Performance Theory and Development of a Resistojet Based Hybrid Electro-Chemical Thruster

IEPC-2019-390

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Giulio Coral[1]
The University of Tokyo, Bunkyo-ku, Tokyo, 133-8654, Japan

Ryudo Tsukizaki[2]
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan

Kiyoshi Kinefuchi[3]
Nagoya University, Nagoya, Aichi, 464-8601, Japan

Daisuke Nakata[4]
Muroran Institute of Technology, Muroran, Hokkaido, 050-8585, Japan

Toru Shimada[5], Kazutaka Nishiyama[6], and Hitoshi Kuninaka[7]
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan

Abstract: We propose a resistojet based hybrid electro-chemical thruster, in which the propellant is preheated by a resistor before entering the combustion chamber, as a solution for missions with high thrust and high I_{SP} requirements. A study on the thermodynamics of the thruster is performed in order to evaluate the feasibility and potential performance. The experiment performed to demonstrate the operation of this thruster and have a preliminary evaluation of its performance characteristics is presented.

Nomenclature

H_f	=	enthalpy of formation
HHV	=	higher heating value
I_{SP}	=	specific impulse
M	=	molar mass
α	=	H_2 dissociation ratio
$\Delta E/m$	=	augmentation ratio (power per unit mass)
φ	=	F:O molar ratio

[1] PhD Candidate, Department of Aeronautics and Astronautics, giuliocoral@ep.isas.jaxa.jp
[2] Assistant Professor, Institute of Space and Astronautical Science, tsukizaki.ryudo@jaxa.jp
[3] Associate Professor, Department of Aerospace Engineering, kiyoshi.kinefuchi@mae.nagoya-u.ac.jp
[4] Assistant Professor, Dept. of Mechanical, Aerospace, and Materials Engineering, nakata@mmm.muroran-it.ac.jp
[5] Professor, Institute of Space and Astronautical Science
[6] Associate Professor, Institute of Space and Astronautical Science
[7] Director General, Institute of Space and Astronautical Science

I.Introduction

The concept of a hybrid electro-chemical thruster (hereinafter HECT) was originally proposed by Pollard and Frisbee in the 1980s, who proposed the idea of reaching high thrust and specific impulse by combining electrical and chemical energy.[1-2] Their work, however, focused on the global thermodynamics of such concept, without evaluating the various potential layouts for constructing the thruster, and hence failed to fully point out the benefits and challenges of such thruster. Other than these studies, patents from Northrop Grumman and Lockheed Martin can be found in the literature, but due to the non-scholarly nature of the publications no information on whether or not the thrusters were actually manufactured can be found.[3-4]

The resistojet based HECT we propose is radically different from those by the above-mentioned companies and, while building upon the theory fundamentals proposed in the past, our goal will be to develop a functioning thruster.

II.Resistojet Based HECT Theory Fundamentals

A. HECT Design Choices

While the basic performance theory of HECTs is common for all construction approaches, and has been well detailed by Pollard, the specific layout selected for heating and combustion (different heating mechanisms, pre- or post-combustion heating, etc.) will affect the thruster design and capabilities.

For a series of practical reasons, we choose to pursue the concept of a thruster with resistive heating of the fuel only and combustion chamber located after the heater (unlike those proposed by Northrop Grumman and Lockheed Martin). Furthermore, we select hydrogen as propellant, due to its superior heat capacity and HHV, which lead to a higher I_{SP}.

The design choices we made lead to two thruster systems:

- A regeneratively cooled HECT, suitable for steady state operation (Fig. 1)
- An uncooled HECT, simpler and more suitable for preliminary testing (Fig. 2)

B. HECT Thermodynamics

In the design we proposed, the maximum energy that can be deposited to the H_2 propellant before combustion is easily determined by the temperature the resistor material can withstand as:

$$\left(\frac{\Delta E}{m}\right)_{H2} = \frac{\alpha\, \Delta H_f}{M_H} \tag{1}$$

