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New generation Propellant Flow Control components for Electric Propulsion systems: Status of achievements at Alcatel Alenia Space Italia/Laben-Proel

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Abstract

The Propellant Flow Control /Conditioning Unit (PFCU) is currently identified as a potential area for improving the overall performances of new generation Electric Propulsion (EP) systems. New mission profiles for the EP systems ask for challenging features on the PFCU. In this context Alcatel Alenia Space Italia S.p.A. LABEN Directorate, Proel Tecnologie Unit (hereinafter called also AAS-I/LABEN-Proel) has developed, under ESA GSTP contract (funded by ASI), innovative PFCU components, namely:

- **A Proportional Valve (PV) with high pressure isolation ("off ") capability when de-energized, capable to withstand the tank high pressure, on one side, and to provide the propellant flow/pressure regulation on the other side.**
- **A propellant Mass Flow Sensor (MFS) able to provide the propellant mass flow rate telemetry and feedback for PV closed loop operation.**
- **A Low Pressure capillary (LPC) i.e. an active device thermally actuated, originally developed in the Russian HET thruster technology, now miniaturized and improved in performances.**

The paper describes the details on the PV, MFS and LPC technology solutions, realization aspects, technical features as well as the results achieved with the performed experimental characterization campaign. An overview of the potential application perspectives of these components within the European Space Programs and an outlook on potential applications in "Cold Gas" propulsion systems, is in addition presented.

Nomenclature

AAS-I = Alcatel Alenia Space Italia S.p.A
AAS-I/LABEN-Proel = Alcatel Alenia Space Italia S.p.A, LABEN Directorate, Proel Tecnologie Unit
ASI = Italian Space Agency
BB = Bread-board
CGMS = Cold Gas Micropropulsion System
DIL = Dual In Package
EP = Electric Propulsion
ESA = European Space Agency
GEO = Geostationary Earth Orbit
GIE = Gridded Ion Engines
HET = Hall Effect Thrusters
LEO = Low Earth Orbit
LPC = Low Pressure Capillary
MEO = Medium Earth Orbit
MFS = Mass Flow Sensor
MFS-EA = Mass Flow Sensor Electronic Assembly
PFCU = Propellant Flow Control/Conditioning Unit
PV = Proportional Valve
S-MFS = Silicon Mass Flow Sensor

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I. Introduction

Within an EP system, the Propellant Flow Control Unit (PFCU) is asked to interface, on one side, the high pressure (up to about 200 bar) propellant tank and, on the other, to provide the necessary regulations/conditioning of the propellant gas mass flow rate to the thruster discharge chamber and to the cathode/neutralizer, in order to allow the thruster operation at the required thrust level (also variable in the course of the same mission).

The different mission profiles on GEO, MEO, LEO and Science Satellites impose to the EP systems a wide range of operating regimes and operating powers, real time thrust actuation, thrust and specific impulse variable in wide ranges , fine controllability, as well as a long operational lifetime. This approach gives rise to challenging requirements also on the PFCU, e.g. fixed flow/slightly adjustable, variable flow with coarse accuracy, variable flow with fine accuracy, real time actuation of the flow rate set point, very long cycled (1,000,000 cycles and more) and/or continuous (up to 30,000 hours for the mission to Mercury) operation, modular conceptions/architectures, reduced mass and sizes, etc.

The demand of a high degree of flexibility, reliability and throttleability on PFCU is unavoidably associated to the introduction of innovative components (with respect to conventional electro-mechanical and passive devices), based on solid state, often miniaturized technologies. In addition, new PFCU design approaches should result in modular conceptions and architectures for sustaining operation with both GIE (Gridded Ion Engines) and HET (Hall Effect Thrusters) EP systems, in a wide range of thrust (for instance 20-500 mN) and specific impulses (for instance 1500 - 4000 sec).

AAS-I/LABEN-Proel has successfully developed, new components for PFCU's with the aim of :

- decreasing mass, dimensions, power consumption of components with respect to existing traditional technologies
- achieving PFCU architectural simplification (lower number of components) and modularity
- increasing the reliability of the whole PFCU also drastically reducing the components moving parts
- supporting wide operating ranges and different EP technologies without the need of a significant redesign
- interfacing directly the high pressure tank, featuring an electronic flow regulator based on a single stage
- realizing closed loop pressure and/or flow regulators by using the same actuation device (the PV component)
- easily operating the PFCU in closed loop control systems with different sensing elements (mass flow, pressure, beam/discharge current, etc.)
- favoring fast manufacturing/test cycles, while containing the cost of recurring products.

The innovative propellant management components developed by AAS-I/LABEN-Proel will support the realization of a new generation PFCU units for EP systems. These components include a Proportional Valve PV, a Mass Flow Sensor (MFS), and a Low Pressure Capillary (LPC) that can be combined, assembled and controlled in order to obtain propellant gas regulated flows.

II. Proportional Valve (PV)

The PV has the purpose of actuating the very fine and fully analog regulation of the propellant gas flow flowing thorough the PV body. Assessed Candidate technologies for the PV have been magnetostrictive and piezoelectric ones. The former has been selected in the USA by Marotta , whereas about the latter we did not find out past significant developments. AAS-I/LABEN-Proel choice has been to use piezoelectric materials/actuators for the PV technology/concept definition.

The PV , conceived and developed taking into account the following guidelines:

- minimization of mass and external dimensions;
- high inlet pressure withstanding capability
- intrinsic safety as normally closed when de-energized
- minimization of internal and external leakage
- very fine flow regulation
- use, as far as possible, of space qualified materials
- reliability
- very low power consumption

exhibits the following main features:

- Operating Gas: Xe, Ar Kr, N_2, He (up to now tested with Xe and N_2)
- Analog operation with extremely low associated noise
- Direct interfaceability to the high pressure tank
- Exit orifice opening regulated by an actuation mechanism based on a stack of piezo-electric disks “low voltage” powered and on a plunger/shutter moved along the PV axis
- Normally closed with high pressure isolation when de-energized (unpowered); in rest condition the shutter is forced against the orifice both by the spring strength and by the upstream pressure

- Operation - starting from a high pressure (up to 200 bar) - in closed loop with possibility to accomplish :
  - pressure reduction and regulation (feedback from a pressure sensor)
  - pressure reduction/mass flow regulation (feedback from mass flow sensor)
  - pressure reduction/HET thruster discharge current regulation (feedback from HET thruster discharge current)
- Wide operational ranges (no or limited need for design scaling up/down): up to 30 mg/s with Xe operation
- Fast Time Response (depending however from the piping length): < 1 sec
- Low external and internal leakage: < 5 10^{-8} scc/s @ 150 bar GHe
- Low mass (<200 g) , dimensions (ϕ46 x 48 mm) and power consumption (< 0.1 W)

The main elements/parts composing the PV (see also Fig. 1 and 2) are:

- piezo ceramic actuator bender stack
- antagonist S-shaped springs
- shutter or plunger
- orifice
- electric interface
- mechanical housing

