INNOVATIVE XENON REGULATION FOR ELECTRIC PROPULSION

SPACE PROPULSION 2018

SEVILLE, SPAIN / 14 – 18 MAY 2018

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KEYWORDS: propulsion components, pressure regulator valve, flow regulator valve, coupling tests, krypton valve,

ABSTRACT:

Air Liquide has developed, with the support of the French Space Agency CNES, a xenon (or any other gas such as Krypton) flow regulator in rupture with standard systems. A very light valve, less than 10 grams, delivers a xenon mass-flow directly from the tank outlet pressure, covering the whole range of pressures from BOL (Begin Of Life) to EOL (End Of Life): typically from 200 to 3bar (which are our current requirements, but this range can be adapted to higher pressures). Mass flow rate covers thrusters needs from 0mg/s to 20mg/s and is fully flight adjustable. Response time and stability can be tuned thanks to PID regulation loop. 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. This component is derived from a helium pressure regulator onboard Rosetta Philae and will be onboard ExoMars 2020 rover. This paper presents results of xenon regulation in closed-loop under vacuum (in laboratory and coupled with a thruster) and the results of endurance tests.

1. INTRODUCTION

The electric propulsion is a major breakthrough in platform architecture, enabling satellites size reduction and propellant mass savings compared to classical chemical propulsion. Moreover, to increase the competitiveness of the electric propulsion subsystem, Air Liquide Advanced Technologies proposes a micro regulation valve, normally closed and based on thermal expansion, with the aim to significantly reduce the regulation plate mass and complexity. This technology is already used on MOMA-GC of ExoMars 2020 rover. This new regulator has been designed to be able to deliver a xenon mass flow rate from 0mg/s to 20mg/s (corresponding to thrusters range up to 5kW) with upstream pressure from 3 bar to 200 bar. This technology was initially developed to regulate an Helium mass flow, and it will be used inside the MOMA-GC (gas chromatograph) of the ExoMars Rover.

The main advantages of this regulation valve are:

- compatibility to high pressures
- compatibility with many gas
- very low leak rate (<10-7 mbar.L/s)
- very low mass (some few grams)
- size (some centimeters of length and some millimeters of diameter)
- Can regulate downstream pressure and/or mass flow rate depending on the mounting and the control law
- High reproducibility of performances

2. MULTI FUNCTION VALVE

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. The micro MFV is really compact (some few centimeters of length and some few millimeters of diameter), as shown on Figure 1, and can support a 200 bar inlet pressure. Fluidic interfaces are two capillary pipes whose size and material can be adapted depending on the required interface.

Figure 1 : Air Liquide Multi Function Valve

When the valve is electrically powered with a calibrated current (around few hundred of mA), the surrounding winding ensures the heating of the component which induces a calibrated space between the valve seat and the valve piston. 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 1

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
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	3-200bar
External environment	Atmosphere down to vacuum
Thermal environment	-40°C / 110°C

Table 1 : Key features of Air Liquide micro Multi Function Valve

3. TEST BENCH

A test bench dedicated to micro MFV performances characterization has been developed by Air Liquide (see Figure 2). This test bench is compatible with He, N2, Xe, Kr and Ar. It feeds the regulating valve with an upstream pressure between 1bar and 200bar. Thanks to a vacuum chamber, the micro MFV can be characterized under a secondary vacuum environment. The base plate on which the valve is fixed can be regulated in temperature from ambient up to 110°C. A vacuum pump can be used to have a primary vacuum downstream the micro MFV to be representative of conditions encountered in the feeding line of a thruster. Moreover, the output of the test bench can be easily plugged to a thruster. This test bench can be coupled with a spectrometer to perform valve internal leak rate test or with a compressor to perform Xe high pressure tests.

The test bench is instrumented to perform the following acquisition during tests:

- Upstream pressure and temperature
- Valve temperature
- Valve power supply
- Vacuum in test chamber
- Temperature of base plate
- Downstream pressure and temperature
- Mass flow rate downstream the valve

For closed loop tests a Labview program has been developed and is used for regulation. A PID feedback loop is used to control the valve on the downstream pressure. The feedback loop can be easily settled on discharge current of the thruster

