ADVANCES ON COST-OPTIMIZED HIGH-PRESSURE FLOW CONTROL UNIT WITHIN HIPATIA-PROJECT

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ABSTRACT:

AST Advanced Space Technologies GmbH is working on development of a novel propellant flow control unit for propulsion subsystem around the Helicon Plasma Thruster (HPT) technology in cooperation with SENER and the consortium members in frame of the EU funded H2020 program HIPATIA (Helicon PlasmA Thruster for In-space Applications). The Helicon technology reduces complexity compared to the conventional ion thrusters due to the absence of a dedicated neutralizer and a simpler thruster design.

In frame of that, AST works on additional reduction of complexity and cost of the unit based on its flight-heritage HP-FCU design. The paper outlines the technical goals and milestones of the HIPATIA development activity and the chosen approach in order to achieve a low-cost propellant management system.

Flow characteristics and performance of the flow control unit are characterized and presented in the current paper. Trade-off study is conducted and cost-reducing concept based on building blocks for EQM is presented.

NOMENCLATURE:

AST	Advanced Space Technologies
EBB	Elegant breadboard model
EGSE	Electrical Ground Support Equipment
EQM	Engineering Qualification Model
FCU	Flow control unit
HPT	Helicon Plasma Thruster
HP-FCU	High-pressure flow control unit
LEO	Low Earth Orbit
PFCU	Propellant flow control unit
P&ID	Piping and instrumentation diagram
TRL	Technology readiness level
U3CM	Charles III University of Madrid

1. Introduction

Based on reduced costs of access to space, space engineering is experiencing a dynamic development. The market is facing an increased demand for small satellites due to reduced frame size of components and huge satellite numbers for constellations. The trend towards electric propulsion can be observed with the need for accurate but inexpensive propellant flow regulation. AST's existing commercial product, the High-Pressure Flow Control Unit (HP-FCU), manufactured in serial production, is a suitable solution combining electric pressure regulation and flow control unit in a single device. It can feed an ion thruster of any type (e.g. GIE, HEMPT, HET) as well as the corresponding neutralizer with xenon or krypton. The HP-FCU has been designed for a large scale manufacturing resulting in a mass below 1 kg and a footprint size of a cell phone [2].

This paper outlines the technical goals and milestones of the HIPATIA development activity and the chosen approach to achieve a low-cost propellant management system.

The flow control unit developed within HIPATIA is based on building blocks with long lead items manufactured in high quantities for stock storage. It allows a late integration by readily tested components. This approach enables an extremely fast and still customized manufacturing within weeks.

In the current contribution we present the key aspects of AST's heritage high pressure flow control unit (RADICAL), followed by design optimization for the use with the Helicon Plasma Thruster technology. Results from tests at unit level as well as results from first coupling tests are presented.

2. Propellant Management in HIPATIA Subsystem

The HIPATIA project aims to verify functionality and performances of electric propulsion system based on HTP technology. The HTP offers acceptable performance level, while eliminating usage of neutralizer line, electrodes, high voltage electronics and complex manufacturing, driving costs down. The propulsion system consists of Thruster Unit (TU), Radiofrequency Generation and Power Unit (PFCU) and the Propellant Flow Control Unit (PFCU). PFCU provides thruster unit with required flow rate, as shown in Fig. 1

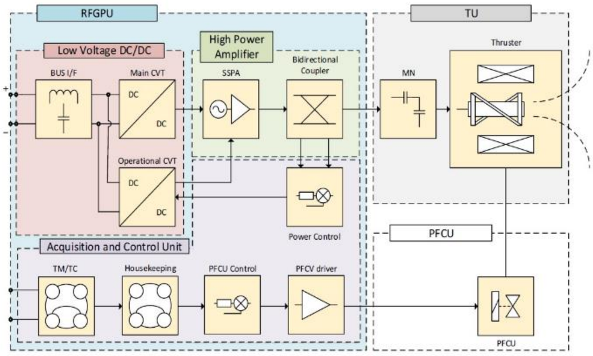

Figure 1: HIPATIA propulsion subsystem overview

HIPATIA technology has high disruptive potential on the small satellites constellations market for LEO and MEO region [1]. The HPT is also scalable for very low orbits since it provides a cathodeless solution that can operate in the conditions of those orbits.