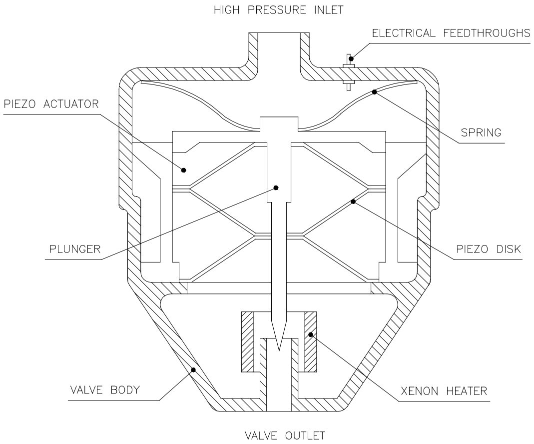


Figure 1. PV operation mechanism

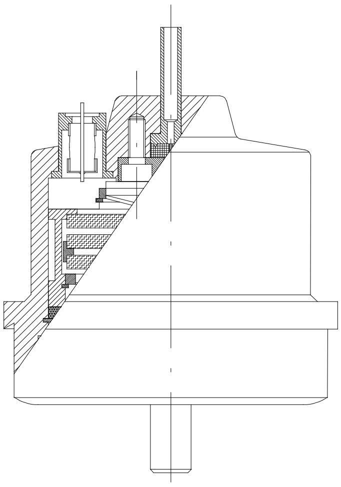


Figure 2. PV mechanical assembly

Piezo-actuators

The PV actuator is located upstream the orifice, in the high-pressure section. The actuator assembly operates by pulling the shutter away from the orifice. For the PV actuation mechanism a piezo-based actuator has been preferred to an electro-magnetic one, for two main reasons: its reduced power consumption and its better ability to produce sub-micrometric movements; in addition forces as high as thousands of Newton are obtainable.

The proposed piezo-based actuator is made with an assembly or stack of piezo “ring benders” (see Fig. 3 and 4) working in series. This configuration ensures a relatively large “stroke” needed not only to move the shutter but also to recover possible plays due, for instance, to thermal variations or mechanical tolerances. An additional features of this ceramic material is the capability to be actuated by a relatively low driving voltage (<200 V).

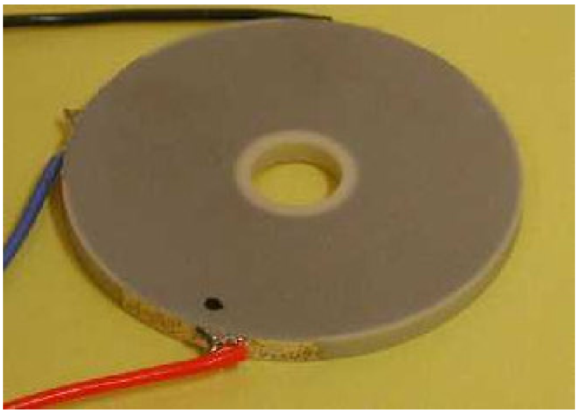


Figure 3. View of the ceramic ring bender, realized with the multi-layer ceramic technology

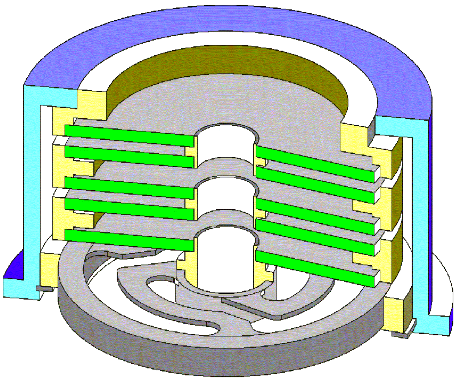


Figure 4. Cutaway view of the PV actuation mechanism

The PV actually implements a very accurate and compact construction for which it has been possible to use only three piezo-ceramic disks, which ensure a total stroke above 150 μm, largely enough to ensure operation and recovery. The ceramic ring benders can be arranged in a stack with the necessary number of devices to allow the correct valve operation in all the required conditions.

Shutter

The shutter is a plunger (see Fig. 5) made by an integral piece of titanium, one end of which is and coupled to the sub- mm dia. orifice; accurate construction and mounting allow fine regulation to be done. The main S-shaped spring (see Fig. 6) forces the shutter against the orifice, while the actuator acts in the opposite side, being coupled to the other end of the shutter through a mechanical ring. The shutter is hollow and the gas is expected to pass inside it. In rest condition the shutter is forced against the orifice both by the spring strength and by the upstream high pressure

Figure 5. Titanium shutter or plunger moved by the piezo-ceramic actuation mechanism

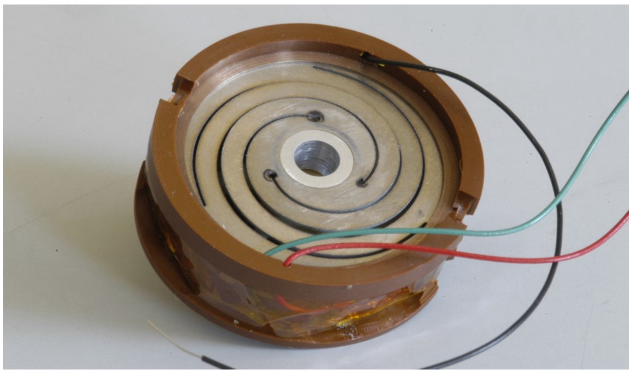


Figure 6. Sub-assembly of the PV, with close up of the S-shaped spring

Orifice & heater

As The PV should guarantee an internal leakage theoretically zero when the valve is fully closed, the orifice plate is made with a soft material, able to be elastically deformed to produce a good seal when the shutter conical termination is forced is forced against the orifice walls. The PV EM2, whose design has been finalized to operate with Xe, includes a heating provision, just close to the orifice-shutter coupling; the incoming xenon gas is held at a temperature around 400 K in order to avoid phase transitions and subsequent flow rate instability. In the EM2 design the heating provision is realized by introducing two heaters: the first inside the hollow shutter, the second around the soft material orifice.

Antagonist S-shaped springs

A passive elastic device is used to press the shutter against the orifice. Two S-shaped springs are used in the valve: one is the main spring which forces the shutter against the orifice, the other has the task of maintaining assembled the different parts of the actuator and recover the working mechanical tolerances. This configuration is intrinsically safe, as the inlet pressure works together with the spring, pushing the shutter against the orifice, thus tending to close it.

The main S-shaped spring (see Figures 7a, b, c) was designed to generate a force necessary to guarantee a safe sealing force of the shutter against the orifice, in the whole pressure range 2-150 bar foreseen upstream the orifice.

The spring design, optimized through a stress-analysis computer program, was made taking into account the

- little axial dimension;
- dimensional constancy of the connection diameters;
- easy construction with general-purpose machine tools.

The spring/s design evolution is shown in the figures here below.

