Use of a “wide dynamic range” Electronic Flow Regulator to increase the flexibility and versatility of Electric and Cold Gas Small Propulsion Systems

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Abstract: The propellant flow regulation is a key function of a satellite Propellant Management System. The fundamental components to perform a very fine and stable regulation of the propellant (gas) flow, namely the mass flow and the “control actuation” valve have been developed and qualified by TAS-I for applications to Cold Gas Micro Propulsion and Electric Propulsion. The paper addresses a review of the building blocks and components arrangements versus the identified application areas and a description of the developed mass flow regulation components with relevant exhibited performances. The identified specific applications, transversal to different propulsion technologies, namely addressing the Cold Gas Micro Thrusters (fully qualification achieved within GAIA Program), the Flow regulation/throttling of Electric Thrusters and the Propellant Gauging are also discussed in the paper. For what concerns the propellant gauging, specific applications to both Electric and Chemical Propulsion are presented.

Nomenclature

MFS = Mass Flow Sensor
LP TV = Low Pressure Thruster Valve
HP/LP RIV = High Pressure/Low Pressure Regulation & Insulation Valve
EPR = Electronic Pressure Regulator
MPR = Mechanical Pressure Regulator
FEE = Front End Electronics
TAS-I = Thales Alenia Space Italia
CFD = Computational Fluid Dynamic
EP = Electric Propulsion
CGP = Cold Gas Propulsion
CP = Chemical Propulsion
MPS = Micro Propulsion System
HPF/LPF = High Pressure /Low Pressure Filter
HPT/LPT = High Pressure /Low Pressure Transducer
HEMPT = High Efficiency Multistage Plasma Thruster (Thales ED, Ulm)
HET = Hall Effect Thruster (Snecma)
RIT = Radiofrequency Ion Thruster (EADS/Astrium ST, Lampoldshausen)
MT = (Cold Gas) Micro Thruster (Throttleable Micro Thrust Actuator used for GAIA Program)
PCB = Printed Circuit Board
PGD = Propellant Gauging Device
TBC = To Be confirmed

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I. Introduction

THE "fine" regulation/conditioning of propellant in terms of pressure and flow rate is retained a fundamental issue for increasing flexibility and versatility of Small Propulsion systems, based on gaseous propellants, dedicated to the accurate attitude/orbital control and manoeuvring of spacecraft/satellites.

In particular, the possibility of finely throttling, in a wide dynamic range, the propellant flow rate at the propulsion thrust actuator inlet, is an asset that significant enhances the application spectrum of both the Electric and Cold Gas Propulsion systems, especially in challenging missions where both throttleable and highly repeatable thrust levels in the sub-millinewton (mN) range are required.

In addition also Chemical Propulsion could benefit from advanced gas flow sensing devices, placed within the pressurant gas (He, N_2) fluidic line for application of "indirect propellant gauging", which allows the obtainment of the information about the chemical propellant consumption on the basis of the measurement of the pressurant flow rate, integrated versus time.

TAS-I is currently working on a new generation flow regulator systems based on 3 key fluidic components:
- Low Pressure Thruster Valve with throttling capability LP TV (equipped with micro nozzle)
- High/Low Pressure Regulation & Insulation Valve (HP/LP RIV)
- Mass Flow Sensor (MFS)

This 3 key components are arranged in different configurations, according to the targeted application. In this context three main applications areas have been identified:
- Thrust Regulation in a Cold Gas Micro Propulsion System
- Mass Flow Regulation in an Electric Low thrust Propulsion Systems.
- Propellant Gauging (MFS stand alone)

In the following the key fluidic components, all developed at TAS-I, are presented and described and the relevant assembly arrangements, referred to the identified application areas, are introduced and discussed.

II. Review of key "fluidic" components

A. Components Arrangement versus application area

Tab. 1 presents an overview of the Fluidic components arrangements/configurations versus the identified possible application areas that are transversal to various propulsion system (in "primis" EP and CGP but also CP as a possible application extension).

Configuration /Arrangement	Implemented Function	Application Area	Potential Application Programs/ Technologies
MFS positioned upstream a throttleable LP TV	Detect and measure the propellant flow to drive the micro thrust closed loop control/regulation through the LP TV (with nozzle) used as actuator of the control	Cold Gas Micro Propulsion	GAIA (ongoing) Microscope (baselined) Euclid Lisa Pathfinder (TBC)
MFS positioned downstream a HP/LP RIV	Detect and measure the propellant flow to drive the Mass flow Closed loop control/regulation, through the HP/LP RIV used as actuator of the control	Flow regulation to the Electric Propulsion thrust actuators (e.g. ion/plasma thruster); Flow regulation can be done either from an upstream regulated low pressure or directly from the high pressure at the tank outlet.	Micro RIT HEMPT Other gridded Ion Engines
HP/LP RIV Stand Alone, Placed upstream the thrust actuation device	Use of a thruster Parameter (e.g the Discharge, Beam Current	See Note above	Micro RIT HET Thrusters Other Gridded Ion