Furthermore, PFCU closed-loop operation based on the thruster feedback signal is developed. The implementation of the closed-loop may increase specific impulse of the propulsion system. The PFCU should be optimized for those operation modes in order to realize the advantages of the whole system.

3. Development Plan

The aim of the HIPATIA Project is to advance the development status of the HPT up to TRL 7 for the complete EP System. Therefore, the impacts associated to having a disruptive thruster in high TRLs would not be achieved unless the complete EP system has proven its integration and operation consistency [1].

Development logic of the propellant unit for HIPATIA is illustrated in Fig. 2. In the first iteration the PFCU elegant breadboard (EBB) is manufactured, which is based on HP-FCU technology developed at AST. After test campaign and design iterations of the whole system the PFCU EQM follows which consolidates the test outcomes and design optimization and raises its TRL to 6.

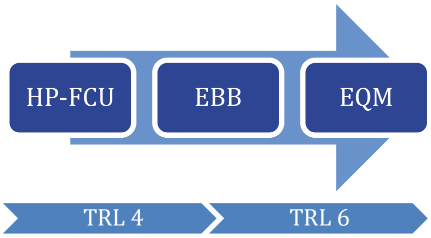

Figure 2: Development logic of PFCU in HIPATIA

4. AST's High-Pressure Flow Control Unit

The PFCU design for HIPATIA is based on AST's HP-FCU. Hundreds of customized units with HP-FCU design currently operate in LEO, providing a solid basis for HIPATIA propellant flow control.

The basic HP-FCU model is a two-stage flow regulator unit, which reduces gas pressure from the tank of the spacecraft (S/C) to a controlled pressure and translates it to the desired flow rate on the anode and cathode lines. The unit is based on the principle of flow rate regulation by switching valves. It consists of filters, high-pressure sensor, high-pressure valve, plena, low pressure valve, low pressure sensor and flow restrictors. HP-FCU is designed for inlet pressures up to 300 bar (450 bar proof) and outlet pressures up to 50 bar, depending on choice flow restrictor and pressure sensor type and required flow range. Typical internal controlled pressures range between 0.5 to 4.5 bar.

5. PFCU Elegant Breadboard Model

The main approach for HIPATIA PFCU is to integrate propellant control unit into EP as deep as possible, by adjusting it to the specific TU and subsystem requirements (e.g. absence of neutralizer line, alternative propellants) while maintaining the maximum flexibility and PFCU manufacturing costs at minimum. The last goal is achieved by a new manufacturing approach. Therefore, the PFCU design is simplified since pressure sensors can be omitted in case of closed-loop operation of thruster unit. The adjustment of the PFCU to the HIPATIA EP is accomplished by means of Elegant Breadboard Model (EBB).

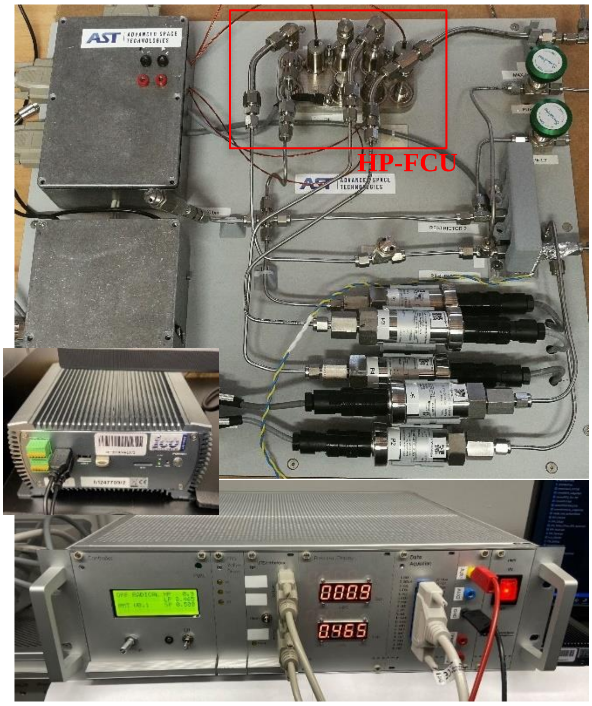

Figure 3: Propellant Flow Control Unit EBB (on top) with EGSE (bottom) at AST's facility

In order to evaluate PFCU performance and to conduct coupling tests with the thruster the elegant breadboard model (EBB) was manufactured. EBB model is used in order to access all flow parameters and support the development of the closed-loop control strategy. Detailed P&ID of the EBB is shown in Fig. 4. The EBB consists of HP-FCU with additional fluidic interfaces and two exchangeable flow restrictors, which provide flexibility for the tests. Since only one line is needed the second line could be used in case the requirement of the flow range for the thruster changes during coupling test and fast design iterations.