Figure 7a. Last Version of the S-shaped spring

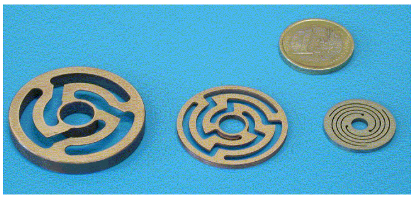


Figure 7b. Intermediate series of S-shaped springs, made in Cu-Be alloy

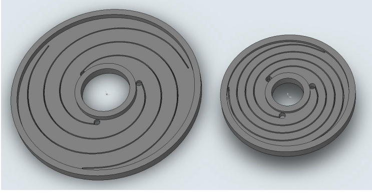


Figure 7c. PV internal spring miniaturization

Electric Connection

Three wires are used to feed the actuator across the PV wall using ceramic feedthroughs. The needed electronic drive is a regulated voltage power supply, controlled with input voltage dependent on loop controller (typically 0–5 V) and featuring:

- Voltage regulation capability: 0 – 200 V
- Peak Power: 0.5 W

Mechanical PV housing

The valve body (see Fig. 8), made in Ti, is closed by a cap welded on the circular edge in order to ensure the required gas tightness.

The need of ensuring at time same time adequate resistance to pressure and reduced mass, led to adopt a titanium alloy for the body and for the back cover. Gas inlet and outlet are realized through metallic tubes (made in Fe-Ni-Co alloy) brazed to the cap (inlet) and to the valve body (outlet).

Two different PV EM's have been realized and successfully tested. The EM2 design (see fig. 9) differs from EM1 as regards its ability to manage high pressure xenon at its inlet: this feature is obtained by inserting a heating provision. The body of the EM2 PV is slightly longer, in order to house the heating provision.

Figure 8. Photo PV EM1Body

Figure 9. Photo of the PV EM 2 Body, with heating provisions

The EM2 design, specifically developed for the xenon mass flow actuation, has been supported by modelizations of the PV ducts (see Fig.10 and 11) close to the actuator-seal coupling and computer simulations, as well as by extensive experimental investigation activities

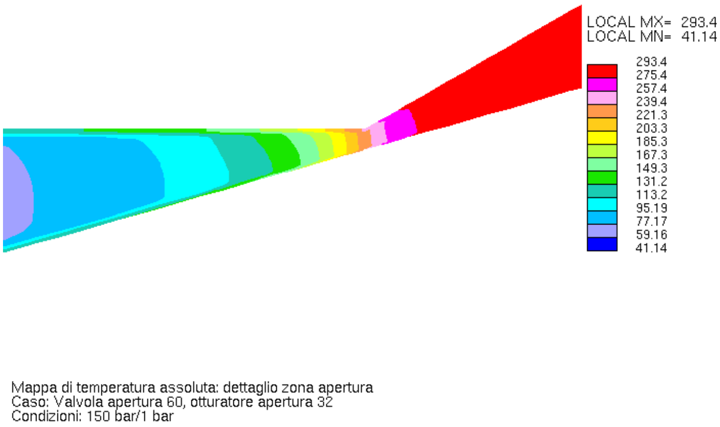


Figure 10. Temperature mapping of actuator-seal coupling

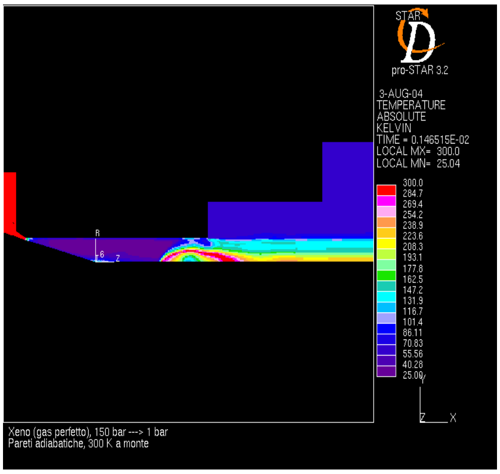


Figure 11. Numerical simulation about xenon flowing through the valve showing evidence of bubble formation

Tests performed on the PV

The PV EM's have been submitted to the following tests

- Burst (2.5 MEOP) pressure test.
- On-off upstream pressure structural test
- Proof (1.5 MEOP) pressure test.
- On-off upstream pressure cycling test.
- Internal leakage test.
- External leakage test.
- Maximum flow rate at the minimum upstream-downstream ΔP.
- Opening/closing lifetime cycling test.
- Cold temperature (-40°C) operation
- Thermal cycling & humidity test.
- Functional/performance experimental characterization as pressure regulator
- Sine, random, shock
- Functional/performance experimental characterization as mass flow controller

The Tab. 1 here below summarizes the EM1 and EM 2 achieved features

Parameter	**EM 1 model**	**EM 2 model**	**Remarks/achievements**
Operating Gas	N2, Xe	N2, Xe	
Operating (inlet) Pressure: N2	2-170 bar	2-170 bar	
Operating (inlet) Pressure: Xe	2-30 bar	2-170 bar	
Mass Flow range: N2	0.01-11 mg/s	0.01-11 mg/s	
Mass Flow Range: Xe	0.02 – 30 mg/s	0.02 – 30 mg/s	
Proof pressure (1.5xMEOP)	250 bar	250 bar	
Burst pressure (2.5 MEOP)	425 bar	425 bar	Test executed using a suitable liquid
Internal leakage	<5.0 x10^{-8}sccs GHe at 150bar	<5.0 x10^{-8} sccs GHe at 150bar	
External leakage	<5 x10^{-8} sccs GHe at 150bar	<5.0 x10^{-8} sccs GHe at 150bar	Test executed on the body valve
Response time	< 200 msec	< 200 msec	
Power consumption	<0.1watt	<0.1watt	
Heater	No	Yes, with additional power consumption of 3 – 5 W	Only for gas xenon regulation 3W
Non Operating Temperature	-30 + 70°C	-30 + 70°C	
Operating Temperature	20 to + 50 °C	-30 + 50°C	20°C are referred to Xe operation
Temperature test	15 hours at 120°C	15 hours at 120°C	
Tested temperature cycle (no operation)	-10°C to 80°C	-10°C to 80°C	10 cycles 60min at –10°C 60min at +80°C
Life cycle test		On going	40 million cycles done to date; 10^9 cycles goal
Sine Vibration	LISA Pathfinder level		Successfully passed
Random Vibration	LISA Pathfinder level		Successfully passed
Shock	LISA Pathfinder level		Successfully passed
Weight	180g	195 g	EM02 With heater
Dimension	Φ46 x 45 mm	Φ46 x 48 mm	
Electrical connection	Three feedthrough brazed to body	Five feedthrough brazed to body	Three wires for EM01 e Five wires for EM02
Piping interface	Tube 1/8" inch	Tube 1/8 inch	AISI or Titanium version

Table 1. Performance features achieved for PV EM 1 and EM2

The values appearing in the table has to be intended as reference values for the testing activities rather than technology limits. Significantly high operating pressure is manageable and has been already achieved together with device miniaturization.

III. Mass Flow Sensor (MFS)

For this sensor a thermal concept has been adopted and implemented in order to achieve both a high sensitivity and a fast time response. The sensor structure is heated and at zero mass flow rate the system is thermally symmetric, giving the temperature profile shown in the Figure 12 and making $\Delta T=T_1-T_2=0$.