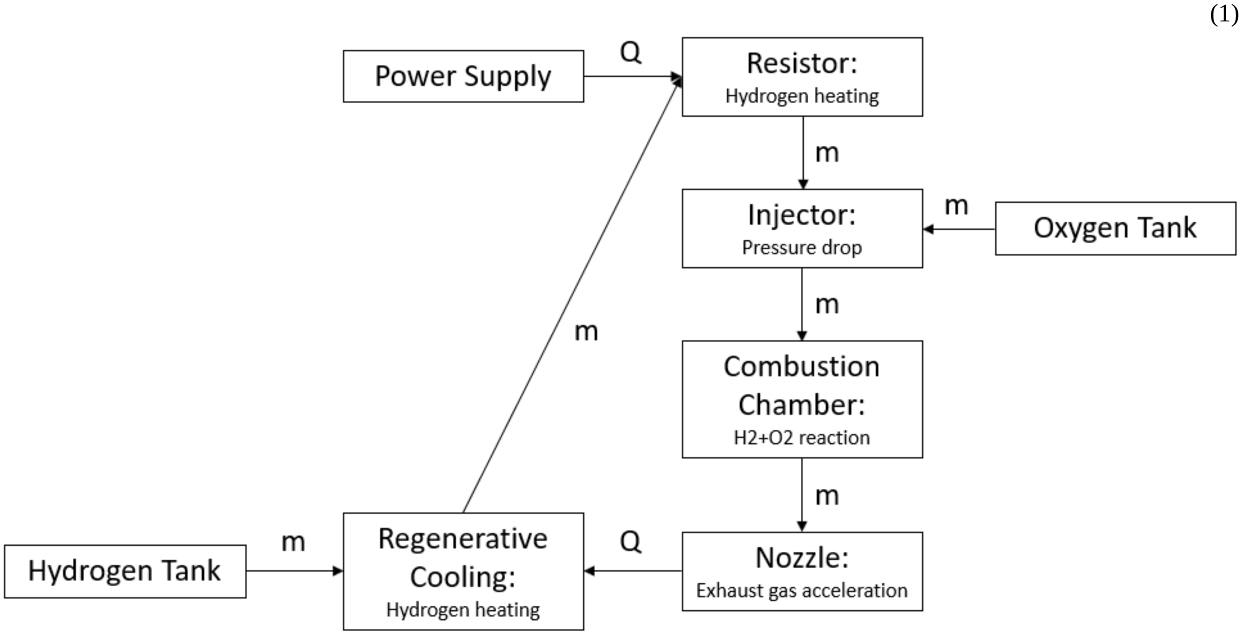

Figure 1: Regeneratively cooled resistojet based HECT.

Steady state hydrogen heating by tungsten resistojet in excess of 2000K has been demonstrated in the past, with total efficiency up to 80%.[13]

The actual ΔE/m is then calculated accounting also for the oxygen mass, leading to:

$$\frac{\Delta E}{m} = \frac{\alpha\,\varphi\,\Delta H_f}{\varphi\,M_H + M_O} \tag{2}$$

With the H_2 temperature determined, we can obtain the combustion properties by equilibrium simulation (with Cantera integrated into MATLAB, or standalone software as RPA or NASA CEA).[5-8]

Knowing the combustion properties, we can obtain the I_{SP} assuming an ideal nozzle. Performing such calculations for different values of α and φ, we can observe the performance pattern as we transition from pure chemical mode to pure electrothermal mode. We plot the thrust/power ratio and I_{SP} as function of φ and T_{inH}.

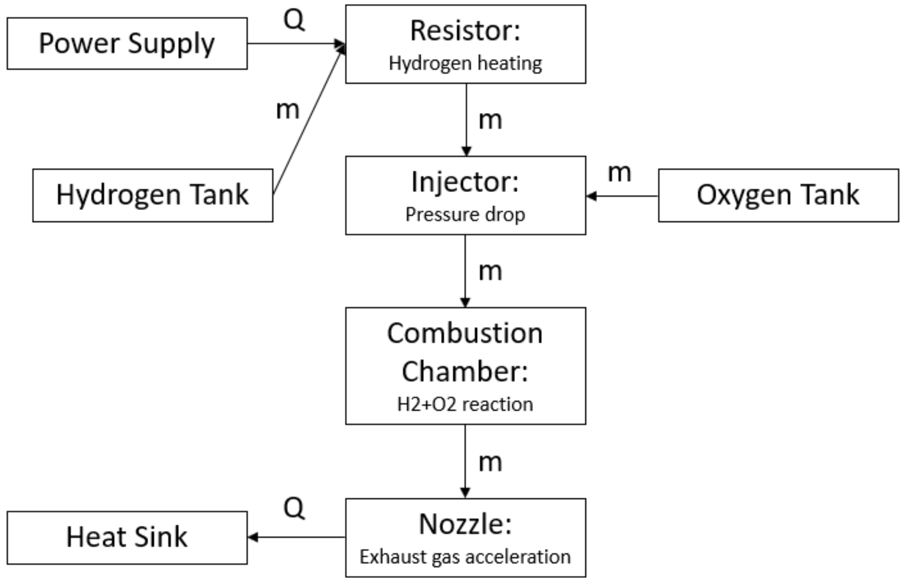

Figure 2: Uncooled resistojet based HECT system design.