Configuration /Arrangement	Implemented Function	Application Area	Potential Application Programs/ Technologies
	or RF Power) to drive the Mass flow Closed loop control/regulation, through the HP/LP RIV in the role of actuator of the control		Engines
MFS Stand alone, placed in between the Pressure Regulator (MPR or EPR) and the thrust actuation devices	Propellant Gauging	Electric Propulsion Cold Gas Propulsion Chemical Propulsion (pressurant gas)	Alphabus/Alphasat Spacebus Small GEO

Table 1. Fluidic Component arrangements versus application areas

B. Low Pressure Thruster Valve with Nozzle (LP TV)

The LP TV (see Fig. 1a) is basically a low pressure regulation valve, normally closed, which provides isolation against low pressure (few bar) with low leakage, and allows tight – analog – control of the propellant flow during operation, taking advantage by piezo- technology actuation mechanism. The piezo-actuator power consumption is very low (< 100 mW) and the design is compact and lightweight. The main TV components are:

- Piezo-electric actuator (see Fig. 1b) based on thin ceramic ring benders, which are stacked by a S-shaped spring;
- Plunger, which closes the valve orifice;
- A second S-shaped spring, which pushes the plunger against the orifice (valve fully closed) when the piezo actuator is not powered;
- Ceramic feedthrough for electrical connections;
- Inlet pipe connection;
- Micro Nozzle (see Fig. 2a and 2b), manufactured through an electro-erosion process and integrated in the valve body, downstream the exit orifice;
- TV Body, including 2 parts: the housing enclosing all the TV internal parts and the welded closure cap, to the rear side.

The TV used as Thrust actuator within the MT (GAIA Cold Gas Micro Thruster) operates in conjunction with a MFS (see after) placed upstream the TV itself.

Figure 1a. GAIA TV

Figure 1b. Piezo ceramic actuator based on a set of piezo ring piezo-ceramic benders

Figure 2a. LP TV Nozzle (cutaway) close up

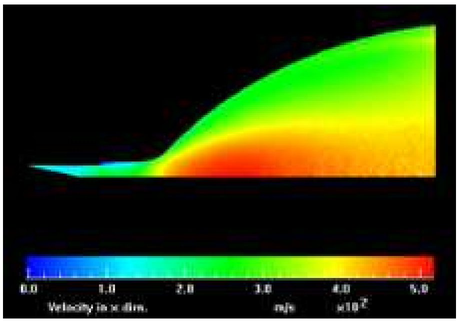

Figure 2b. CFD Simulation of the velocity distribution at the nozzle exit (at a flow rate of 5 sccm)

The main features of the GAIA LP TV are below summarized:

Inlet pressure	
Nominal inlet operating pressure:	1 bar abs.
Max expected inlet pressure (MEP):	4 bar abs.
Proof pressure:	6 bar abs.
Burst pressure:	10 bar abs.
Mass flow rate	
Min. N_2 flow rate @ nom. inlet pressure:	0.05 sccm
Max. N_2 flow rate @ nom. inlet pressure:	50 sccm (up to 100 sccm achievable)
Leakage	
Internal leakage @ nominal inlet pressure:	$<10^{-6}$ scc/s GHe
External leakage @ nominal inlet pressure:	$<10^{-8}$ scc/s GHe
Main dimensions & mass	
ext. diameter:	30 mm
total length:	64.3 mm (feedthrough & nozzle-cover enclosed)
mass:	< 100 g

C. Mass Flow Sensor (MFS)

The MFS is a fundamental component of both an EP and CGP fluidic conditioning equipment. It is the feedback sensor of the thrust (operation within a Cold Gas MT) or mass flow (operation within an EP Flow regulator) closed loop control. It is used to measure/monitor the actual mass flow rate flowing through to the Flow/Thrust Control actuator (being the MFS placed in series with this latter).

With the MFS device developed by TAS-I, the mass flow information is obtained from the measurement of the "temperature unbalance" that manifests in presence of the mass flow, between two temperature sensors, while a constant amount of power is provided in between.

Substantially, the TAS-I MFS device is a differential calorimetric flow gauge which detects the heat amount transported by the fluid (gas). Practically the heating power **W** can be theoretically related to the thermal unbalance $\mathbf{\Delta T = T_2 - T_1}$, through the simple relation:

$\mathbf{W} = \dot{m}\ \mathbf{C_p \Delta T}$, being $\dot{m}$ the gas mass flow rate and $\mathbf{C_p}$ the gas specific heat.