When a steady fluid mass flow rate m_s flows through the sensor (see Fig. 11), the assumed temperature profile is unsymmetrical, with T_1 dropping and T_2 staying nearly constant and a ΔT arises. T_1 drops because the mass of hot fluid leaving the region carries energy away at a rate $m_s C_pT_1$, requiring an increase of the local heat transfer rate to support this energy loss and maintain equilibrium. T_2 changes a little when the flow occurs since this region both receives and loses heat from the flowing fluid. However the use of $T_2 - T_1$ signal available from the bridge circuit has the advantage of giving zero output for zero flow rate and allowing the instrument to be much less sensitive to ambient temperature changes. Practically The heater power W can be theoretically related to the $\Delta T= T_2 - T_1$ through the simple relation:
$W = m_sC_p\Delta T$

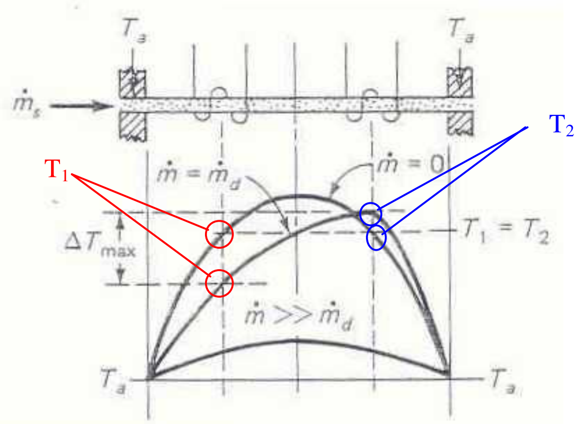


Figure 12. MFS operation concept

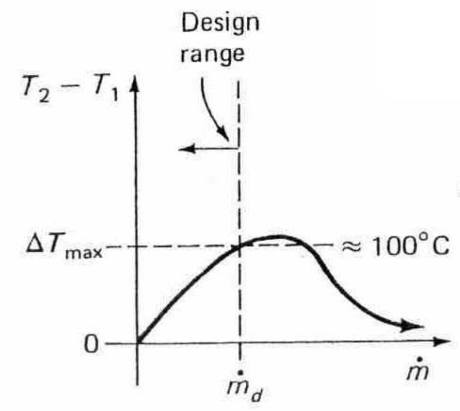


Figure 13. Detectable ΔT versus mass flow rate level

The MFS has been implemented in silicon structure (Silicon-MFS or briefly S-MFS) featuring a xenon flow duct with built-in high sensitivity (series-arranged) thermal sensing arrays and built-in heating provisions.

The S-MFS chip is bonded onto a DIL (Dual In Line) ceramic IC package, that allows a high mechanical strength. The ceramic package is coated with a metallic film. A properly suited cap, which provides two ¼” tubes for the gas inlet and outlet, is soldered the DIL package (see Fig. 14 a, b, c). A micro-channel has been drilled into the cap allowing the gas to flow along the chip surface, as required for operation of differential temperature structures.

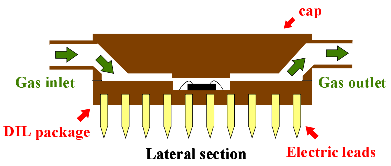


Figure 14a. S-MFS Lateral section

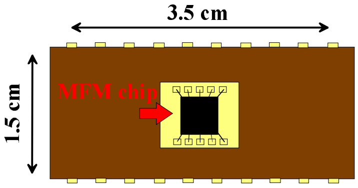


Figure 14b. Top view of the ceramic DIL Package

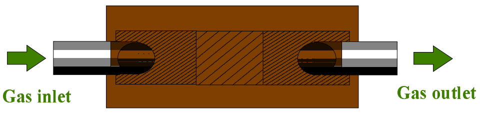


Figure 14c. Bottom view of the cap

On the chip there are many differential temperature flow meters structures and operational/ Instrumental amplifiers. The structures used for the silicon MFS are showed in Fig. 15 and 16. In the right figure it is possible to visualize the central heater and the two sensing thermopiles that detect the gas temperature at the inlet and at the outlet of the structure.

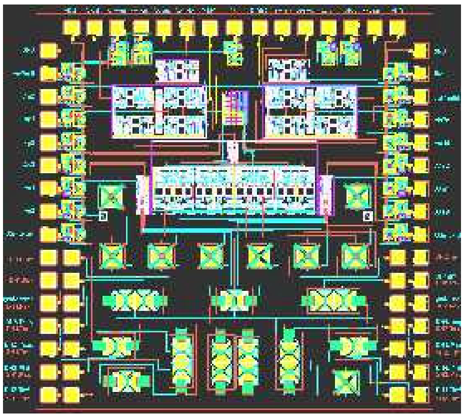


Figure 15. Layout of the S-MFS chip. The flow meters are positioned in the bottom of the chip

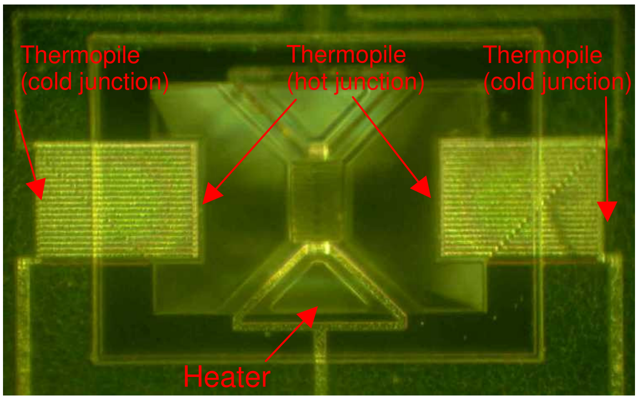


Figure 16. S- MFS structure

The S-MFS total mass, including the stainless steel structure soldered on the DIL package, is currently about 50 g. The ducts geometry inside the S-MFS allows the gas flow to lap the sensing structures on the chip.

