Innovative Xenon/Krypton Feed Management System for Electric Propulsion

IEPC-2019-A-601

Presented at the 36th International Electric Propulsion Conference Universitätsring 1 1010
Vienna, Austria
September 15 – 20, 2019

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Abstract: Air Liquide is developing a Feed Management System (FMS) compatible with Xenon and Krypton and Smallsat and Cusebsat market constrains. The heart of the FMS is based on a Multi-Function Valve (MFV) developed in Air Liquide with the support of the French Space Agency CNES. A very light valve, less than 10 grams, delivers a mass-flow directly from the tank outlet pressure, covering the whole range of pressures from BOL to EOL : typically from 300 to 5bar. The FMS mass flow rate covers thruster needs from 50µg/s to 20mg/s and is fully flight adjustable. Electric Propulsion architecture is greatly simplified with this disruptive architecture, bringing in one component two functions: pressure regulation and mass flow rate regulation. This new approach brings competitiveness for future product lines in terms of recurring cost, reliability, number of component, mass, volume and simplicity.

Nomenclature

ALAT	=	Air Liquide Advanced Technologies
BOL	=	Beginning Of Life
BPRU	=	Bang-bang Pressure Regulation Unit
CNES	=	Centre National d'Etudes Spatiales (French Space Agency)
EOL	=	End Of Life
FMS	=	Feed Management System
GC	=	Gas Chromatograph
MFV	=	Multi Function Valve
MOMA	=	Mars Organic Molecule Analyser
PID	=	Proportional – Integral – Derivative
TRL	=	Technology Readiness Level

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I. Introduction

The electric propulsion is a major breakthrough in platform architecture, enabling satellite size reduction and propellant mass savings compared to classical chemical propulsion. Due to the emergence of constellation, the target cost has become a real argument to select a subsystem. Moreover, to increase the competitiveness of the electric propulsion subsystem, Air Liquide Advanced Technologies proposes a Feed Management System based on a micro regulation valve, normally closed. This FMS has been designed to deliver a xenon mass flow rate from 50µg/s to 20mg/s for the anode (corresponding to thrusters range up to 5kW) with upstream pressure from 5 bar to 340 bar. A cathode line can be added to the FMS with ratio anode/cathode of the thruster considered constant +/-10% . This ratio can be easily tune to answer customer needs. The Table 1 presents the main requirement taken into account to design and test the FMS. The Figure 1 presents P&ID taking into account for the FMS development and a first overview of the FMS.

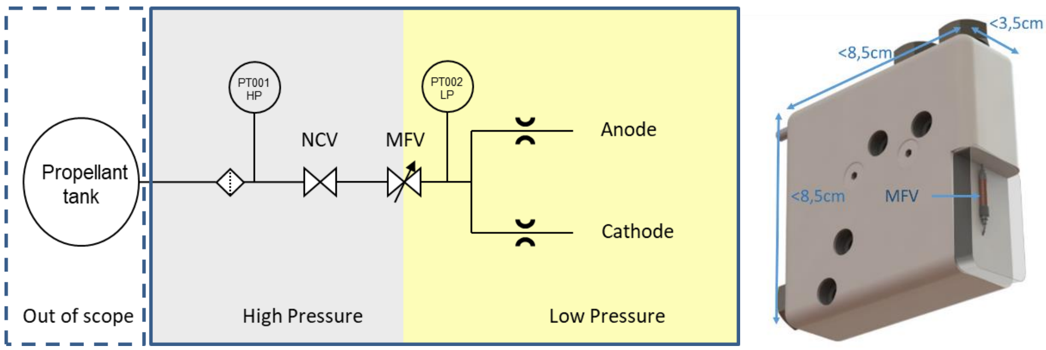

Figure 1 FMS P&ID and 3D model

The FMS is designed following main targets defined by the market needs:

- Regulated flow rates in a single stage from the initial high tank pressure all the way down to end-of-life tank pressure. This eliminates the need for a separate high pressure regulator upstream of a low pressure flow control system
- Positive shut-off which also means that additional upstream valves could be eliminated
- Very important industrialization capability of the PMA design for low recurring cost target
- Very low mass: thanks to the selected component and materials, the targeted mass is <600g.
- Very small overall volume: thanks to the selected components, with important possibility of shaping and so adaptation of interface constraints. Its small overall volume makes it compatible with Cubesat.
- High level of accuracy and stability of flow rate regulation.
- Reliability: MFV valve contains very few components and has no friction part which ensures an important life duration as it has been demonstrated during endurances cycling tests.
- High level of tightness due to process of manufacturing used for the MFV.
- A subsystem ready for integration and used without any other operation except measurement check.
- 300bar at inlet pressure compatibility.