As we can see in Fig. 3 and 4, at the bottom of the chart the performance is barely affected by the hydrogen injection temperature, due to the low amount of hydrogen injected. On the contrary, at the top of the charts, the energy released by combustion is practically negligible, with the thruster behaving very similarly to a regular resistojet. The most interesting performance range is in the mid-range of φ, with both electrical and chemical energy contributing meaningfully.

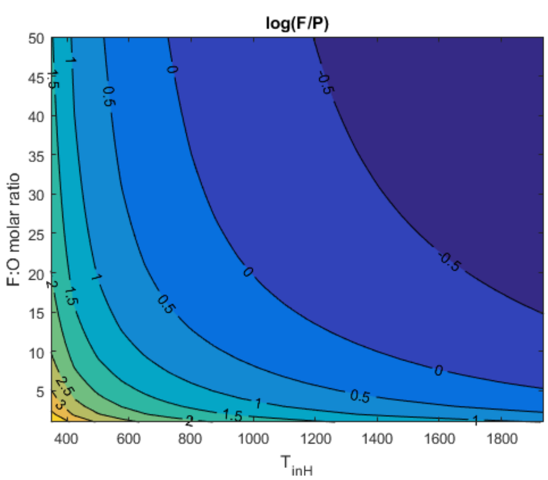

Figure 3: Thrust power ratio as function of φ and T_{inH}

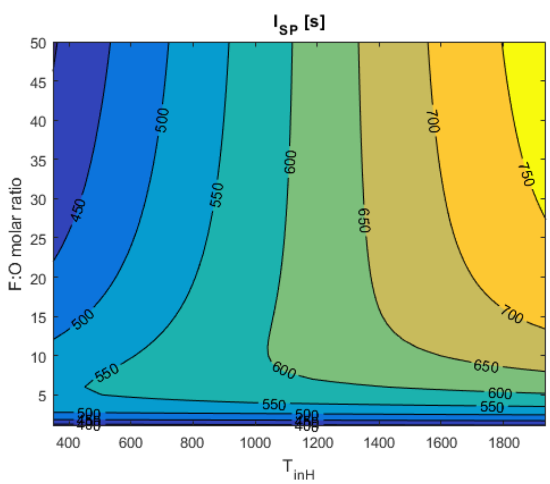

Figure 4: I_{SP} as function of φ and T_{inH}

III.HECT Experiment Preparation

A. Engine Proof-of-Concept Prototype

For the development of the HECT, the first prototype is constructed following the system design of Fig. 2. A schematic of the thruster is shown in Fig. 5.

As for the electrothermal segment, the thruster utilizes a 13-layers 80mΩ 3D printed (by selected laser melting) Inconel resistor for heating the propellant, theoretically capable to heat the H_2 up to more than 900K.[11-12] The design adopted requires a ceramic insulating layer to be introduced between the resistor and the injector plate.

After the injector plate, the thruster largely resembles a combustion engine, with replaceable orifices controlling the mass flow mounted on the H_2 line (after heating) and on the O_2 line and injecting in a cylindrical combustion chamber. A high temperature spark plug, powered by a 15kV AC transformer, ignites the fuel-oxidizer mixture, as at the temperatures involved the mixture is not self-igniting. Although the engine is ultimately designed to be operated in vacuum (using electrical power is not reasonable otherwise), the first prototype utilizes a straight nozzle, and is hence operated in atmospheric condition.

Since regenerative cooling is not utilized in this prototype, the thruster can't be operated steady state, and performance is reduced due to the unrecovered heat.