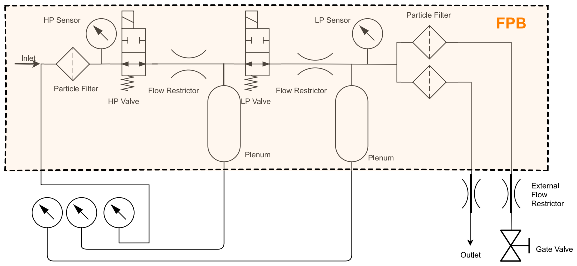

Figure 4: P&ID of PFCU elegant bread board model

Furthermore, the EBB is complemented by AST's EGSE, providing control of the PFCU during performance and coupling tests.

Two identical EBBs were manufactured for parallel testing at UC3M in Madrid and AST facilities in Germany. Manufactured PFCU Twin EBB is shown in Fig. 3. The EBB is equipped with capability for open-loop and closed-loop control.

6. PFCU EBB Test Results

The required performance of the PFCU was verified through tests on the EBB. The test campaigns were conducted in 2021 at U3CM' and AST' facilities.

Various parameters were assessed in order to optimize the flow control unit for the HIPATIA system needs. The PFCU EBB model was successfully coupled with the RFGPU and thruster unit using krypton and xenon. Moreover, tests with krypton were carried out at AST in order to assess PFCU performance and compatibility with alternative propellants for HPT.

Flow rate performances and the end of life performance are presented in the following sections.

6.1. Tested Flow Rate Performance

At the project begin it was identified that, closed-loop operation requires detailed knowledge of the transient behaviour of the PFCU.

Operation points for krypton were identified during design iterations and test campaign. The operation points for krypton are presented in Tab. 2.

Table 1: Operation points of TU for krypton

Operational point	Flow rate for krypton
Ignition	67 sccm
Operation point 1	40 sccm
Operation point 2	20 sccm

The transient behaviour of the flow control unit is evaluated in order to enable closed-loop operation and optimize PFCU performance. A typical measurement of mass flow rate stabilization time between operation points is presented in Fig. 5. Set pressure and mass flow rate are shown with respect to time. The difference between the time at which set pressure is commanded and the desired flow rate is achieved is the transition time, also called mass flow rate stabilisation time.

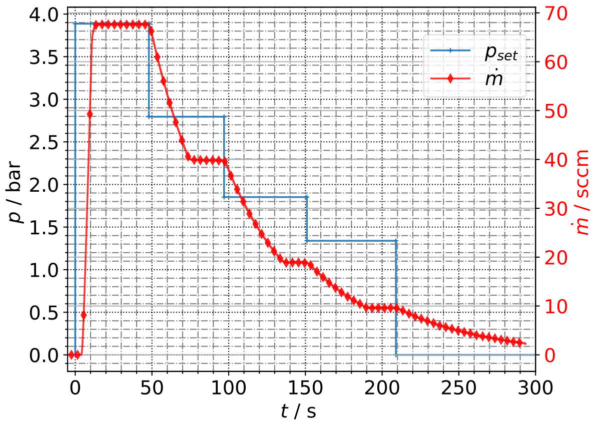

Figure 5: Measurement of transition time between operational points for krypton

It should be noted that stabilization time is also dependant on line-volume between PFCU and thruster, or as in the current case between the PFCU and the measurement device. The measurement results for flow rate stabilization time are summarized in Tab. 2. The transition time between OP2 and cut-off of the EBB is estimated to be 30% higher compared to upcoming EQM due to additional piping in the test setup.

Table 2: PFCU mass flow rate stabilization time for krypton

Transition points	Mass flow rate stabilisation time (s)
Ignition to OP1, OP1 to OP2	<37*
Ignition to OP2	<58*
OP2 to 0	<330*

* High transition time dependent on test setup and used plena, adjustable according to requirements

Relatively high flow rate stabilization time was identified to have impact on EP system performance. However, detailed assessment of this impact showed that no major changes were required for the PFCU EQM design.