The solution described hereafter is only an example of possible solution taking into account the following hypothesis:

1. Mass flow rate regulation through a feedback loop on the downstream pressure. The FMS is an autonomous sub-system. The FMS can also be driven by thruster discharge current.
2. For this system, only one thruster is considered
3. A non SPF free concept is proposed in order to meet as much as possible the target cost. The redundancy is considered at FMS level.
4. The ECSS -E (engineering) are used as guideline, others as reference

Product name	Xenon feed system
FUNCTIONS	
Storage	No
Xenon regulation	2 lines with two mass flow rates always proportional ➔ 2 outlets
Redundancy	No
PERFORMANCES	
Media compatibility	Inert gas (He / Ar / Kr / Xe)
Mass flow rate (given with Xe) (***)	Line 1 : 0,5-10mg/s for line 1 Line 2 : from 0,1 to 1 x mass flow of line 1
External leak rate	10-5mbar.L/s
Internal leak rate	10-6mbar.L/s
SIZING	
Volume	3,5cm x 8cm x 8cm
Mass	500g
Maximum pressure	340bar
Proof factor	1,5
ENVIRONMENTS	
Temperature	-40°C/50°C
Sine (Three axes)	24g
Random (Three axes)	20Hz : 0,008 g^2/Hz 100Hz : 1,0 g^2/Hz 250Hz : 1,0 g^2/Hz 2000Hz : 0,004 g^2/Hz
INTERFACES	
Inlet	Male VCR 1/4"
Outlet	2 Males VCR 1/4"
Electrical	2 connectors (TBC)
Mechanical	M5 (TBC)

Table 1 FMS specification

(***) These flow rates are given as orders of magnitude. For upper or lower mass flow rate please contact us

II. Feed Management System

The FMS developed by Air Liquide relies on the Multi-Function Valve. The overall FMS performance is given by the MFV performance. A section is then dedicated to the performance of the MFV. The other components of the FMS are present to give FMS autonomy, information, robustness and security.

The solution proposed by AlaT is composed of:

- The NCV is a solenoid isolation valve. It is not latch but have very low electrical consumption.
- The MFV ensuring the regulation function of the PMA
- The FMS has two HP barriers of isolation (the NCV and the MFV).
- The HP filter is preferably chosen less than 1 µm filtering.
- One high pressure transducer
- One low pressure transducer for closed loop regulation, not needed if regulation on discharge current
- One orifice for the anode line and another orifice for the cathode line (the second orifice could be removed).
- The electronics is not part of the equipment, ALaT specifies the regulation software taking into account (depending on the thrusters selected) :
    - The thrusters discharge current
    - Or the pressure measurement given by the low pressure transducer

Main of the component are COTS with flight heritage. This strong bias in favor of COST is justify by the market target cost. The COTS mainly come from aeronautic domain. As they are produce and use in a larger amount, they are then more reliable than a space COTS produced at only a few quantity a year. The COTS used have successfully passed mechanical load tests.

This design takes into account DTC constraints for optimizing the MAIT phase while keeping a very high level of quality. Indeed, only brazing is considered which is perfectly mastered by Air Liquide thanks to other space products (cryocoolers). Some elements are screwed (NCV and pressure transducer) for an efficient and robust integration. Considering all these elements, ALAT succeed in developing a very cost efficient product which could be duplicated to reach the right level of robustness for the FMS final concept.

III. FMS Test results

A FMS breadboard has been developed to assess key parameters of the FMS. The breadboard is composed of all the COTS components used for the FMS. Only the mechanical parts are different in terms of materials and aspect. The test bench is described in Y.Fendler et al. 2017.

A. Open loop

Even if this type of test is not representative of the drive method of the FMS in a regulation system, it is useful to enhance our understanding of FMS behavior under various operational conditions. For instance this type of test allows evaluating the FMS operating range, the valve power consumption or the valve opening and closing reactivity.

For this type of test an upstream pressure is settled, for instance 300bar in Krypton, and a defined current is imposed to the valve. When the valve temperature is stabilized, the mass flow rate is measured.

These stationary tests allow us to determine the operating range, i.e. the mass flow rate range which can be regulated for each upstream pressure, and consequently for the different phase of lifetime of the satellite. During this test campaign, we focused on the upper limit of this operating range. These preliminary tests were successful and demonstrated that the valve was able to deliver a mass flow rate up to 20mg/s required by a 5kW class thruster.

This test campaign also allows to determine, for a given upstream pressure, the power required by the valve to deliver a given mass flow rate. These curves represent the ID card of our FMS and are used to compare the reproducibility of produced FMS.

The open loop driving mode can procure a contingency mode in case of the downstream pressure sensor or the discharge current measurement are not more available.

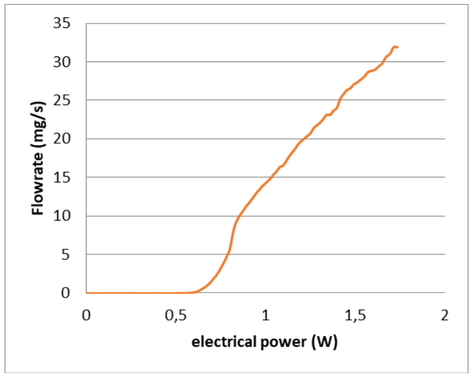

Figure 2 Open loop characterization of the breadboard FMS (anode line) at 300bar with Krypton

B. Close loop test

The close loop test was performed with the FMS breadboard with the COTS components. The Figure 3 presents the two main phases of the regulation performed with the breadboard FMS at 300bar with Krypton:

- The preheating of the MFV in order to accelerate the FMS response time and facilitate the regulation. This phase takes about 1 minute and can be removed to simplify the electronic regulation.
- The regulation phase composed of the transition phase and the stabilized phased

The transition phase takes about 30s with a slight overshoot due to the high inlet pressure (300bar). This overshoot is due to the high inlet pressure and the small downstream volume. This BOL inlet pressure represents the most difficult point to regulate in terms of reactivity and stability of the system. Thanks to the MFV, the stabilization of the mass flow rate is reached in 30s with a tolerance of +/-2%.