The MFS has been implemented in a Si Chip (see Fig 3). The heating element (heater) is positioned in between the upstream and downstream temperature sensing elements (thermo-resistors) which are located on cantilever bridges for **ΔT** detection.

In addition, within the Si chip, two other temperature sensor are realized:

- the intermediate sensor for monitoring of bulk surface temperature
- the right sensor for the monitoring of the gas temperature.

Figure 3. Si Chip (MFS flow sensing element)

The major elements of the MFS are

- Si chip, packaged and bonded on the Al_2O_3 support (see Fig 5a)
- Al_2O_3 support, metalized to allow brazing to the fluidic assembly
- Fluidic assembly (brazed on support) with a plastic cover glued on top in order to provide a closed path for the gas flow (see Fig. 4a and 4b)
- Input/output fluidic connections
- Double Board FEE for the MFS electronic conditioning (see Fig 5b).

Figure 4a. Pre-built o-ring (upper image) to be accommodated in the vespel gas duct (lower image)

Figure 4b. Sealing O-ring placed on the Al_2O_3 support

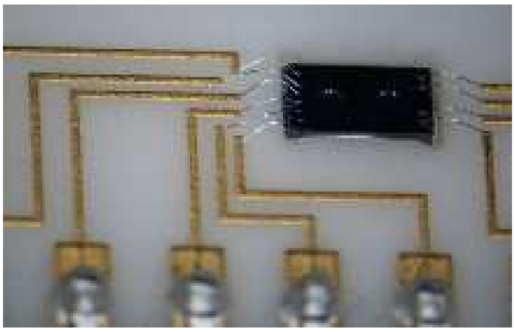

Figure 5a. Bonding of the electrical connection between the Si-Chip and the gold tracks on the Al_2O_3 support

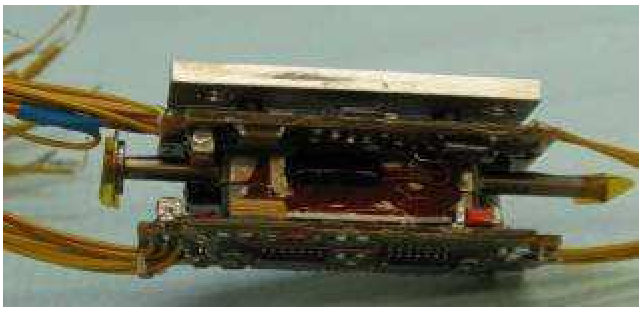

Figure 5b. MFS assembly (without external housing) showing the sandwich structure in which the MFS Fluidic sub-ass.y is placed in between the 2 small PCB's hosting the FEE

The Si structure and the gas duct are integrated and hosted in a mechanical structure to provide mechanical protection, leakage prevention, fluidic and fastening I/Fs. The metallic structure (sealed off) has inlet and outlet ducts (pipes) welded.

The developed MFS design aims at:

- Covering a dynamic range of up 3 order of magnitude in the mass flow level detection
- Improving the device sensitivity and time response, by reducing the cross sectional area for the mass flow which is concentrated on the small Si structure and by increasing the resistance of the thermometers

- Realizing a more rugged package able to withstand the environmental mechanical loads
- Allowing operation with different gases (N_2 and Xe gas, but also He in the next future)

MFS main features are reported here below :

Inlet pressure	
• Nominal Operating (MEOP) :	0 to 2 bar
• Proof :	6 bar
• Burst :	12 bar
Leakage	
• External leakage @ nom. inlet pressure :	< 10-6 sccs GHe
Flow rate @ nominal inlet pressure	
• For CGP Applications with N2:	from 0.005 to 5 mg/s
• For EP applications with Xe:	from 0.05 to 25 mg/s
Main dimensions & mass	
• width:	34 mm
• length:	57 mm
• mass:	< 90 g
Power Consumption.	few mW
Tme response	about 10 ms
Sensitivity	0.1 sccm
Accuracy	up to 1% of the measured flow

The MFS Fluidic sub-Assembly is packaged within a “sandwich” structure which consists in 2 small PCB’s which host the MFS FEE. The whole structure is identified as MFS Assembly. The main features associated to the FEE are:

- Input Power Supply Filtering
- Voltage Reference (very precise and stable) for the front-end acquisition
- Current generation for the MFS internal heater
- Conditioning (through Wheatstone bridge) and Pre-amplification of the MFS output signal
- Low Pass filtering, used for filtering out the noise effects without loosing information on MFS output
- MFS thermal control by powering 2 heaters mounted inside the MFS body
- MFS Temperature sensors conditioning

The FEE is also in charge acquiring and conditioning the signals from the temperature sensors placed on the TV.

The performance of the “couple” LP TV + MFS (of course connected through a suitable closed loop control electronics and associated algorithms) directly affects and determines the performance of the Micro Thrust actuator within the GAIA MPS.