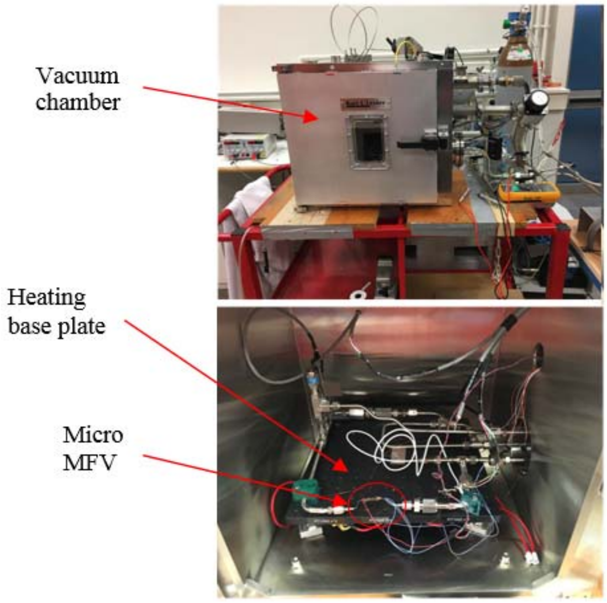

Figure 2 : Micro MFV Test Bench

4. TEST RESULTS

4.1. 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 10-7mbar.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 on Figure 3.

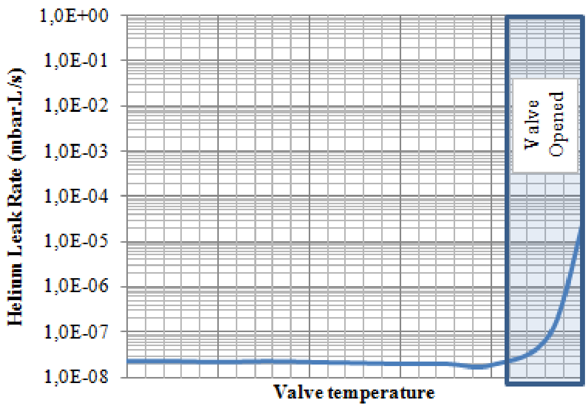

Figure 3 : Micro MFV Leak Test Results

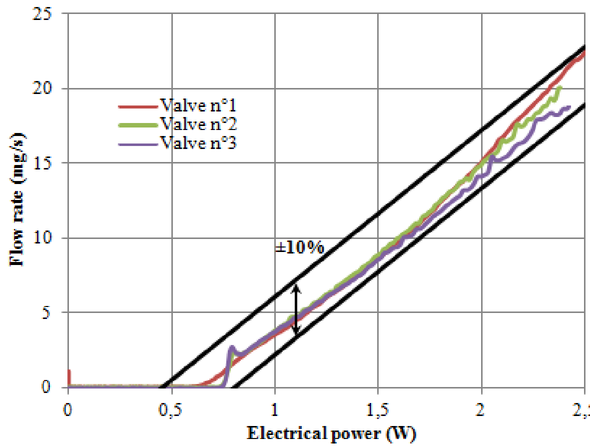

Figure 4 : Micro MFV reproductibility (with Kr / 100bar upstream pressure)

4.2. Open Loop Test Results

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

For this type of test an upstream pressure is settled, and a defined current is imposed to the valve. No regulation based on instrumentation is used to modify the valve power supply. 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 valve and are used to compare the reproducibility of produced valves (Figure 4). With this test, we have demonstrated that the valve manufacturing is well controlled and does not induced a dispersion in the behaviour of different valves which could be a real danger, considering the size of the different parts and of the final component.

The valves tested can have a difference on the measured downstream mass flow rate of the order of 10% for a given power supply as we can see on Figure 4. Such a weak gap can be easily counterbalanced by the closed loop regulation; indeed this component is not dedicated to an open loop use.

4.3. Closed Loop 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 105% 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.

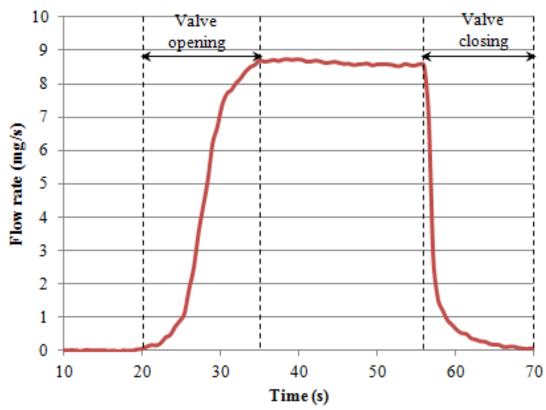

Figure 5 : Closed loop test configuration with Kr with 150

bar upstream

These tests demonstrated that the transient phases (opening and closing of the valve) can be reduced up to 10s (closing) and to 20s (opening) maintaining the flow rate with a very 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

The following sequence was performed: thruster ignition (micro MFV opening) ➔ OP2 ➔ OP1 ➔ OP2 ➔ OP3 ➔ OP2 ➔ disengaging thruster (micro MFV closing)
On the Figure 6 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.