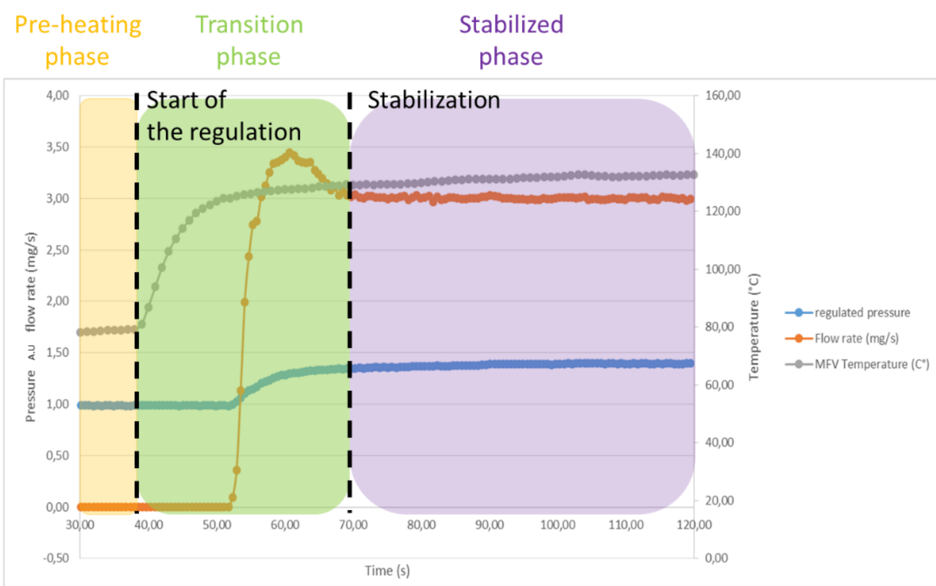

Figure 3 Close loop test at 300bar with Krypton

The Figure 4 presents a closed loop regulation performed with the FMS breadboard at 300bar in Krypton. The aim of this regulation was to drive two different but proportional mass flow rate (ie Anode and Cathode) with one FMS. As the regulation is based on the downstream pressure signal the flow rate follow the same behavior. The proportionality is ensured by the orifices. As the gas going through the MFV is heated, the regulation thanks to the couple pressure/ orifice is less sensitive to temperature variation. The thermal stability of the system is still to be demonstrated.

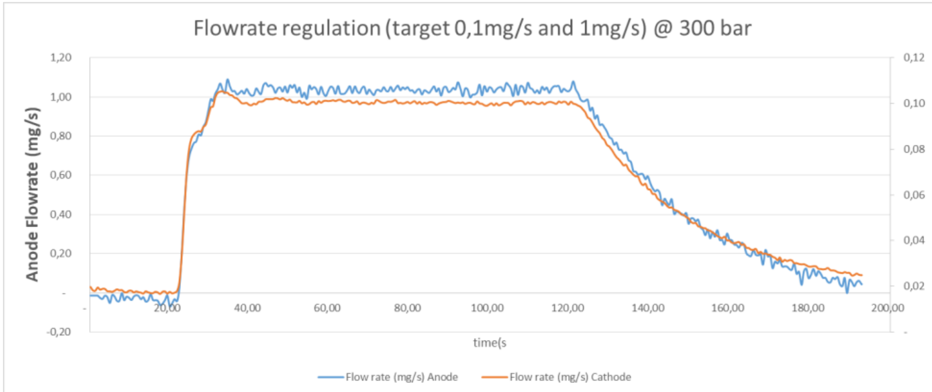

Figure 4 FMS breadboard test driving two proportional flow rate

The observe noise on the Blue curve is only due to the resolution of the mass flow meter.

IV. Multi-Function Valve, the heart of the FMS

The Air Liquide micro Multi-Function Valve (MFV) is a regulation normally closed valve based on thermal expansion. This component has also already been used as ON/OFF valve on the MOMA-GC ExoMars 2020 rover. The micro MFV is really compact (some few centimeters of length and some few millimeters of diameter), as shown on Figure 5, and can support a 200 bar inlet pressure. A current development, supported by the French Space Agency, aims to make this valve compatible with 300bar upstream pressure. Fluidic interfaces are two capillary pipes whose size and material can be adapted depending on the required interface.