D. HP/LP RIV

The HP/LP RIV has been developed in the frame of the ESA ARTES 8 contract “Proportional Valve for High Power EP”. The component features the actuation, in a very fine and fully analog way, of the gas (propellant) flow through the valve body. The HP/LP RIV exit orifice opening is adjusted by an actuation mechanism based on a stack of piezo-electric “thick” rings, powered by a “low voltage” bias signal. A metallic plunger, mechanically coupled to the piezo-stack, is moved (back and forth) along the valve axis, as a consequence of the piezo-stack voltage bias, thus regulating the actual open area of the exit orifice in a smooth and progressive analog way.

The main HP/LP RIV features are below summarized:

- Direct Interfaceability to the high pressure tank (up to 300 bar)
- Normally closed when de-energized, performing insulation from the high pressure in the tank
- Compatibility with a variety of gases such as Xe, N_2, Ar, Kr, He

- Operation in closed loop control in conjunction with different sensing elements:
  - Pressure Transducer for the actuation of a pressure regulation strategy
  - Mass Flow sensor for the actuation of a mass flow regulation strategy
  - Discharge/beam current sensor as well for the actuation of a mass flow regulation strategy
- Fully analog operation with an extremely low noise

The HP/LP RIV main elements/parts are:

- Piezo ceramic actuator stack made with a multi-layer ceramic technology
- Antagonist S-shaped spring (made with an electro-erosion process)
- Piezo-actuator "return" spring
- Plunger or shutter (made with Ti and kept in the axis of the valve by means of two springs located at two opposite ends of the plunger itself)
- Polymeric Seat containing the exit orifice
- Heating provisions (necessary only for operation with Xe at an inlet pressure higher than 40-50 bar)
- Electric interface
- Mechanical housing (made with a Ti alloy): bottom cover cap joined to the cylindrical structure by plasma welding process
- Gas Inlet and outlet pipeline: Kovar tubes brazed to the cap (inlet side) and to the Valve body (outlet side)

The HP/LP RIV actuator configuration foresees the use of 2 separate piezo-stacks:

- Base Piezo stack (31 mm height)
- Regulation Piezo stack (33 mm height).

The HP/LP RIV is shown in Fig. 6.

Figure 6. HP/LP RIV developed and pre-qualified within ongoing ARTES 8 contract with ESA

When the HP/LP RIV is not powered a preloaded spring, pushes the plunger against the Polymeric (vespel) seat keeping the valve orifice closed.

When the HP RIV is powered the 2 coaxial piezo stacks (mounted one inside the other) provide both the force (against the spring) to detach the plunger from the orifice seat and the necessary stroke to fully open the orifice. The movements of both the piezo actuators are added for maximising the overall displacement (free stroke)

The main features of the HP/LP RIV developed for EP applications are below summarized:

Mass flow rate: 0 ÷ 300 sccm GXe

Inlet pressure:
Nominal operating pressure: 150 bar abs.
Proof pressure: 300 bar abs.
Burst pressure: 600 bar abs.
Leakage:
Int. leakage @ nom. inlet pressure: $< 10^{-6}$ sccs GHe
Ext. leakage @ nom. inlet pressure: $< 10^{-8}$ sccs GHe
Main dimensions & mass:
ext. diameter: 33 mm
total length: 61mm (feedthrough - cover included)

mass:	<200 g
Power Consumption	
Operating with N2 and Xe (P<40-50 bar)	< 200 mW
Operating with Xe (P> 40-50 bar)	< 5 W in most of cases
Time response:	< 200 ms

III. Cold Gas Micro Thruster Application

The MT functions (see also Fig 7a and 7b) are:

- to provide and throttle the micro-thrust (from 0 to some hundreds of micro-N) according to the issued thrust level commands sequence, with the required accuracy and time response
- to provide insulation (closure of the nozzle throat) with very low leakage
- to monitor the propellant mass flow

The key features of the MT developed and successfully qualified for GAIA are:

- ➢ Extremely wide thrust range to be covered (3 order of magnitude) starting from 1 µN up to 500 µN
- ➢ Extremely low thrust resolution (≤ 1µN), thrust bias (≤0.5 µN) , thrust noise (1 µN/√Hz from 0.01 Hz to 1 Hz and 0.045 µN/√Hz above 1 Hz), thrust scale factor knowledge error (≤1% of thrust)
- ➢ Very long operational time in orbit of about 60,000 hrs (total impulse for each Micro Thruster of 10,000 Ns) and high number of on/off cycles (102 millions)
- ➢ Fast thrust response time (<300 msec@63% of the new commanded thrust level, at a command frequency of 1 Hz)
- ➢ Specific Impulse: > 60 sec at thrust level higher than 100 µN