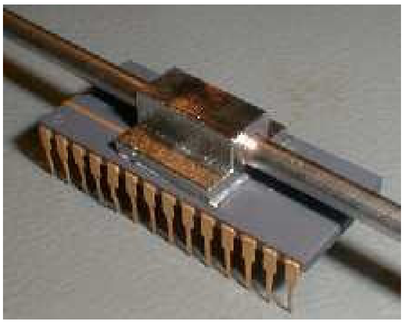


Figure 17. S- MFS with DIL package inserted in the gas flow

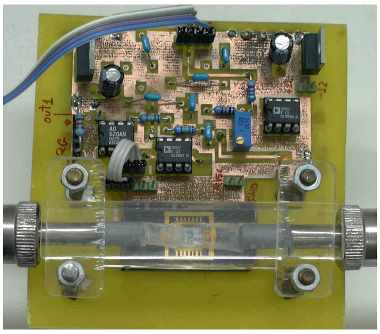


Figure 18. S-MFS DIL Package and BB conditioning electronics

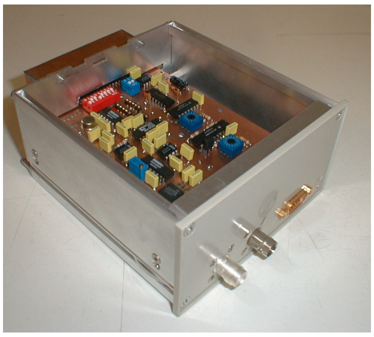


Figure 20. Electronics for the MFS (MFS-EA) integrated in the accommodation box

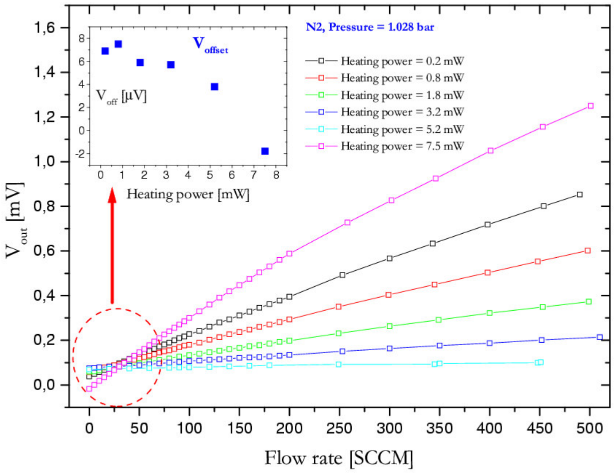


Figure 21a. S-MFS verified performances with Nitrogen

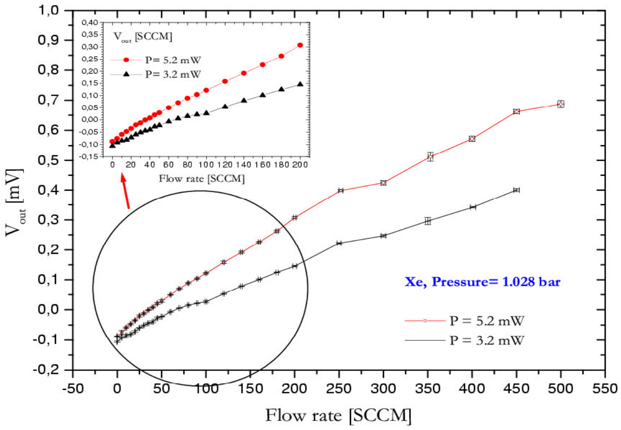


Figure 21b. S-MFS verified performances with Xenon

The output voltage signal from the sensing elements is in the range (100 ÷ 1000) µV. This signal is amplified by a differential instrumentation amplifier and filtered by a Low Pass Filter with a cutoff frequency lower than 50 Hz, according to the block scheme in Fig. 22.

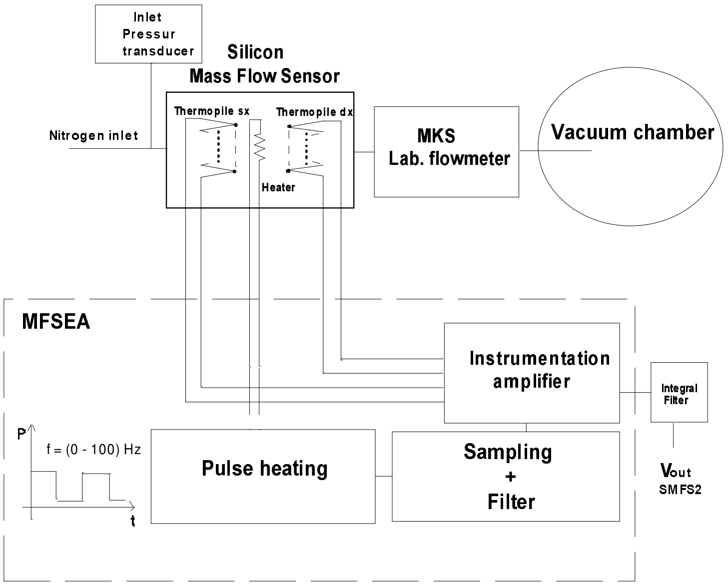


Figure 22. S-MFS and electrical conditioning concept

V_o is the output signal correlated to the Xenon mass flow. A conditioning approach based on heater modulation has been conceived in order to perform the best possible separation between sensor and electronics offsets on one side, and the useful signal on the other side.

The MFS-EA (MFS- Electronic Assembly) is the signal conditioning electronics for evaluating Silicon Mass Flow Sensor (S-MFS) characteristics and performing the final characterization; the conditioning electronic produces a voltage output in the range 0-5 V, corresponding to a flow variation in the range 0-300sccm (being this latter flow rate value taken as a reference).

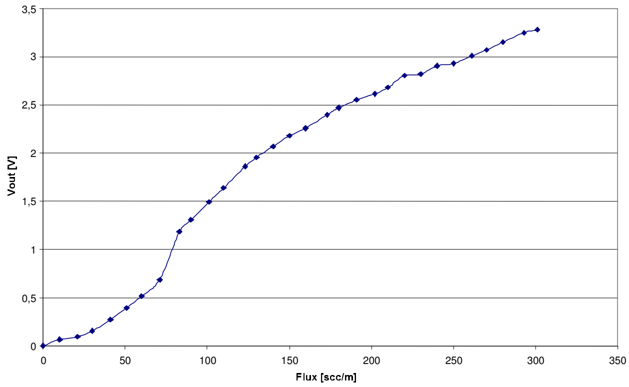


Figure 23. S-MFS Test results at 0.5 bar inlet pressure and 0 to 300 scc/m of Xe, averaged on 512 measures

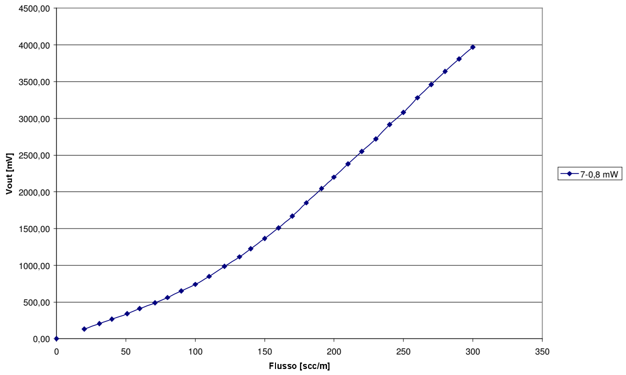


Figure 24. S-MFS Test results, at 0.5 bar inlet pressure and 0-300 scc/m of N_2, averaged on 512 measures

The main S-MFS obtained performances are presented in Tab. 2

Parameter	Silicon Mass Flow Sensor
External leakage	<1.0 x10^{-8} sccs GHe
Response time	< 200 msec
Power consumption	<1watt
Weight	<50gr
Dimension	18x35x13 mm, including housing
Packing	DIL 28pin
Out signal	0÷1000uV DC
Range	2÷300sccm
Resolution	2sccm
Operational gas	Nitrogen/Xenon
Accuracy	±5%

Table 2. S-MFS obtained performances

AAS-I/LABEN-Proel is currently pursuing an evolution of the S-MFS design, from which an order of magnitude improvement in both the resolution and operation at very low flow rates is expected.