When the valve is electrically powered with a calibrated current, the surrounding winding ensures the heating of the component.. On the contrary when the valve power supply is switched off, the valve cools down (mainly by conduction and radiation) and closes. The power consumption of the micro MFV is lower than 3W (depending on the requested opening). The opening temperature of this valve is settled during manufacturing depending on the mission thermal environment. This parameter can easily be adapted to fit customer requirements. To minimize the power consumption it is recommended to settle the opening temperature, by keeping a reasonable margin, just above the maximal temperature expected during the mission. The leak rate measured with Helium is lower than 10^{-7} mbar.L/s. Main characteristics of the valve are summed up in Table 2 Key features of Air Liquide micro Multi- Function Valve.

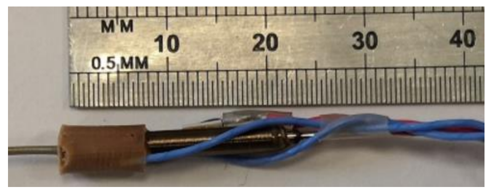

Figure 5 Air Liquide Multi Function Valve

Type of Valve	Normally Closed / Regulation electronically controlled micro valve (can also be used as an ON/OFF valve)
Size	Length < 25mm Diameter < 3,5mm
Weight	<10g
Internal/External Tightness	<10^{-7} mbar.L/s
Media	Inert gas (He / N2 / Xe / Kr / Ar)
Mass flow rate range	0-20mg/s
Power Consumption	< 3W
Inlet Pressure	5-300bar
External environment	Atmosphere down to vacuum
Thermal environment	-40°C / 60°C

Table 2 Key features of Air Liquide micro Multi- Function Valve

This sections will recall only the key characterization of the MFV which are directly link to the reliability and performances. More details can be found in Y.FENDLER et al. 2017.

A. Leak Test Results

The internal leakage of the component has been determined with Helium for different upstream pressure up to 180bar. The measured leak rate is always lower than 10^{-7}mbar.L/s until valve temperature is lower than valve opening temperature. An example of curves obtained (representing Helium leak rate as a function of valve temperature) is presented in.

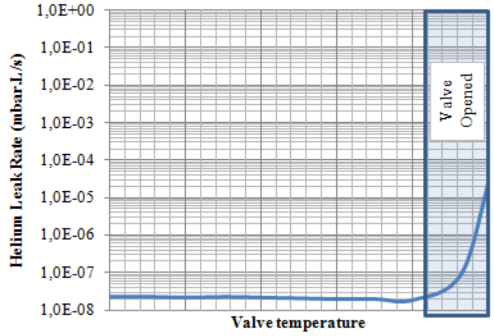

Figure 6 MFV leak test

B. Test Results

A PID controller was developed under Labview with the aim to ensure the following performances: the targeted mass flow rate has to be reached in less than 30s and no overshoot greater than 5% of targeted mass flow is admitted.

The PID controller is used to regulate the pressure downstream the valve. The mass flow rate is ensured by a calibrated orifice located downstream the plenum and the micro MFV.

Some preliminary tests were performed with Krypton. For different upstream pressures (from 3bar to 150bar) the P, I and D parameters were optimized to obtain a targeted downstream plenum pressure as quickly as possible without significant overshoot. In all the cases the targeted mass flow rate were obtained in less than 20s.

The flow rates are regulated with an accuracy and a stability of ±2%.

At the end of these tests, the closing duration of the micro MFV after power supply extinction is measured. An example of results is given on Figure 5.

These tests demonstrated that the transient phases (opening and closing of the valve) can be reduced up to 10s to 20s, and that the flow rate can be regulated with a good accuracy and stability on the whole operating pressure range.

A test sequence with several operating points in xenon was performed. Three operating points, representative of a 5kW range thruster, were targeted:

- OP1 : 8,5mg/s
- OP2 : 11mg/s
- OP3 : 16mg/s

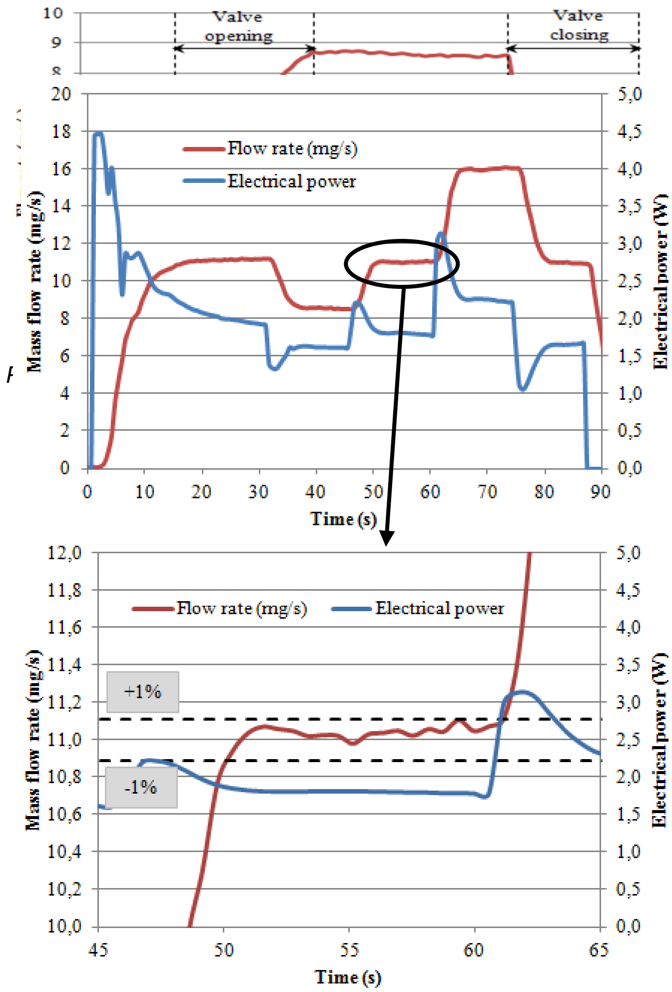

Figure 8 Sequence in closed loop configuration with Xe

The following sequence was performed: thruster ignition (micro MFV opening) ➔ OP2 ➔ OP1 ➔ OP2 ➔ OP3 ➔ OP2 ➔ disengaging thruster (micro MFV closing).

In the Figure 8, the results obtained with xenon for an upstream pressure of 10bar are presented. For the opening of the micro MFV, the first targeted mass flow rate is reached in 20s. All the other transient phases (from an operating point to another one) are shorter than 10s.

All the targeted mass flow rate are reached and are regulated with a stability of ±1%.

The power consumption of the valve is below 3W (average), and can reach 4,5W (peak) at the opening.

This sequence was tested with different upstream pressure from 3bar up to 50bar (the upper limit that can be reached with xenon without compressor).

We can conclude that the micro MFV is able to regulate a flow rate from 0mg/s to 20mg/s with an excellent stability (±1% of targeted mass flow rate) and accuracy for an inlet pressure from 200bar to 7bar (for high flow rates). Some additional works are performed by ALAT to decrease this low limit of pressure to 3bar.

C. Endurance Test Results

Some endurance tests were performed on this concept of regulated valve. 20,000 opening / closing cycles were performed. Some leak tests and a valve characterization in Helium and in open loop were performed at the beginning of the valve endurance test and all the 2,500 cycles. It was observed that the leak rate was not affected by the opening / closing cycles. A leak rate below 10^{-7} mbar.L/s is obtained all along the endurance test. The tightness of the valve is not affected by the successive opening and closing cycles.

A discrepancy is observed between the several different characterizations performed all along this endurance test (cf.Figure 9). The behavior of the valve is slightly affected by these cycles, but this effect is easily balanced by a closed loop regulation.

Regarding these results it appears that the valve maintains its low leak rate and is able to regulate on the same range of flow rate all along its lifetime. We can conclude that there is no expected degradation of valve functioning during its lif**e**.

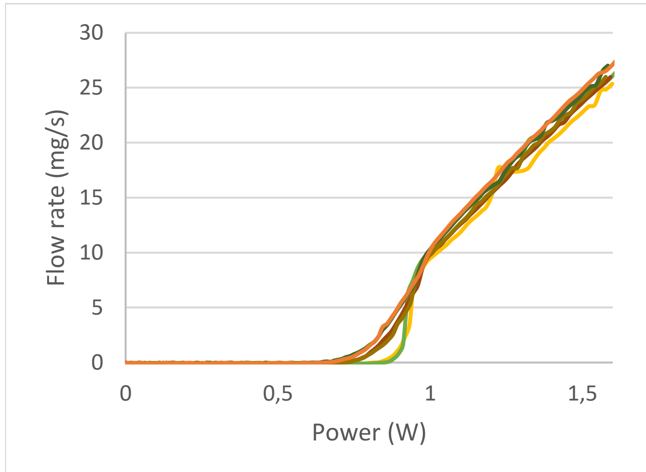

Figure 9 Calibration curves before, during and after lifetime test (20 000 on/off cycles)

D. Impact of thermal environment

The micro MFV concept is based on thermal expansion of materials and on temperature regulation of the valve. It is important to demonstrate that this valve can be used in thermal environments commonly specified for such a component. A test of regulation stability was performed with a temperature increase of the base plate. During this test the mass flow rate is regulated, thanks to the PID controller, at a value of 8,5mg/s in Kr with an upstream pressure of 70 bar. When the targeted mass flow rate is obtained, the temperature of the base plate is increased up to 90°C. The Figure 10 shows that the mass flow rate is not affected by the temperature increase of the environment. The PID controller counterbalances this environment temperature increasing by decreasing the power supply of the valve.

Moreover the opening/closing temperature of the valve can be tuned during manufacturing process. This temperature is generally settled from 20°C to 40°C, depending on the required margin, above the upper limit of the operating and non-operating temperature range requirement. We can observe that, even at 90°C the tested valve keeps its tightness. It ensures that the valve is tight on its whole temperature operating range. Moreover the closing time of the valve is not affected by a "hot" environment. As seen on figure 9, less than 20s are required for the valve closing at 90°C, which is typically the closing duration at ambient temperature.