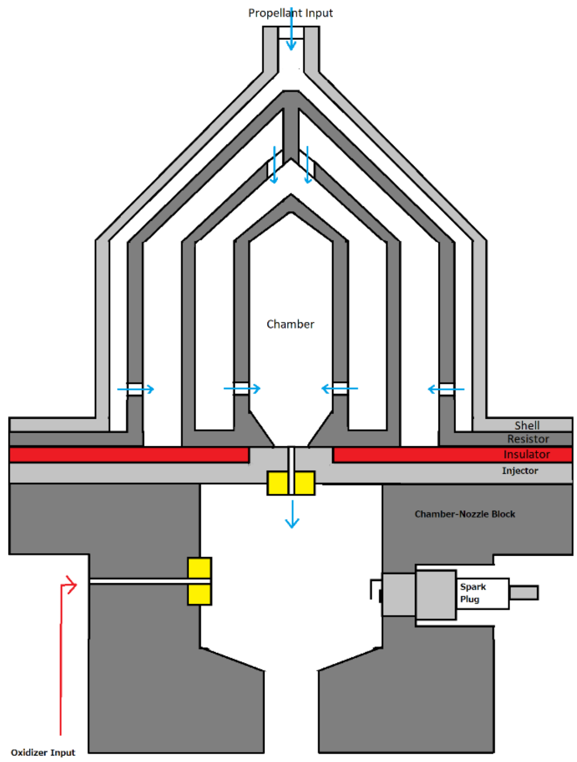

Figure 5: Uncooled resistojet based HECT schematic.

B. Electrical, Feeding and Data Acquisition System

Due to the novelty of the project and the strict safety requirements applied by JAXA to the use of H_2/O_2 mixture and power supplies, a new feeding and electrical system was prepared to support the experiments. In Fig. 7, the fuel lines are in black, electrical lines in red, and data acquisition in blue.

Two nearly identical fuel lines have been manufactured for H_2 and O_2, each including a gas bottle mounted pressure regulator (PR), a pressure relief valve (PRV) protecting the system from anomalies, two redundant pneumatic valves (PV) and a check valve (CV) preventing backflow. In the H_2 line, the resistor is represented by a heat source. For each line, a support line running on N_2 is used to energize the PVs and purge the system, and it is remotely controlled by solenoid valves (SV). A picture of the H_2 line assembly, before the SVs are put into their purge box, is shown in Fig. 6.

The electrical system consists of a high current power supply (PS), with peak output of 5kW at 20V-250A, connected to the resistor, and a high voltage transformer (NT, as it is derived from neon signboards) operating at 15kV-20mA used for the spark plug.

The data acquisition system is composed by the two mass flow meters (MFM) connected to a PC by serial ports, a series

Figure 6: H2 feeding line assembly.