IV. Low Pressure Capillary (LPC)

The LPC is a simple thermo-throttleable capillary device, developed at advanced prototype level, with no moving parts which realizes a mass flow regulation actuating a thermal conditioning of a very narrow stainless steel tube. The LPC is manufactured by brazing the two ends of the capillary tube to the inlet and outlet piping of the gas line and by integrating a heating resistor within a compact package (ϕ 18 mm X 34 mm length). The micro-tube is directly heated and configured within a miniaturized assembly.

The basic development uses very small (50-100 μm diameter) stainless steel tube. Since the flow range is necessarily limited, two MFS devices have been manufactured, covering different flow ranges, in order to demonstrate operation at the extremes of the required flow range. The support of theoretical equations, see Tab. 3, allowed to define the device dimensioning with respect to the desired flow range.

$$\mu = \mu_0 \left(\frac{T_0}{T} \right)^{-\frac{1}{2}}$$

$$\dot{m} = \frac{\pi D^4}{256 \mu R_g T L} (p_i^2 - p_0^2)$$

Laminar flow regime assumed

D: pipeline diameter
L: pipeline length
p_i: inlet pressure
p_0: outlet pressure
μ: gas viscosity
μ_0: viscosity at the reference absolute temperature T_0
R_g : R/M_W
R is the universal constant
M_W : gas molecular weight

Table 3. Theoretical Physical relations and parameters at the basis of the LPC Design

The Fig. 25 a, b, c below show:

- thermo-capillary coil of length 45 mm and internal diameter of 100 μm (10÷100 scc/min of Xe flow range varying the inlet pressure from 0.8 bar to 2.5 bar);
- two stainless steel supports brazed to the thermo-capillary.

Figure 25a. Thermo-capillary LPC1 and supports

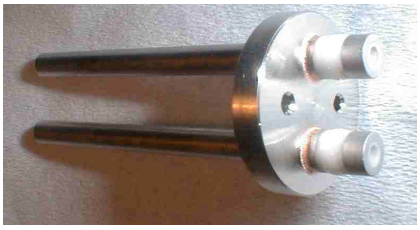


Figure 25b. Main flange and 1/8'' fluid interfaces

Figure 25c. Thermo-capillary LPC1, Al_2O_3 insulator and flange

In order to cover the total flow range a second thermo-capillary LPC2, with length of 30 mm and internal diameter of 150 μm (30÷300 scc/min flow range, range varying the inlet pressure from 0.8 bar to 2.5 bar), has been realized.

Fig. 26 shows the main flange and the ceramic Al_2O_3 insulators brazed to two 1/8 inch inlet and outlet tubes which are the LPC fluid interfaces. The same figure shows the implementation of electrical connections. The thermo-capillary supports are used also for electrical connections. Direct heating is performed using a current power supply. Fig. 27 shows the final LPC assembly.

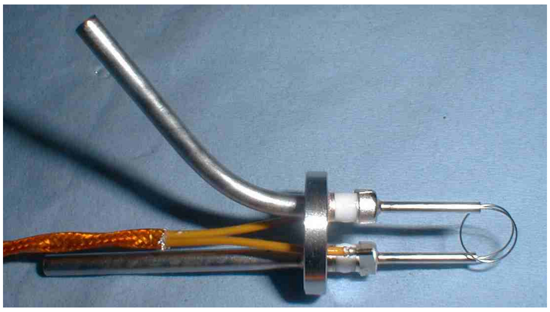


Figure 26. TLPC1 electrical connections

Figure 27. LPC final assembly in a cylindrical stainless steel housing

The main significant LPC features/performances are presented in Tab. 4.

Parameter	LPC1	LPC2
Operating pressure	0-3 bar	0-3 bar
Mass flow dynamic range	1:3 to 1:5	1:3 to 1:5
Flow rate	1-100 scc/m	100-500 scc/m
External leakage	<1.0 x10^{-7} sccs GHe	<1.0 x10^{-7} sccs
Power consumption	<2watt	<2watt
Weight	50 g	50 g
Dimension	ϕ 17 x 40 mm	ϕ 17 x 40 mm
Hydraulic interface	Tube 1/8" inch	Tube 1/8 inch
Operational gas	Nitrogen/Xenon	Nitrogen/Xenon

Table 4. Achieved performances for T-LPC technology

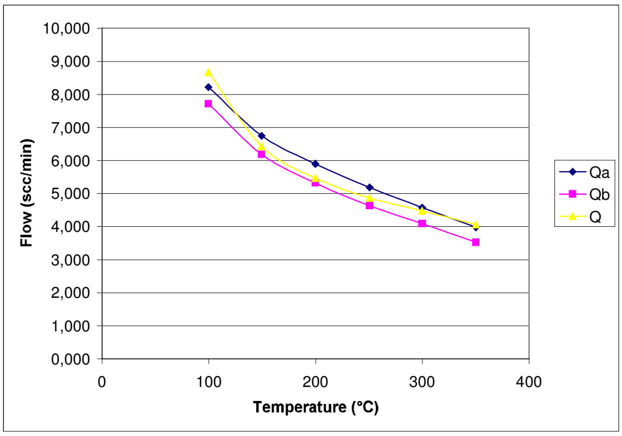


Figure 28a. LPC1 performances at P = 0.8 bar

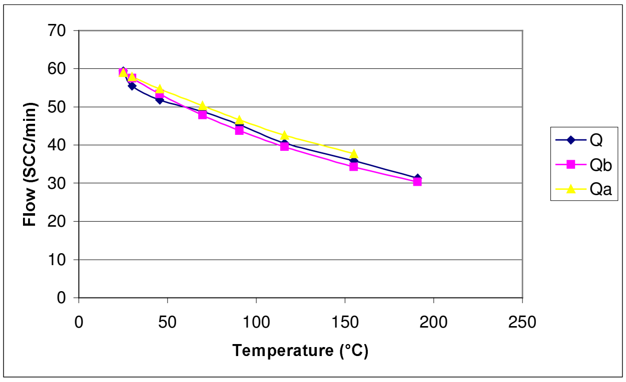


Figure 28b. LPC1 performances at P = 2.5 bar

Q is the measured mass flow rate and Qa and Qb are the theoretically calculated mass flow rates

The measurements made on the two devices LPC1 and LPC2 have demonstrated :

- the possibility to get the desired 1:3 operating range with low electrical power according to the requirements
- the consistency with the flow rate theoretical values and with discrepancy of 2–3% from the measured value.

V. Operation of the PV, MFS, and LPC within a closed loop flow control system

By using the presented PV, MFS and LPC components, direct flow regulation was achieved using:

1) PV in closed loop with the S-MFS (Fig. 29a.), starting from high pressure tank;
2) LPC in closed loop with the S-MFS, starting from an already reduced pressure (Fig. 29b.).