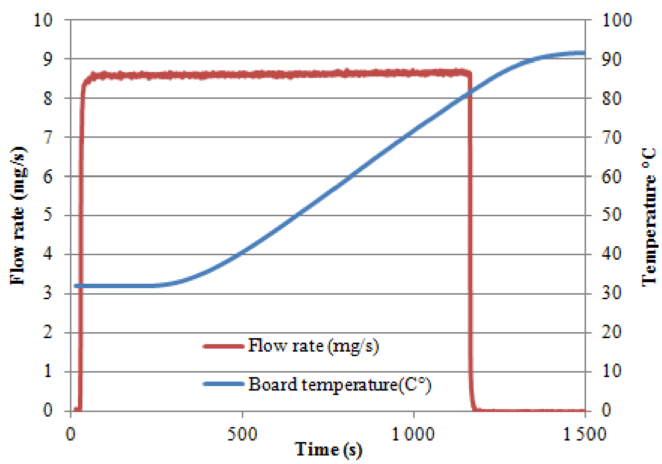

Figure 10 Mass flow rate evolution of the valve with a variation of the temperature environment

The environment temperature seems to have no significant impact on valve behavior and on its closing duration.

E. Coupling test with thruster

In the frame of CNES project and in part, Air Liquide managed to perform coupling tests with 1kW range Hall Effect thruster. These tests have been performed in CNRS laboratory (ICARE). The thruster was mounted on the test bench PIVOINE_2G.

The goal was to validate the performances of the valve and the thruster for different flow rate and different upstream pressure. The foreseen sequence is described in *Figure* 11

Operating point	F1	F2	F3
Discharge current (A)	2,5	3	4,2
Discharge volatge (V)	350	350	350
Xenon flow rate	2,5	3,5	5

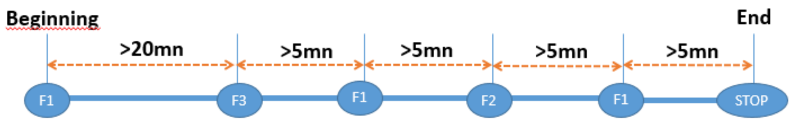

Figure 11: Operating point for coupling tests

5 different upstream pressures were considered and tested: 180 bar, 120 bar, 60 bar, 10 bar, 3 bar.

Initially it was foreseen to duplicate these tests points with 2 different closed loop regulation: one based on the discharge current of the thruster and another one based on the pressure downstream the valve. However, due to the configuration of the thruster test bench (with a very long pipe between the valve and the thruster), a high inertia was present between the instruction on the valve and the discharge current feedback. Thus, high response time of the system was observed with poor flow rate stability. This behavior was highly improved while regulating the flow rate on the pressure transducer.

As a consequence, closed loop regulation on discharge current was only performed on high pressure.

The *Figure* 12 shows the flow rate regulation (blue curve is the discharge current and orange curve the downstream pressure) performed by the valve for 180 bar upstream pressure of Xenon with closed loop based on discharge current.

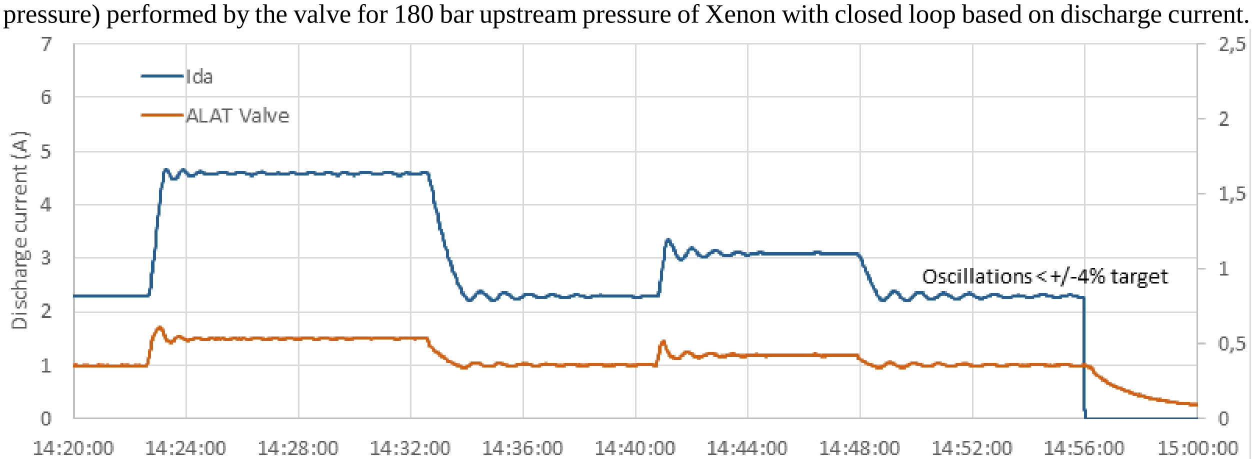

Figure 12 : Discharge current regulation for 180 bar upstream pressure

As explained, response time and flow rate stabilization is not optimized due to configuration of test bench. On the *Figure* 13, the same sequence is plotted but with regulation on the pressure transducer downstream the valve. Then we note a better flow rate stability with lower response time (~30s for opening).