The MT unit (see also Fig. 8a and 8b) includes:

- Mechanical Housing and inlet pipeline
- TV (Thrust Actuator) able to perform very small variations of the effective nozzle throat in order to implement tiny throttling capability of the propellant mass flow
- MFS assembly including the FEE & Electrical connectors (x 2)
- Inlet Low Pressure Filter (Filter Unit)
- Thermal Conditioning of the MFS assembly
- Internal Pipe work

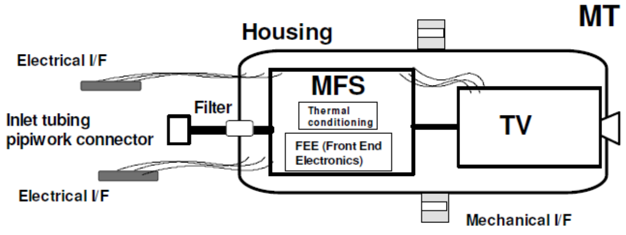

Figure 7a: Sketch of the MT configuration

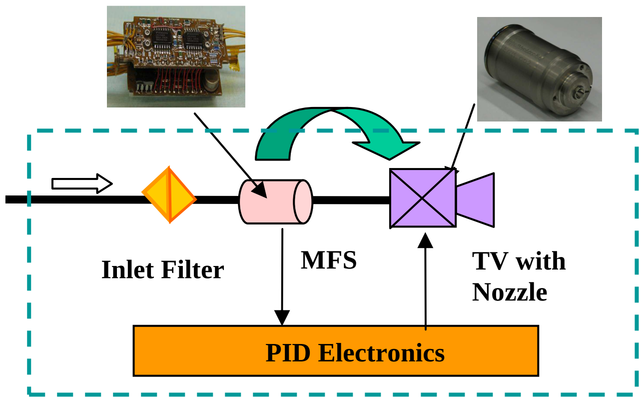

Figure 7b: MT closed loop operation principle

The **Micro Thruster (MT**), can be identified as the real “heart” of the whole MPS. The MT is realized by operating the TV in closed loop control with a MFS (positioned upstream the TV).

The MT key components are:

Thruster Valve (TV) with incorporated micro-nozzle, able to configure a variable cross section orifice upstream the nozzle, on the basis of a piezo-electric actuation mechanism whose operation is extremely smooth, fast, noise-free and no power consuming.

Mass Flow Sensor (MFS), based on a thermal concept and implemented on a Silicon Chip, which detects and measures the actual mass flow rate at the TV inlet and provides, to the closed loop control regulation system, the set point to command the TV actuation mechanism

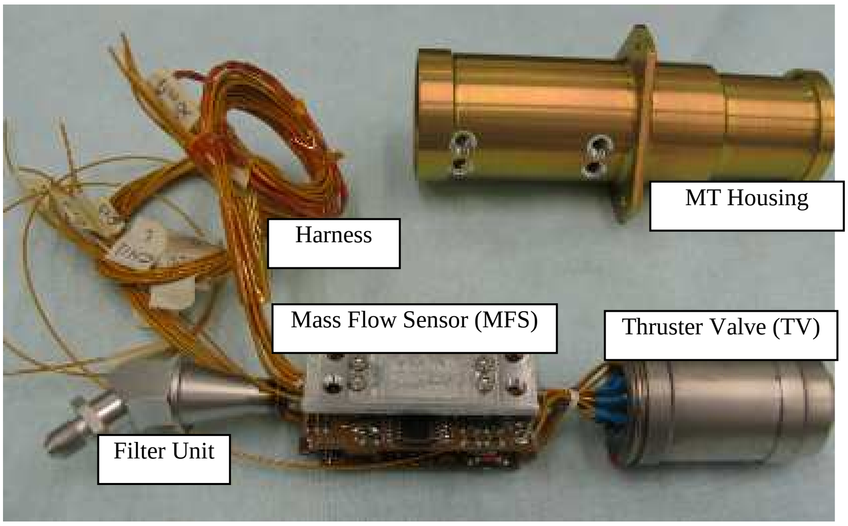

Figure 8a: MT Key elements/sub-assemblies before final MT integration

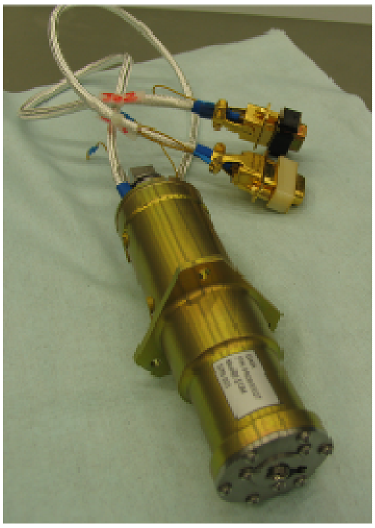

Figure 8b: Integrated MT EQM (the 2 electrical connectors are visible)

IV. Flow Regulation application

In this application (see Fig. 9a and 9b) the MFS is placed downstream the HP/LP RIV, so the actual mass flow rate to the Electric Thruster is measured and monitored through the MFS and used to drive the HP/LP RIV as mass flow control actuator. For the identified application the configuration shown in Fig. below is therefore implemented.