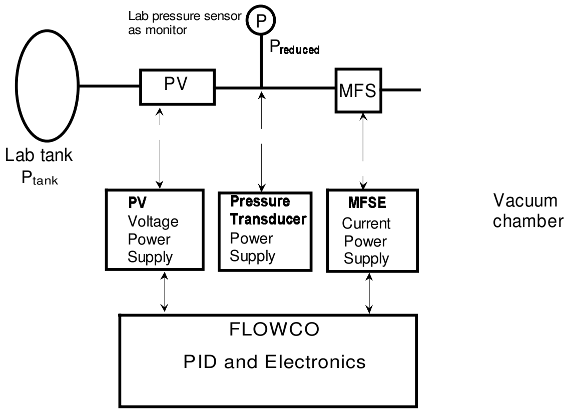


Fig. 29a. PFCU operation based on PV Flow Control

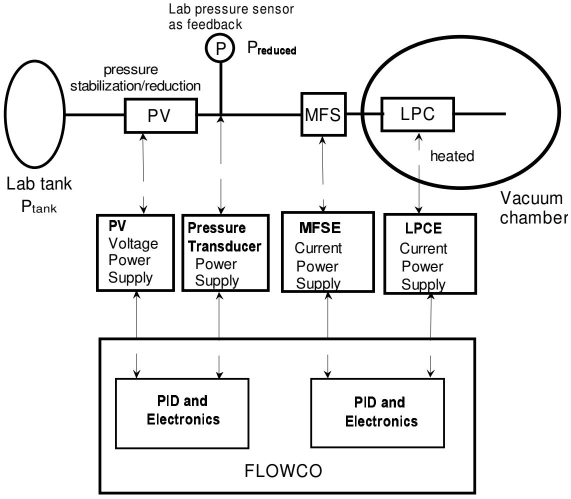


Fig. 29b. PFCU operation based on LPC Flow Control

We underline that in the case of Fig. 29a, the pressure reduction and flow regulation is performed in a single stage using the PV, provided that a feedback mass flow value is available from the MFS. The PV control loop can be directly commanded in terms of mass flow whatever is the upstream tank pressure. The obtained curves are just the MFS responses to the actual mass flow and gas type.

In Fig. 30a to 30d, here below the results achieved using the developed S-MFS as feedback sensor are reported.

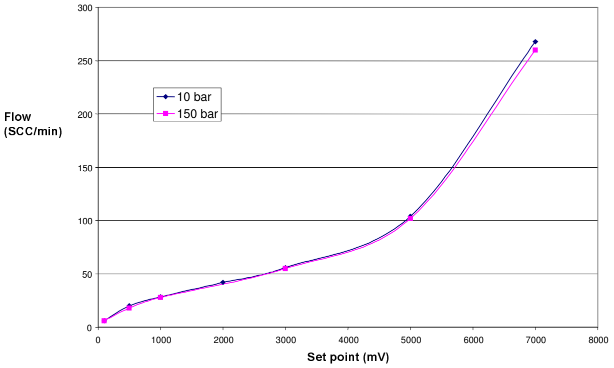


Figure 30a. PV Flow Control test results with Xenon (closed loop PV EM2 + S-MFS)

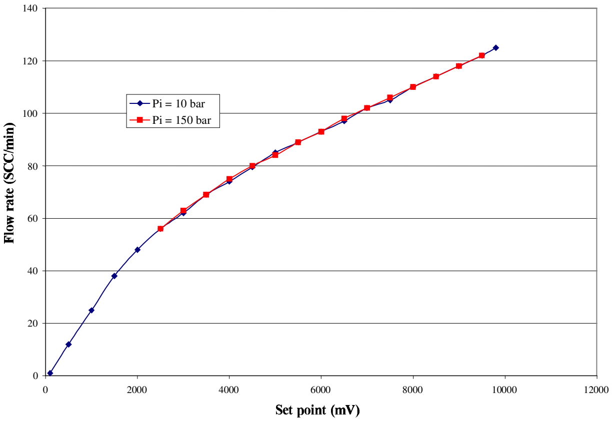


Figure 30b. PV Closed loop results with Nitrogen (PV EM1 + S-MFS)

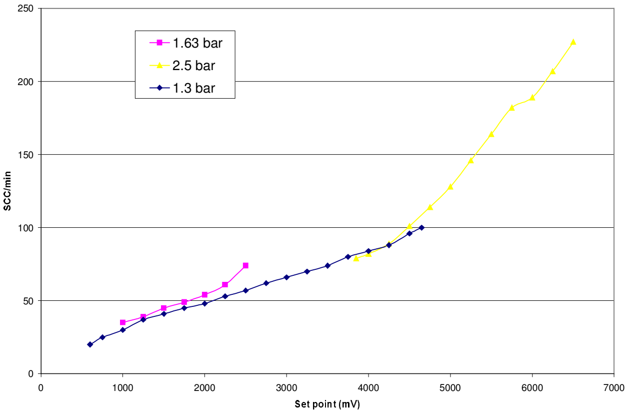


Figure 30c. LPC2 closed loop (S-MFS+LPC2) with Xenon

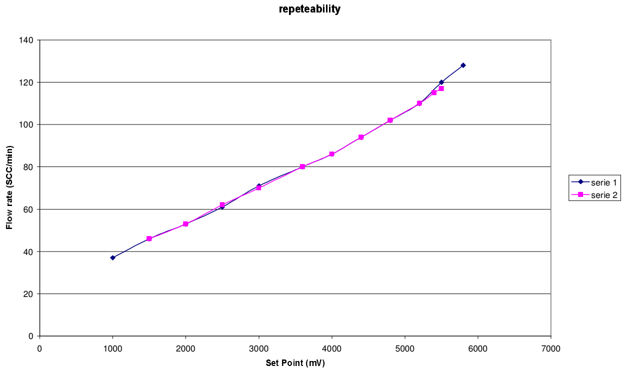


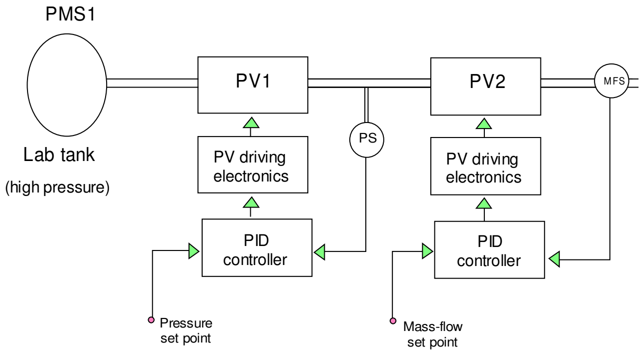
Fig. 30d. TLPC+S-MFS, closed loop repeatability (Pi= 1,45Bar); gas Xenon

VI. Possible applications of the PFCU components within Propulsion System of ESA spacecraft

In this paragraph an outlook is provided concerning the possible utilization of the described PFCU components within Propulsion Systems (not only Electric) of approved ESA programs. Three ESA programs are here considered as reference scenarios for the PFCU components utilization, namely Alphabus/Alphasat, BepiColombo and Gaia

The ESA Large Platform Mission Project will is based upon a new multi-purpose platform, named Alphabus. Alphabus will be equipped with Electric Propulsion to meet the challenging standards foreseen for this new platform.