6.2. Critical Inlet Pressure

The critical inlet pressure, at which the mass flow rate drops below its nominal value by more than 5% was measured. The minimum inlet pressure could be correlated to the set pressure. Ratio of 1.5 of inlet pressure to set pressure is derived. At this pressure ratio nominal flow rate can be maintained.

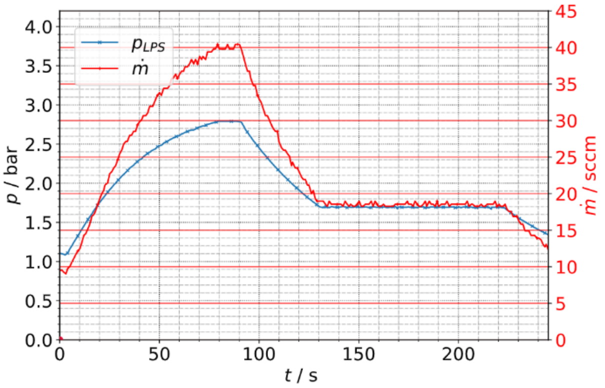

Figure 6: Coupling test of EBB PFCU with thruster unit

6.3. Mass Flow Rate Stability

Mass flow rate stability for krypton was measured. Krypton has less molar weight than xenon resulting into higher ripple of the mass flow. It was confirmed that the PFCU is capable of maintaining mass flow rate stability of $\leq 0.3\%$ for ignition phase and $\leq 0.5\%$ for OP2. The compliance with the system requirements was confirmed.

6.4. Coupling Test with Thruster Unit

Coupling test campaign with the thruster unit was successfully conducted at UC3M in Madrid. Fig. 6 shows thruster ignition and transition to the operation point 1. Commanded internal pressure (p_{LPS}) and measured xenon flow rate ($\dot{m}$) are shown with respect to time. The flow parameters were captured with AST's EGSE. It was confirmed that PFCU EBB can operate with TU and provide it with the desired mass flow rates and required accuracy.

6.5. Test Results Summary

Coupling tests with xenon were successfully conducted with the TU. Additionally, PFCU performance was assessed within test campaign with krypton. High precision measurements of the unit performance were conducted. The measured performance of the EBB with regards to critical inlet pressure, mass flow rate stability was successfully confirmed. The transient behaviour of the EBB PFCU was characterized and assessed for the EQM model.

7. PFCU EQM Approach

Once the data and key performance aspects have been gathered, engineering qualification model (EQM) can be manufactured. Based on the test results and further evolution of requirements, the PFCU design matures to allow for enhanced performances.

The EBB model' HP-FCU contains internal channels and forms the baseplate, fluidic connections and some fluidic functionality of the unit. The EQM is based on more modular concept. The flow path board (FPB) of EQM has a general internal design and can be lately equipped with components which match desired flow regimes and other propulsion subsystem requirements. A stock of premanufactured components such as FPB and flow restrictors is used to manufacture new flow control unit or to apply adaptations after design iterations.

This building block approach used in the EQM manufacturing is visualised in Fig. 7. The main feature of such approach is that the unit can be easily adapted to the specific custom requirements without harming the qualification status of the components.