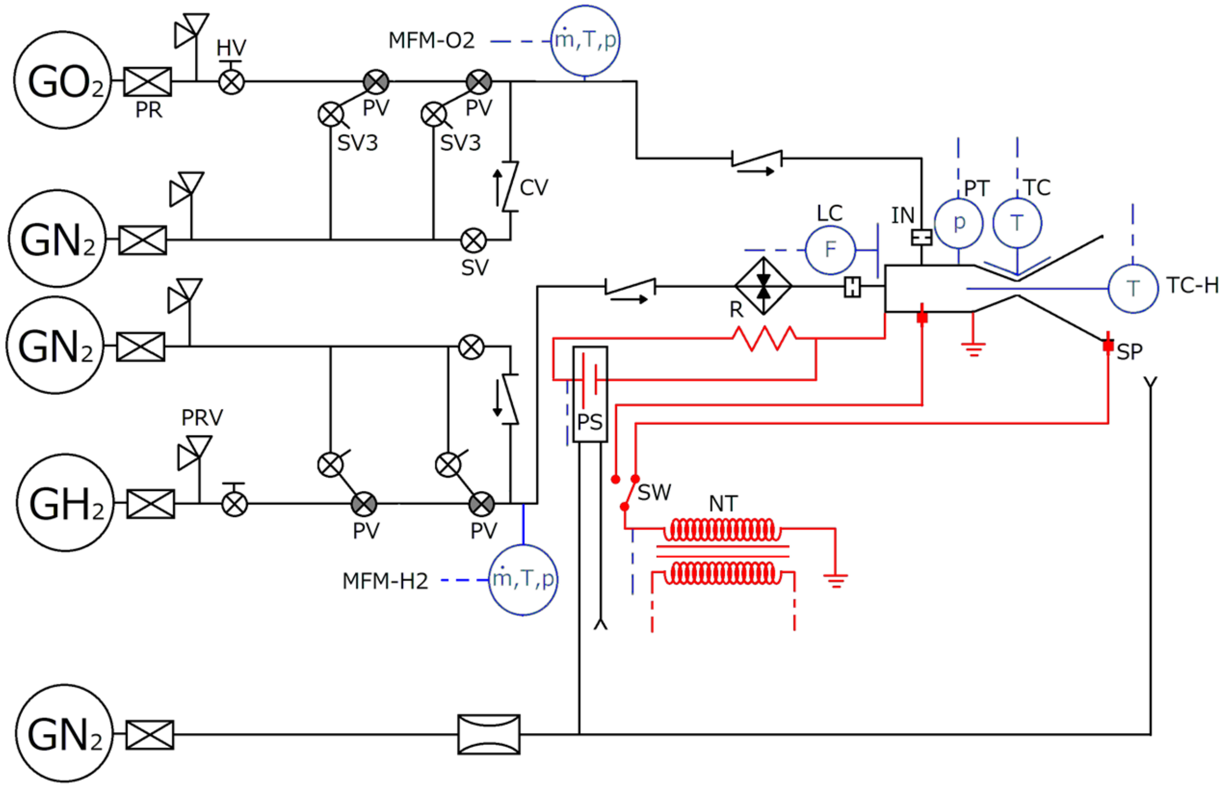

Figure 7: Uncooled resistojet based HECT feeding system schematic.

of engine mounted sensors (load cell LC, pressure transducer PT, thermocouple TC) and output measurement lines from the electrical system.

The system is designed for high flexibility, allowing to control the mass flow by replacing the injector orifices (IN) and the power deposition through the power supply. Except for the orifice replacement, the entire system is controlled by auto-sequence, to reduce the possibility of human error during operation.

C. Experiment Procedure

The above mentioned auto-sequence is coded by ladder programming and implemented in a Omron Zen sequencer, following the information mentioned in Tab. 1. A 10s gap between selected events is set to allow detection of anomalies and, in case, activate the emergency stop. As the experiment is controlled remotely from a separate room, anomalies are detected based on the parameters monitored by the data acquisition system and by closed-circuit cameras.

Command	Event
10s SV pulse	N_2 purge
Open PV H_2 line	H_2 flow start
Start PS	H_2 preheating
Open PV O_2 line, 2s NT pulse	Combustion start
Close PV O_2 line, stop PS	Combustion stop, heating stop
Close PV H_2 line	Termination

Table 1: HECT experiment auto-sequence.

IV.HECT Experiment Results

A. Proof-of-concept Tested Conditions

With the flexibility allowed by the experiment setup, nine HECT conditions were tested (plus one pure chemical), as described in Tab. 2. The main objective was to test performance at different F:O ratios and power deposition levels. As the F:O ratio is controlled by the orifices, which for simplicity were not replaced at each test (only when changing the F:O ratio), the different H_2 temperature will affect the actual flow.

B. Data Analysis

An example of the load cell output, with the auto-sequence events indicated, is shown in Fig. 8. The HECT thrust is measured during combustion, after the initial overpressurization (due to ignition) of the combustion chamber. Results are corrected accounting for the thermal drift of the thrust stand and long period oscillations.

The resulting data points (preliminarily analyzed) are then shown in Fig. 9-10, comparing the I_{SP}, F/P ratio and ΔE/m for the different testing conditions.

Test ID	H_2 ṁ [g/s]	O_2 ṁ [g/s]	φ	P [W]	H_2 ΔE/m [J/g]
H1	0.238	0.226	16.71265	275	1155.462
H2	0.264	0.213	19.66986	363	1375
H3	0.267	0.196	21.61883	566	2119.85
H4	0.172	0.22	12.40745	209	1215.116
H5	0.166	0.218	12.0845	340	2048.193
H6	0.168	0.225	11.8496	426	2535.714
H7	0.138	0.299	6.839596	147	1065.217
H8	0.132	0.297	7.160202	244	1848.485
H9	0.128	0.297	7.324615	333	2601.563
C	0.134	0.297	7.053333	0	0

Table 2: HECT experiment mass flow and power testing conditions.