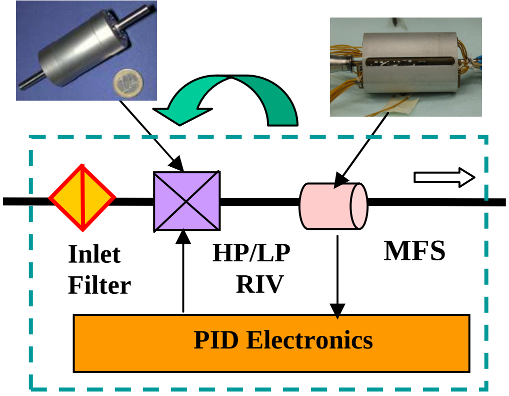

Figure 9a: Flow regulation scheme for Low Thrust Electric Propulsion

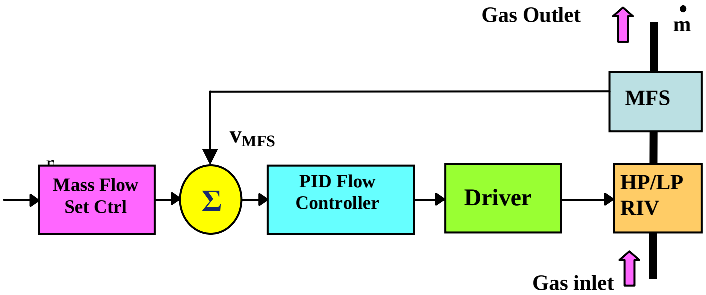

Figure 9b: Sketch of the Flow Closed loop control

The Pressure at the HP/LP RIV inlet is usually the P_{REG} coming from an upstream Pressure Regulation Device (can be either a traditional MPR or an innovative EPR).

As the HP/LP RIV can be directly interfaced to the high pressure tank, it is possible, in principle, to set-up a single stage flow regulator assembly (see sketch of Fig. 10), avoiding thus the necessity of an upstream Pressure reduction/regulator stage. In addition the Flow Control could be achieved not only on the basis of the signal generated by a flow sensing element (such as the MFS) but using different physical parameters such as the thruster Discharge or Beam Current. Typically the flow regulation at the inlet of a HET thruster is performed to achieve a selected value for the discharge current (this value is normally related to a stable operation of the thruster discharge). Fig. below represent a single stage flow regulator associated to a HET propulsion system based on 2 HET thrusters (nominal and redounded).