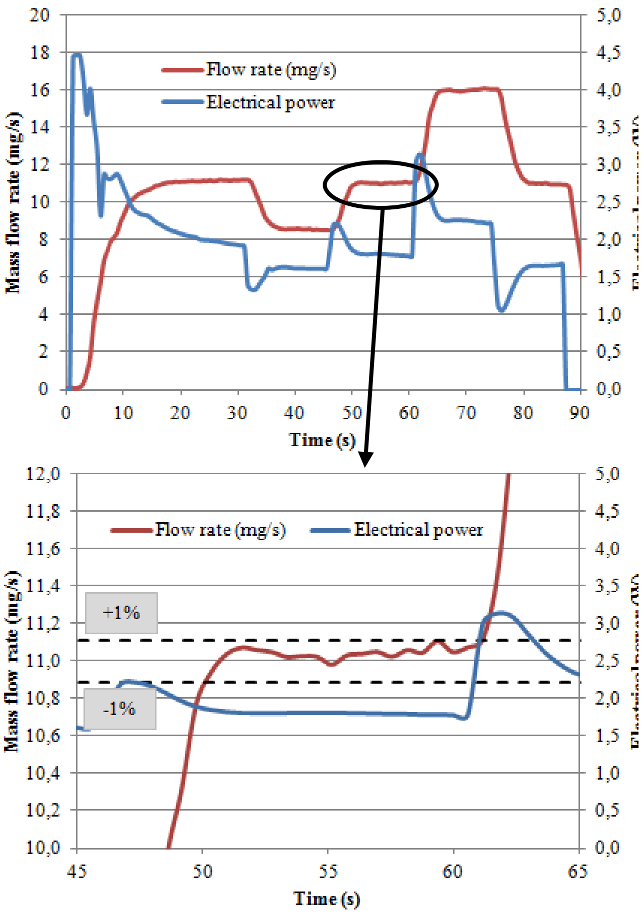

Figure 6 : Sequence in closed loop configuration with Xe

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).

4.4. Endurance Test Results

Some endurance tests were performed on this concept of regulated valve. 10,000 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 five different characterizations performed all along this endurance test (cf. Figure 7). 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 life.

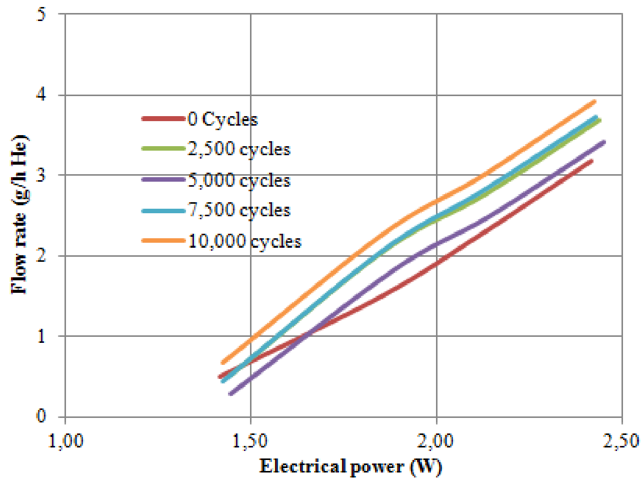

Figure 7 : Evolution during endurance test

4.5. 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.

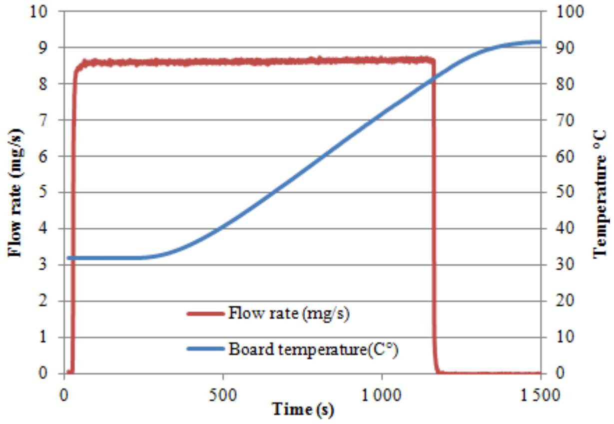

Figure 8 : Mass flow rate evolution of the valve with a variation of the temperature environment

The Figure 8 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.