A key element of the PFCU of the EP system on Alphabus is the PV for which ESA has issued a dedicated contract. Within the PFCU of the Alphabus EP the PV will be employed for actuating both the Pressure and the Flow Regulation closed loop controls. For the first task the PV will be operated in conjunction with a pressure sensor and for the latter task the sensing element will be the thruster discharge/beam current or a Mass Flow Sensor. The baseline scheme proposed for the Alphabus PFCU is below presented (see Fig. 31 a). The Fig. 31b is referred to an optional configuration where a single stage PFCU is adopted for the mass flow closed loop regulation using, as set point of the control system, the Discharge Current of an HET Engine.



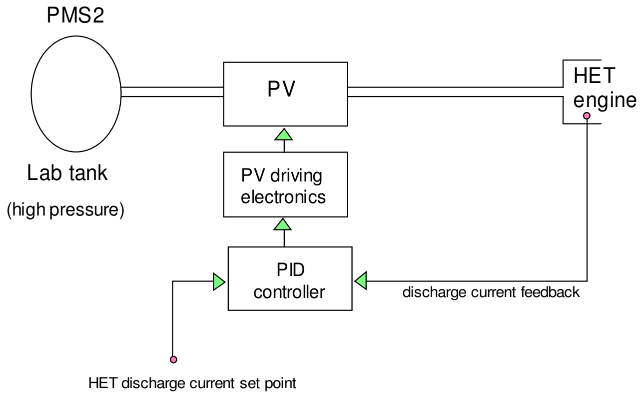
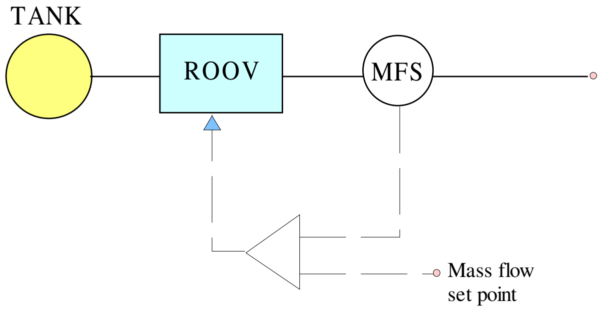


Figure 31a. Alphabus baseline PFCU for the EP system **Figure 31b. Alphabus PFCU optional configuration**

BepiColombo is the ESA cornerstone mission for the exploration of planet Mercury. For this very challenging deep space mission the EP is being considered for optimizing the spacecraft transfer/cruise to Mercury, considering the best trade off among launch costs, payload ratio and transfer time. Most likely the EP on Bepicolombo will be asked to operate at a variable thrust level and specific impulse. Both these parameters have to be directly measured and controlled during the mission evolution. So a PFCU, single stage, based on a PV and a MFS operating within a closed loop control system appears to be the best approach (see schemes of Fig. 32a and 32b).

In this framework AAS-I/LABEN-Proel is ready to provide a proposal for the whole PFCU to the potential suppliers of the BepiColombo EP system.



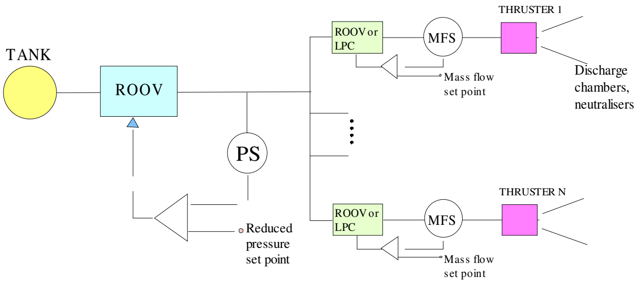


Figure 32a. Single stage mass flow regulation in a GIE EP system **Figure 32b. Double stage mass flow regulation in a GIE EP system**

Outside the EP field the PV and MFS components could find a very important and challenging application within Cold Gas Micropropulsion System (CGMS) used for the orbital/attitude control of science satellites for fundamental physics applications. ESA is strongly pursuing this application area through a set of missions, such as, GAIA, Lisa, Darwin. GAIA will be the first opportunity to embark a new generation European Cold Gas Micro-Propulsion system. AAS-I/LABEN-Proel is currently considered as a serious candidate to offer the whole CGMS, within which both PV's and MFS's will be employed, according to the functional scheme reported in the below Fig. 33.

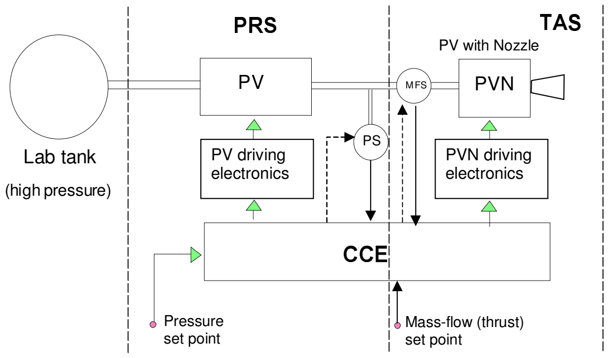


Figure 33. Simplified block of a Cold Gas Micropropulsion System based on The PV and MFS

Figure 34. Evolution of the PV (dim. ϕ30 x 85 mm, mass 105 g) in view of possible application within a Cold Gas Micro Propulsion System

The application of the PV and S-MFS components within a Cold Gas Micro Propulsion System will be the subject of a next paper.

VII. Conclusions

Three basic PFCU components have been successfully developed as new generation devices devoted to support future European space programs. These devices are able to work both stand-alone and in closed loop arrangements and can allow to build whatever PFCU architecture, thus supporting customer needs and different thruster technologies.

The PV valve is an advanced device able to provide both high pressure insulation when de-energized and pressure or mass flow regulation in closed loop with suitable sensors. The regulation capability was demonstrated in a wide range of reference pressures and mass flow rates. The PV mass is less than 200 g, and the power consumption of the actuator is less than 0.1 watt.

Operation at higher pressure has been achieved on an improved design (that will be dedicated to the Cold Gas Propulsion applications) which successfully underwent burst pressure in excess of 800 bar and features reduced dimensions and weight.

The technology development level achieved on the PV is such that the received performance requirement that have oriented the development have been exceeded: the PV is currently a fully engineered device ready for finalization through specific qualification campaigns to new challenging space programs .

The S-MFS device bas been developed up to prototype level and needs technology engineering and consolidation for practical utilization on the space programs. At any rate, the capability of the sensor to operate in a wide mass flow range has been successfully demonstrated, both with Xenon and Nitrogen. The power consumption is the one of its conditioning electronics, since the micro-structure power consumption is in the mW range. The very small dimensions also allow a fast time response. The S-MFS has great margins of improvement in the optimization of the gas duct that interfaces the gas flow to the silicon structure.

The T-LPC is a miniaturized and reliable thermo-capillary which can regulate up to 1:5 flow dynamic range with small power consumption, this device is ready for space qualification.

On the basis of these successful results, AAS-I/LABEN-Proel is ready and strongly committed to undertake follow on activities finalized to the components full qualification and to the PFCU complete realization, within near future European Spacecraft Propulsion programs.

Acknowledgements

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