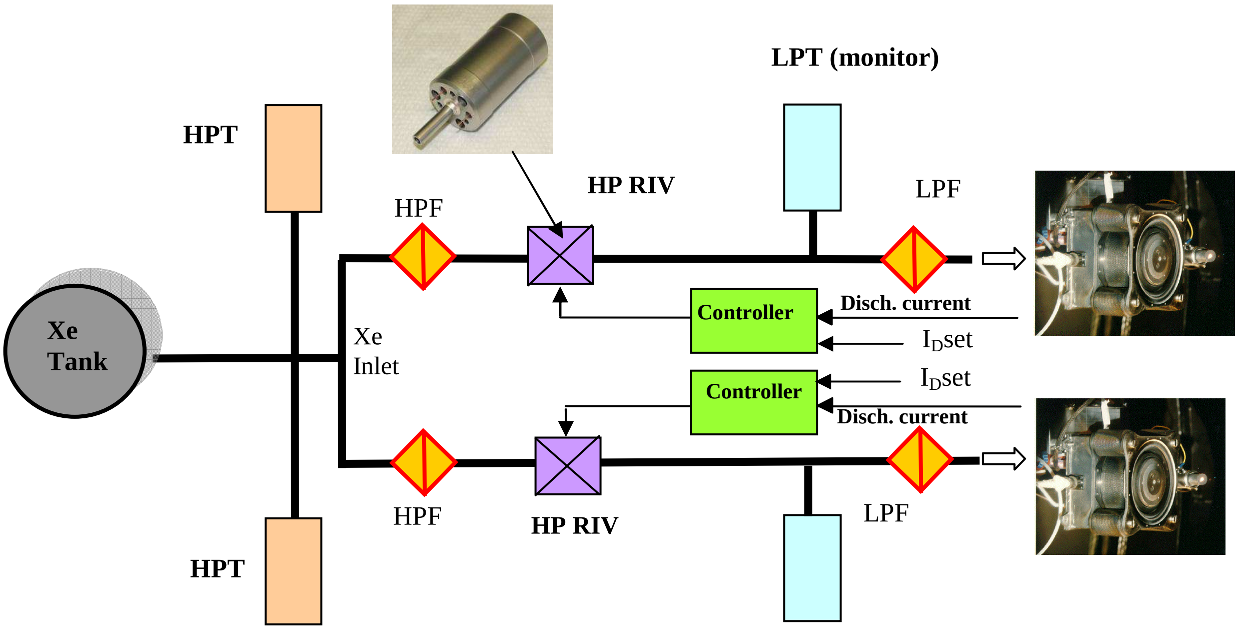

Figure 10. Single Stage Flow regulator

A performance test campaign (see Fig. from 11a to 11d) has been carried out within an ESA ARTES 8 contract for what concern a Laboratory flow regulation set-up including a HP/LP RIV with a downstream MFS.

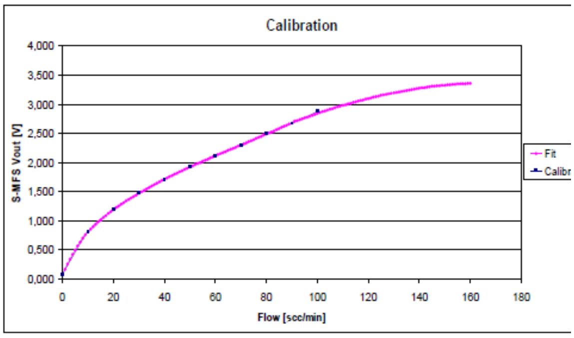

Figure 11a. MFS Calibration Curve

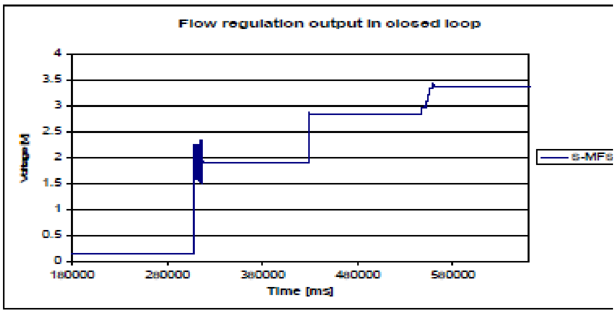

Figure 11b. Flow regulation Tests

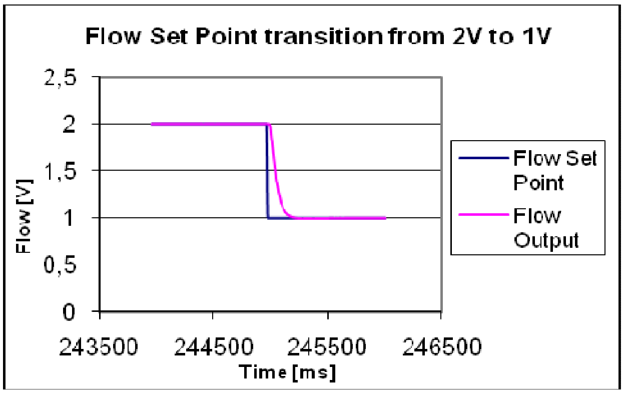

Figure 11c. waveforms of the MFS flow output with a flow set point transition between 80 scc/m and 40 scc/m

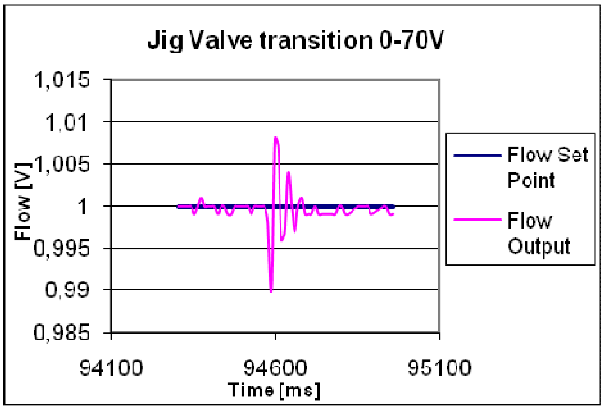

Figure 11d- waveforms of the MFS flow output in presence of a jig valve producing an instantaneous disturbance 0-50 sccm

V. Propellant Gauging

The exact knowledge of the consumed propellant at a certain moment of the operational mission is of fundamental importance for the mission conception and design. Furthermore the determination of the residual propellant in orbit allows the correct prediction of the satellite end of life with better accuracy than the one currently possible with today techniques (based on indirect estimates associated to P and T measurements). This feature can significantly relax the requirements in terms of propellant contingency mass to be embarked on board in order to have sufficient confidence of the whole operational mission fulfilment. This fact can save mass and consequently launch cost or can provide additional flexibility for a potential mission elongation with relevant associated revenues or scientific benefits.