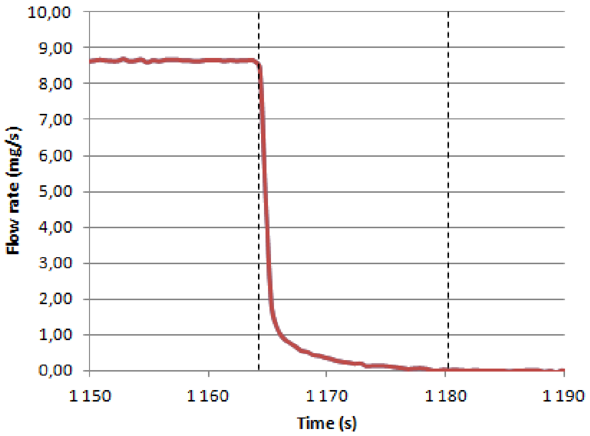

Figure 9: Valve closing in a "hot" environment (90°C)

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

5. VALVE MODELIZATION

An EcosimPro model of the valve has been developed and calibrated on experimental data with the aim to be integrated in a model of a full xenon regulation system (cf. Figure 10). The valve model can be used with Xe and Kr.
The result of the model helped us to find the good PID parameters for regulation without instabilities.

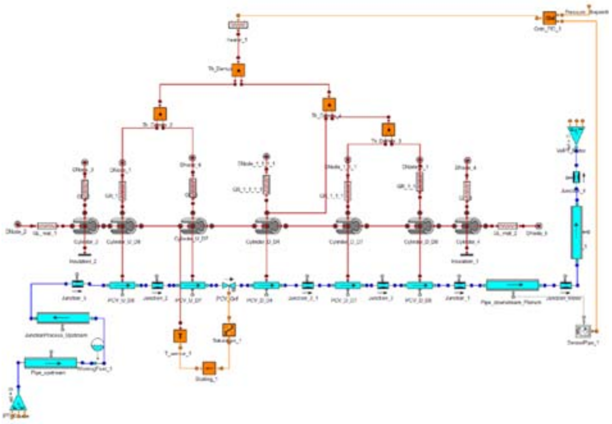

Figure 10: Functional scheme developed with Ecosim-Pro

6. HIGH PRESSURE TESTS WITH XENON

In order to validate the performances of the valve on the whole operating pressure range, high pressure tests with Xenon have been performed thanks to the use of acompressor. We then could test and validate the valve up to a pressure of 180 bars.

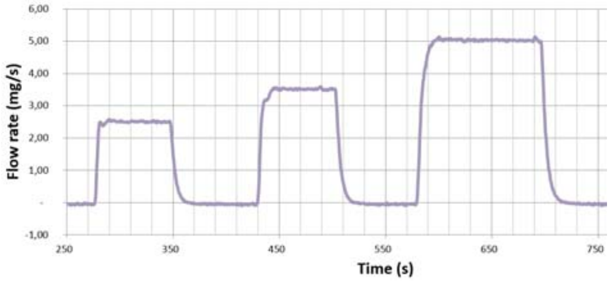

Figure 11 : Flow rate regulation with Xenon high pressure of 180 bar

On *Figure* 11, a closed loop regulation is performed with Xenon upstream pressure of 186 bars and 3 sequential flow rate: 2.5mg/s, 3.5mg/s and 5 mg/s. The valve is able to regulate the targeted flow rate in around 20s with a very good stability and no overshoot.

7. COUPLING TESTS WITH TRHUSTER

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 12

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

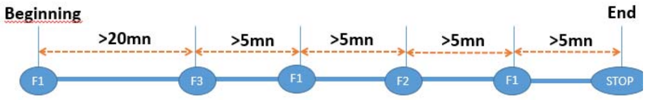

Figure 12: Operating point for coupling tests

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 13 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 13 : 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 14, 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).