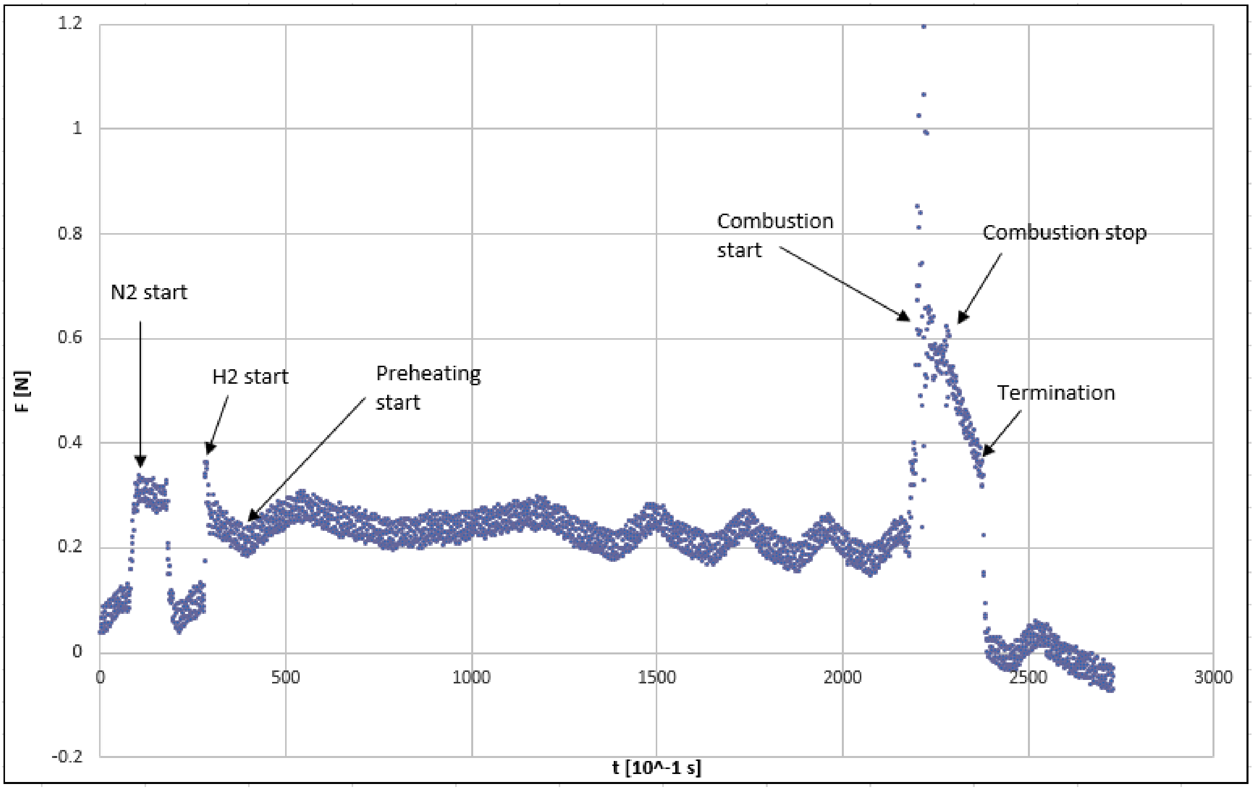

Figure 8: HECT experiment load cell output (example).

The performance is of course capped due to the unexpanded nozzle. As Fig. 9 shows, the basic approach of increasing the I_{SP} by preheating the propellant before combustion is demonstrated. Being this the first experiment on the topic, the H_2 preheating temperature range was kept low (<500K) to avoid overheating/disruptive failure. Hence, the augmentation is in the 10s (or 10%) range. In Fig. 10, the relation between I_{SP} and F/P ratio is shown (in this case, the pure chemical case is not shown, as its F/P would be infinite), but it's more difficult to see the trend, due to the few and relatively close data points.

A further issue with the data collected is the different combustion pressure: the only cases to operate at the nominal 0.35~0.4MPa level were H2 and H3. In the rest of the cases, combustion pressure was substantially lower, meaning the H2/O2 mixture exited the chamber before being fully combusted, leading to lower performance but as well lower heat losses.