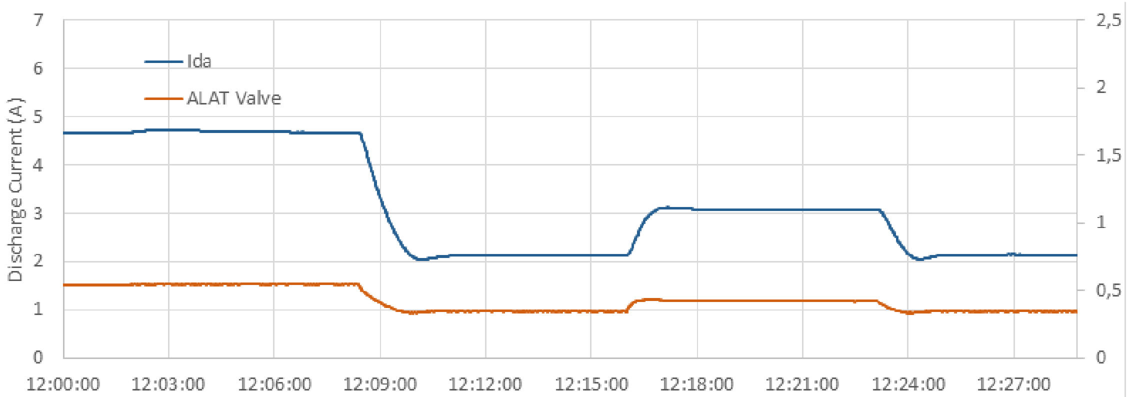

Figure 13 : Downstream pressure regulation for 180 bar upstream pressure

Transient time for closing are around 100s because of the power threshold on the valve. Indeed, to avoid switching off the thruster during test sequence, a minimum power was supplied to the valve. Thus, the valve was continuously heated between different operating points which cannot allow optimization of transient time when reducing the flow rate. Clearly, this threshold could be removed for flight test sequence.
These performances could also be achieved with regulation on the discharge current considering some modifications on the thruster test bench.

The test sequence has also been successfully performed with a pressure of 3 bars upstream the valve as depicted in the *Figure* 14.

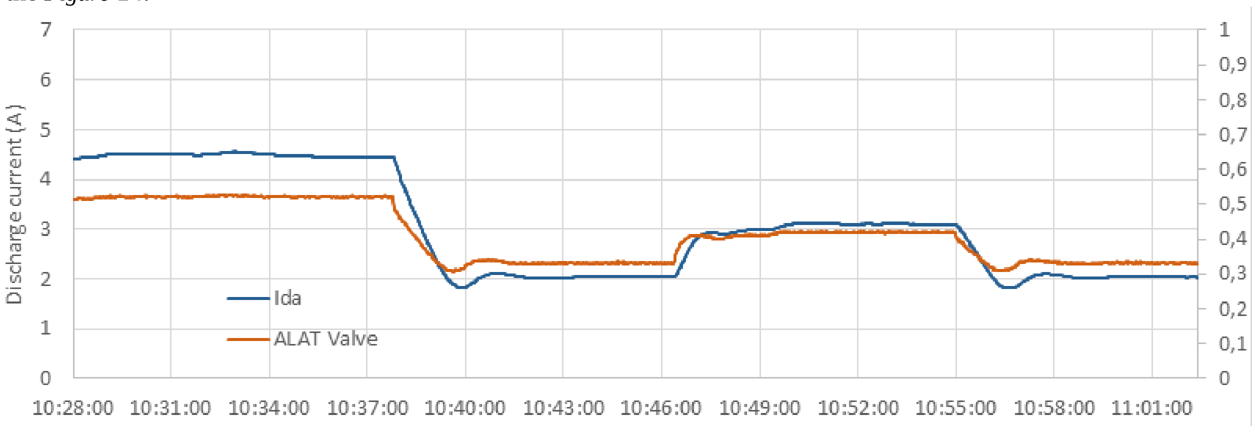

Figure 14 : Downstream pressure regulation for 3 bar upstream pressure

Transient times are obviously higher than for high upstream pressure but the valve succeed on regulating a flow rate of 5mg/s with this low pressure.

V. Propellant Management Assembly for Cubesat

Thanks to its development and heritage on different space project, Air Liquide has developed a tailor-made Propellant Management Assembly (Storage tank + FMS) for 30W Cubesat Thruster (50µg/s of Xenon) included in 1U. As for the FMS, the performance of the PMA relies on the use of the MFV. The PMA is designed with the same COTS as the FMS. This gives more heritage to the COTS used in the FMS. The Figure 15 presents the PMA and the Table 3 resumes the main performances and specifications of the Cubesat PMA.

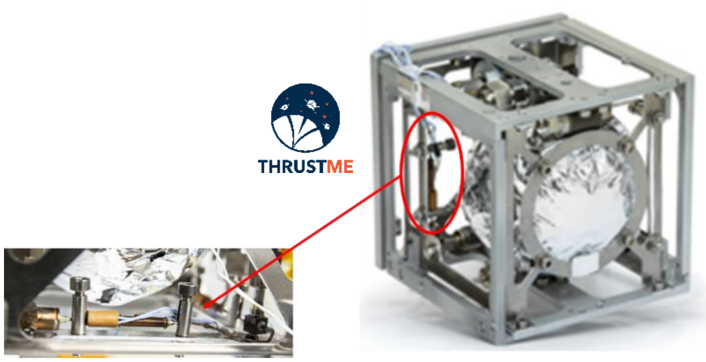

Figure 15 Tailored-made PMA for Cubesat mission

The PMA is designed to provide from 50µg/s up to 150µg/s of Xenon with a MEOP of 140Bar. The Xenon load capacity is 200g.