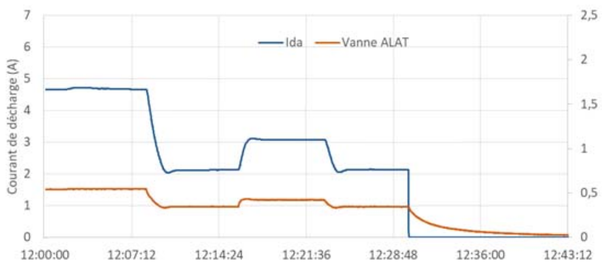

Figure 14 : Downstream pressure regulation for 180 bar upstream pressure

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 15.

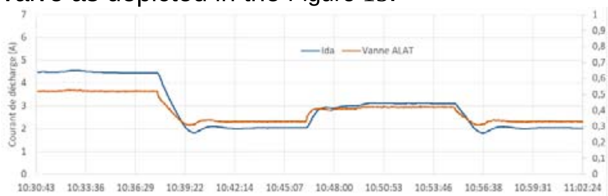
Figure 15 : Downstream pressure regulation for 3 bar upstream pressure

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.

8. SHORT TERMS ON-GOING DEVELOPMENTS

Considering the valve performances measured with laboratory environment and coupled with a thruster, Air Liquide aims now at demonstrating the high reliability and TRL of this product. It is then foreseen to perform pollution robustness tests. Moreover, new lifetime tests with statistical representative batch of valve will be set-up.
In parallel, Air Liquide will continue improving and characterizing the performances by:

- Perform new coupling tests with thruster (with an optimized test bench configuration for discharge current regulation)
- Integrating the valve on regulation line already in development [9].
- Adapting the valve design for compatibility with Krypton
- Adapting the valve design for compatibility with high flow rate of cold gas propulsion.

9. CONCLUSIONS

A micro MFV is under development at Air Liquide. The tests which have already been performed are encouraging. The valve can deliver flow rates adapted to thrusters in the range 100W-5kW. 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 seems to have no significant impact on its performances.

The main strengths of this component are:

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

Considering recent tests with high pressure Xenon and coupled with thruster Air Liquide is confident on potential of this micro MFV to regulate a very accurate flow rate with low response time. Moreover, thanks to its design, the valve provides a high reliability for tightness and performances for more than 10 years lifetime (considering 10 000 on/off cycles).

A high flow rate MFV, based on the same concept and dedicated to cold gas lines, ables to deliver a regulated mass flow rate of some few hundreds of milligrams in xenon is currently developed by Air Liquide.

Some parts of this work have been done in the framework of CNES research and technology program.

10. REFERENCES

1. Duchemin, O., Leroi, V., Öberg, M., Le Méhauté, D., Pérez Vara, R., Demairé, A., Björklund, M., Persson, S., De Tata, M. & Beekmans, S. (2013). Electric Propulsion Thruster Assembly for Small GEO: End-to-End Testing and Final Delivery, IEPC-2013-222

2. Lyszyk, M. & Lecardonnel, L. (2007). Thales Alenia Space Experience on Plasma Propulsion, IEPC-2007-301

3. Lyszyk, M., Baubias, P-P., Naulin, A., Pin, R. & Lecardonnel, L. (2011). XPS Plasma Propulsion System on AlphaBus, IEPC-2011-118

4. Stephan, J-M. (2000). Electric Propulsion Activities for Eurostar 3000. Spacecraft Propulsion, Third International Conference held 10-13 October, 2000 at Cannes, France. Edited by R.A. Harris. European Space Agency ESASP-465, 2001., p.81

5. Naclerio, S., Soto Salvador, J., Such, E., Avezuela, R. & Perez Vara, R. (2012). Small GEO xenon propellant supply assembly pressure regulator panel: test results and comparison with ecosimpro predictions, SP2012-2355255.

6. Duchemin, O., Leroi, V., Vial, V., Öberg, M., Bourgignon, E., Scalais, T., Demairé, A. & Lübberstedt, H. (2010). Electric Propulsion Thruster Assembly for Small GEO, AIAA-2010-6696

7. Biron, J., Cornu, N., Illand, H., Serrau, M., Rigollet, R., L Gray, H. (2005). The Thruster Module Assembly (Hall Effect Thruster) design, qualification and flight, IEPC-2005-213

8. Fendler, Y., Carpentier, S., Barbier, P., Martin, F., Guilbaud, E., Boniface C., H. (2017). Innovative Xenon Regulation for Electric Propulsion, IEPC-2017-202

9. Kuiper, J H. (2017). Development of next generation Fluid Management Systems, Space Propulsion 2018