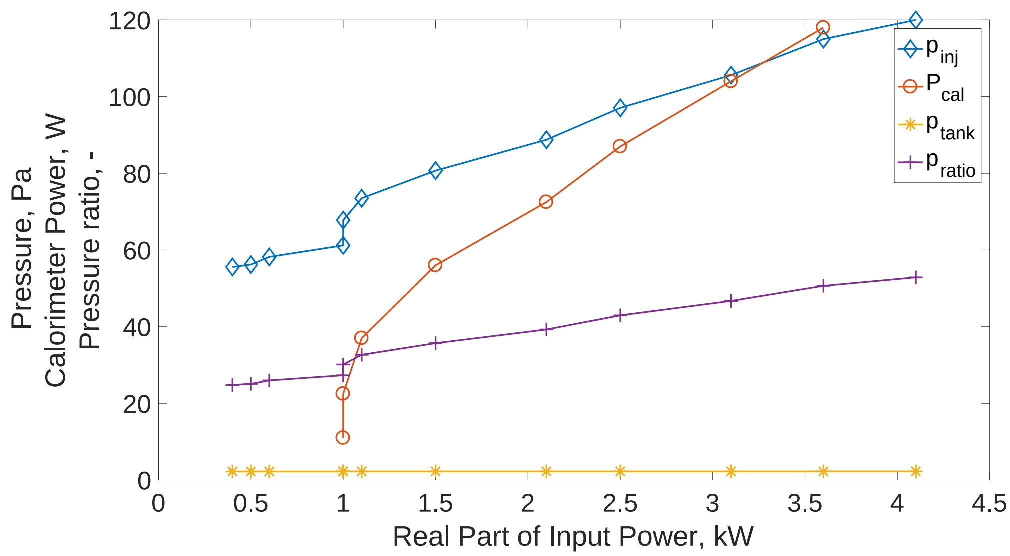

Fig. 7 Calorimeter Power and Pressure at Injector Head vs Real Part of Input Power

Results show that calorimeter power increases together with anode current and pressure of the injector head, Fig. 6. Tank pressure remained constant at 2.2 Pa for the whole test. Less points are available for the calorimeter power, as for low input power, there was no reading possible due to no increase of calorimeter water temperature. However, a steep increase of calorimeter power can be seen when the anode current passes between 1.7 and 2.25 A, corresponding at around 1 kW or the real part of the input power. That is the point at which the plasma starts heating up the water of the calorimeter. As can bee seen, the calorimeter power is still very low. Moreover, the plasma visually seems to be very diffuse at the outlet of the nozzle, therefore the nozzle size might be too large in regards to IPG6-S and its applied mass flow. Further experiments are needed to better understand the behaviour of the facility at whole.

VII. Conclusion and Outlook

A facility has been successfully refurbished and modernized for the operation of IPG6-S in more reliable test conditions. A modular nozzle has been designed and built for IPG6-S, to evaluate plasma acceleration and thrust production, paving the way for the development of the IPT. First tests have shown that IPG6-S ignites, and that the facility operates as it should. IPG6-S was ignited successfully with both mixture of N_2 and O_2, and O_2 and N_2 as single gases. Hysteresis phenomena have been observed: plasma remains ignited after decreasing the anode current much below the ignition condition. This is according to IRS heritage on bigger IPGs. Most of the input power might be taken away by the water cooling system of IPG6-S, as water flows inside the coil, around the coil and the quartz tube, in the injector head, at the bottom flange of the generator, and into the nozzle. A part of the input power might also be absorbed by the water cooling the power supply, this will be analysed my monitoring the power supply as well. Operation with lower mass flows has been performed, and showed that, once ignition is obtained, by increasing the anode current, the real part of the input power does not increase, even though a slight increase in calorimeter power and discharge brightness can be observed. Therefore, investigation is needed to better determine where the power losses are located by monitoring IPG6-S cooling water at the quartz tube, and also by adding additional measurements points for voltage and anode current at the power supply. Also the addition of more Pt100 to monitor water temperature of the power supply will be performed. The pressure ratio for this condition, already states that the flow is supersonic, this suggests the use of a Pitot probe to measure exhaust velocity for the following investigations. New throat section, smaller, will be built based on actual pressure and compared with these first tests. A magnet is foreseen for further investigation in terms of plasma acceleration. Regarding plasma diagnostics, a mini Pitot probe will be developed to measure plasma exhaust velocity. In the future plan numerous test will analyze ignition conditions, and the aim is to extract, if there is, a condition that relates mass flow, or discharge channel pressure, with the coupling efficiency and the volume of the discharge channel, so that will help us developing an efficient IPT for ABEP application.

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