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It has been designed following ECSS as guideline. Proof pressure (>200bar during 5min) and burst pressure test has been carried out on the tank with a burst pressure of 430bar.

The PMA passed the mechanical tests with mechanical loads defined in the Table 3.

The Figure 16 presents the mass flow rate obtained in close loop regulation with the PMA with the tank pressurized with 5bar of Krypton. This inlet pressure is relevant of the EOL of the cubesat, then the desorbitation.

The Figure 16 presents the mass flow rate obtained in the same configuration at 40bar. The flow rate response obtained is satisfactory despite the small plenum volume and the reactivity of the valve. The observe flow rate stability is satisfactory for Cubesat propulsion.

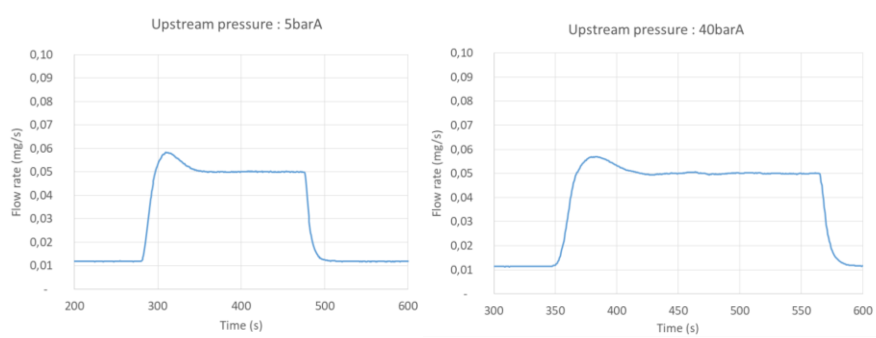

Figure 16 Close loop test with PMA at 5bar and 40bar with Krypton

The PMA performances are:

- Stability of flow rate
- High xenon pressure compatibility

The PMA is planned to be launched on 2020.

Product name	**Propellant management assembly (Tank + Xenon feed system)**
FUNCTIONS	
Storage	Tank for 200g of xenon with heating system for thermal regulation
Xenon regulation	1 regulation line with two ranges of mass flow rate ➔ 1 outlet
Redundancy	High flow rate line can be used as a redundancy of the low flow rate line
PERFORMANCES	
Media compatibility	Inert gas (He / Ar / Kr / Xe)
Mass flow rate (given with Xe) (***)	0,01-0,2 mg/s or 0,5-10mg/s (depending on the line used)
External leak rate	10-4mbar.L/s
Internal leak rate	10-6mbar.L/s
SIZING	
Volume	10cm x 10cm x 10cm
Mass	500g (without xenon)
Maximum pressure	140bar
Proof factor	1,5
ENVIRONMENTS	
Temperature	-40°C/50°C
Sine (Three axes)	13g
Random (Three axes)	20Hz : 0,01125 g^2/Hz 130Hz : 0,05625 g^2/Hz 800Hz : 0,05625 g^2/Hz 2000Hz : 0,015 g^2/Hz
INTERFACES	
Inlet **Outlet**	1/16" SS capillary 1/16"" SS capillary
Electrical	Wires (details on demand)
Mechanical	Cubesat Interface

Table 3 PMA specification

VI. Conclusions

A FMS is under development at Air Liquide. The tests which have already been performed are encouraging. The FMS can deliver flow rates adapted to thrusters in the range 30W-5kW and address different thruster technologies with the 2 output lines. Thanks to the MFV, the transient phases observed are lower than 30s (opening / closing / transition from one operating point to another one) and this component allows a regulation with a good accuracy and stability (<±2% of the targeted mass flow rate). Moreover, the cycling of the valve have no significant impact on its performances.

The main strengths of this FMS are:

- Its compatibility to high pressures
- Its high tightness
- Its low mass
- Its small size
- Its low cost target

Some additional tests are under progress with the aim to reach a TRL6 by the end of the year.

Air Liquide is currently working on an evolution of the cubesat PMA using the current development of the FMS. A proposition is given in Figure 17. In consist on placing the FMS in a cubesat structure and integrate a gas tank designed for the desired load. Depending on the desired gas mass, the PMA can be greater than 1U.

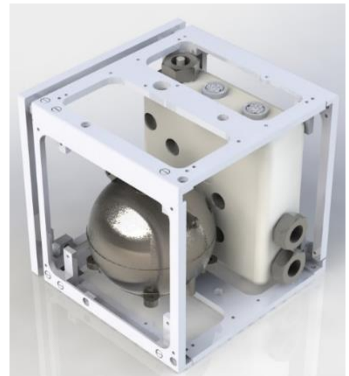

Figure 17 Evolution of the cubesat PMA

Acknowledgement

The authors acknowledge the CNES for the MFV development grant and ThrustMe to design and provide the cubesat structure.

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