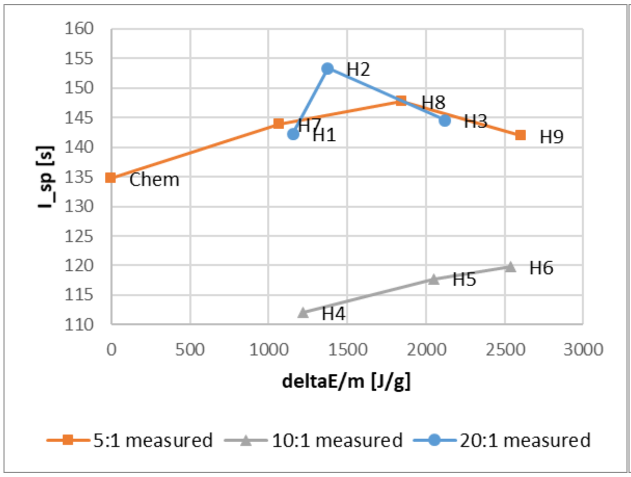

Figure 9: HECT I_{SP} vs $\Delta E/m$.

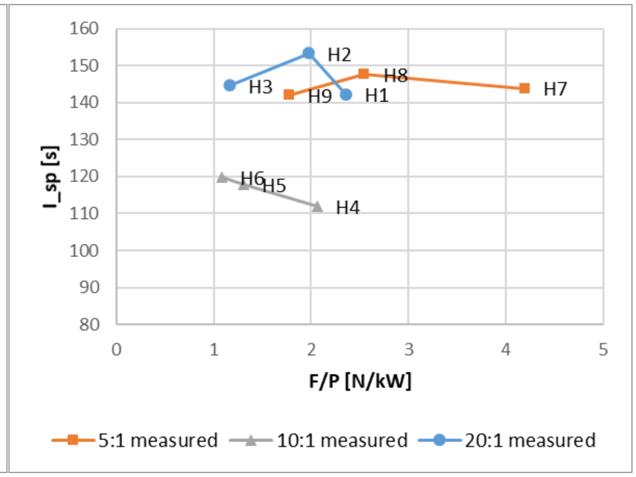

Figure 10: HECT I_{SP} vs F/P ratio.

V.Conclusion and Future Developments

In this research project, we present the concept of a resistojet based HECT, merging the features of electric and chemical propulsion by preheating H_2 through a high temperature resistor and combusting it with O_2. We point out the benefits of such thruster, as our model is theoretically capable of performance levels such as 620s I_{SP} at 1N/kW, or 700s at 0.5N/kW, with a peak I_{SP} near 800s.

A simplified proof-of-concept engine has been manufactured and tested, together with its ad-hoc setup. Although the experiment conditions have prevented us from obtaining conclusive data regarding the heat losses, the working principle of the thruster has been successfully demonstrated, being this the first HECT on record.

Further development of the thruster should include testing at higher power levels (possibly with higher temperature resistor as well) and design of a specialized cooling system.

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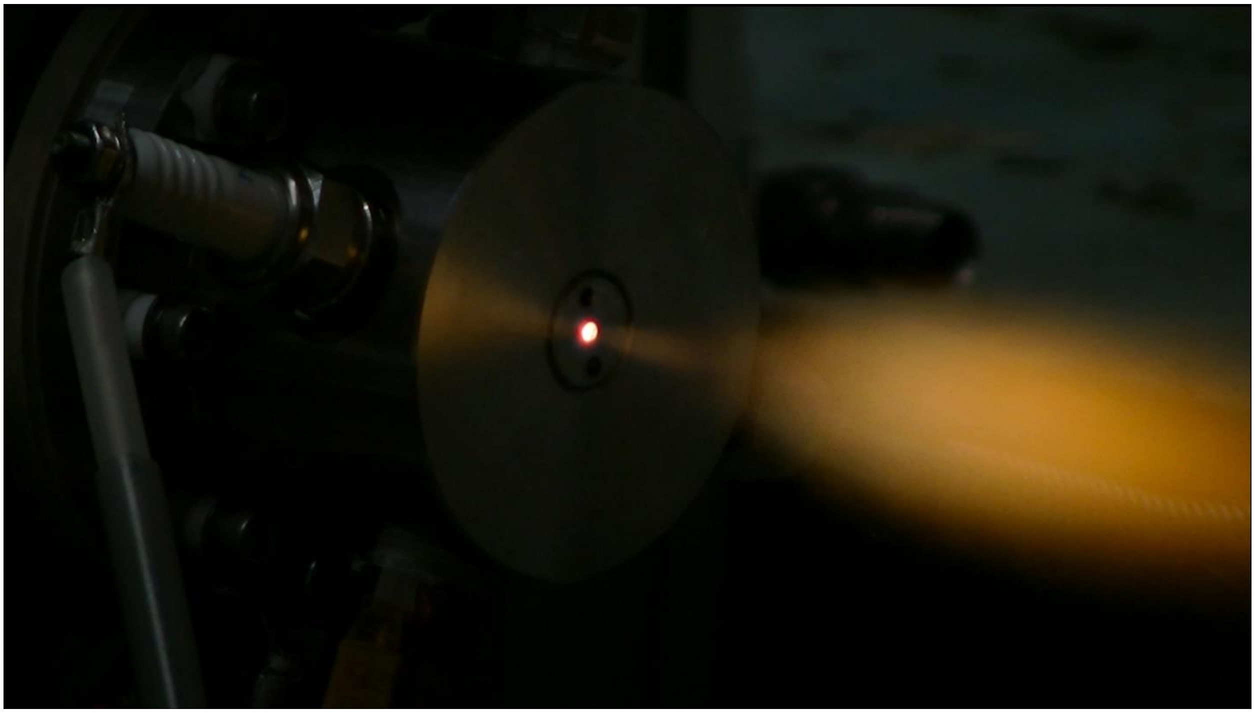
Figure 11: H5 HECT test, 12:1 F:O molar ratio, 2kW/g