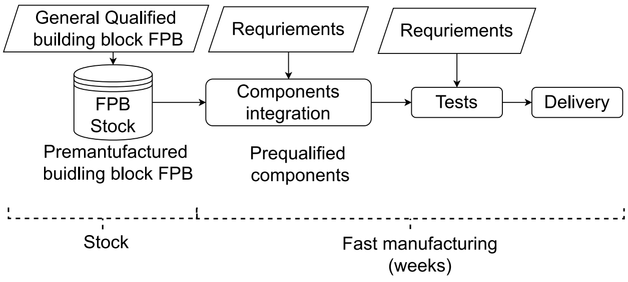

Figure 7: Building block approach for EQM PFCU for HIPATIA

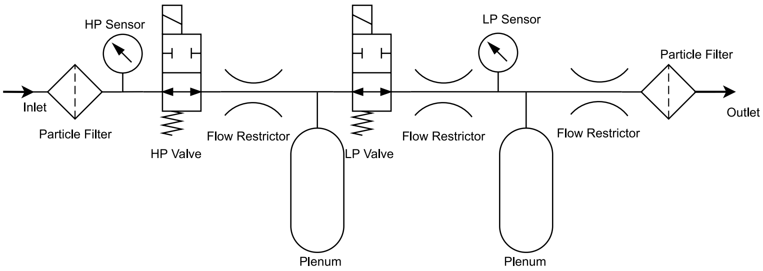

Figure 8: P&ID of EQM with sensors for open-loop operation

This strategy allows long lead item of the FPB and other components to be turned into a general stock product which can be adapted on a fast track.

This approach is applied for the adaptation to the individual thruster requirements at a later integration step.

8. PFCU EQM Design

In the current project phase both designs for closed-loop and open-loop PFCU operation are considered. Two EQMs are going to be manufactured. The first is equipped with sensors and the second relies on feedback signal from the thruster. The EQM1 is shown in Fig. 9. The second volume is subdivided into two due to simplification of manufacturing.

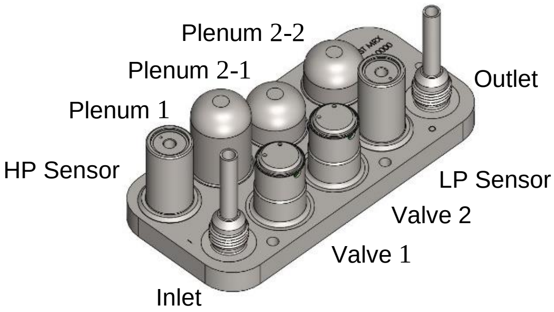

Figure 9: PFCU EQM design

The second EQM pursues concept of closed-loop operation and simplification of the design by omitting of components. The sensors are not required in this case. The EQM2 design allows flow control based on signal obtained from the thruster unit. The concept of closed-loop operation is visualized in Fig. 10. The thruster unit signalizes propellant demand by voltage between 0 to 12 V. Based on that signal low pressure valve is actuated or remains closed. The operation mode of the LP valve is tracked by HP valve and when achieving certain set of parameters, the HP valve is actuated.

9. Summary

Coupling tests were conducted with simultaneous operation of all HIPATIA units including EBB PFCU. Additional tests for transient behaviour of the flow control unit were carried out and the performances were evaluated.

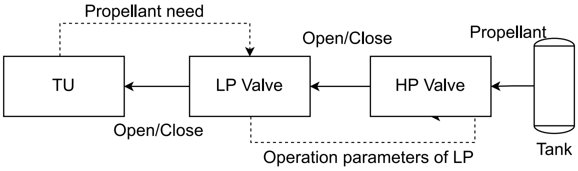

Figure 10: Concept for PFCU EQM closed-loop operation

Especially, the compatibility and flow characteristics for krypton were characterized.

All the gathered data were assessed and used as an input for EQM design. The concepts for closed-loop control operation were worked out and introduced. New manufacturing techniques and building block approach were developed and consolidated for propellant flow control unit EQM production.

10. Way Forward

The manufacturing activities of the PFCU EQMs are already running. The equipment and test facilities for the building block concept are being developed and tested. The coupling test campaign with EQM models of all units of the HIPATIA system is expected in the second half of 2022. Successfully conducted test campaign will raise the TRL of the whole system to 7.

Acknowledgements

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REFERENCES

[1] Mercedes Ruiz, V. Gómez, P. Fajardo, J. Navarro, R. Albertoni, G. Dickeli, A. Vinci, S. Mazouffre, N. Hildebrand ‘The HIPATIA project’s initial development stages: setting the basis to bring the Helicon Plasma Thruster and its associated technologies to intermediate-high TRLs’ *Space Propulsion Conference 2020*, paper 421

[2] Nils Hildebrand, Heiko Dartsch, Hans-Peter Harmann ‘Serial Production of Space Components for Megaconstellations’ in *Space*

Propulsion Conference 2020

[3] Hans-Peter Harmann and Swenja Rothaus ‘Development of a Miniaturized Pressure Regulation System mPRS’ *Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conferenceand 6th Nano-satellite Symposium* 2015

[4] S. Tkatchova ‘*Emerging Space Markets’* Springer Berlin Heidelberg, 2018