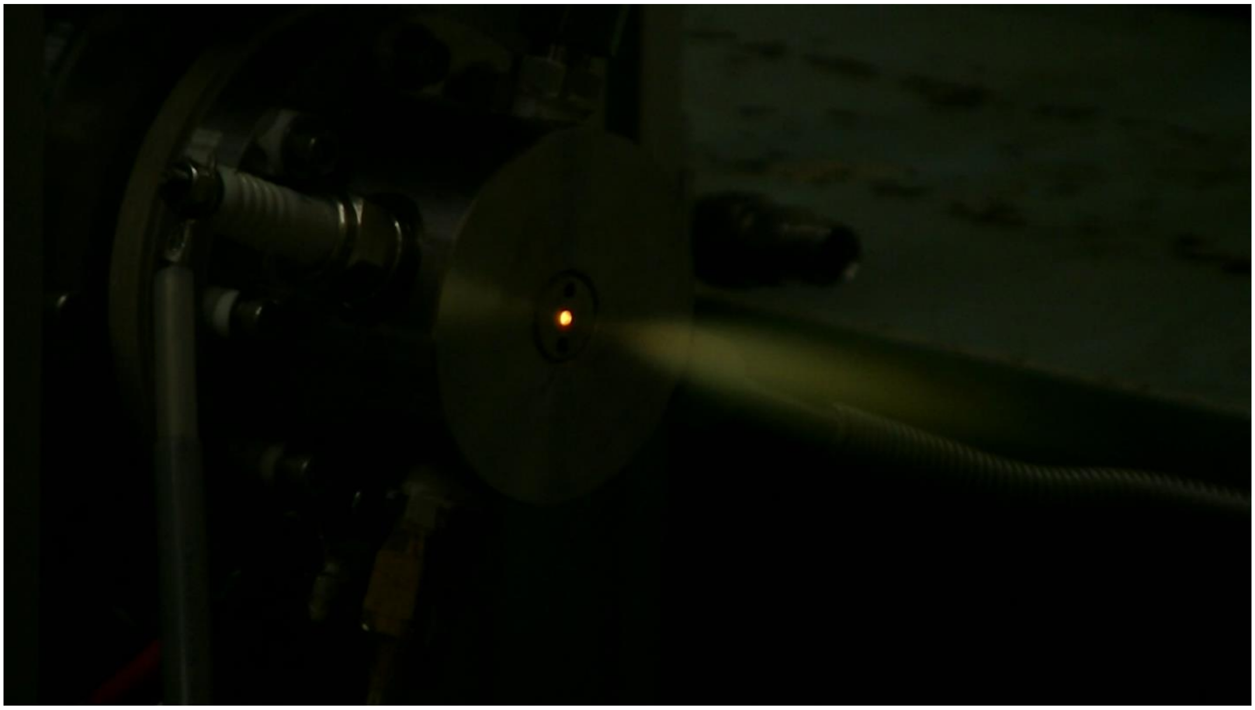
Figure 12: H8 HECT test, 7:1 F:O molar ratio, 1.85kW/g