With this background the spacecraft community agrees that the availability of a simple and compact Propellant Gauging Device (PGD) would be of great benefit. In particular the PGD has to be small, in terms of mass and volume, and with the possibility of integration within the satellite propulsion system with a minimum impact on the platform design.

The MFS based on a Si-Chip and operating according to the mentioned calorimetric concept is a credible candidate (considering the achieved qualification status within GAIA program) for being used as a PGD (see fig 12a and 12b below) on board satellites embarking EP

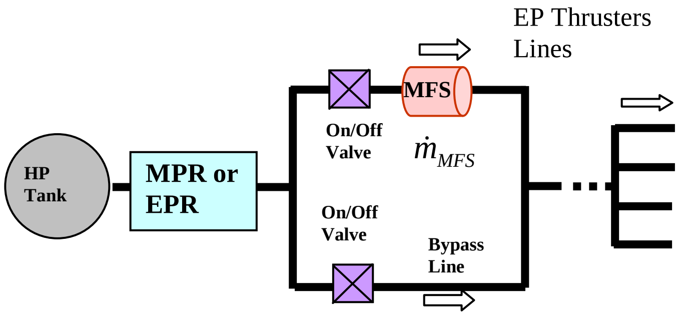

Figure 12a: Sketch for a possible utilization of the MFS as a PGD for EP (The same configuration can be used also within a CGP system

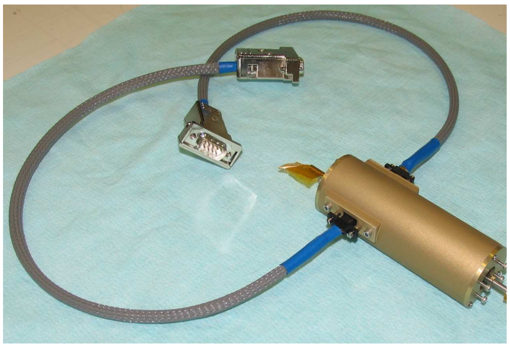

Figure 12b: MFS as stand alone component with dedicated housing usable as a PGD

The Precise propellant consumption evaluation at elapsed time τ of the mission can be done by integrating versus time the mass flow signal generated by the MFS:

$M_{PR}(\tau) = \int_0^{\tau} \dot{m}(t)dt$, where $M_{PR}(\tau)$ is the consumed propellant at time τ.

The same concept can be eventually applied to a CP system for performing the propellant gauging. In this case the MFS can be placed within the “pressurent gas” line, downstream the Pressurant Pressure regulator (MPR or EPR) as shown in the principle sketch of Fig.13.

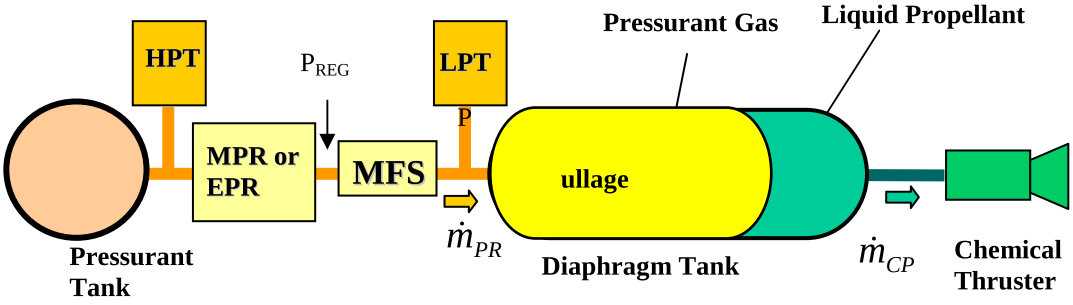

Figure 13: MFS used within a CP system for Propellant Gauging purposes

The Chemical Propulsion propellant consumption can be estimated, according to a simplified approach, by using the Perfect Gas equation law. In this way it is possible to relate the Pressurant gas flow rate ($\dot{m}_{PR}$) to the Chemical Propellant flow rate ($\dot{m}_{CP}$) as follows:

$$\dot{m}_{PR} = \dot{m}_{CP} \cdot \frac{P_0 W}{R_0 T \rho_{CP}}$$, where:

P_0 is pressurant pressure in the gaseous side of the diaphragm tank
W is the pressurant gas (He or eventually N_2) Molecular Mass
R_0 is the universal gas constant
T is the Temperature in °K
ρ_{CP} is the chemical propellant density.

In order to exactly know P_0, that can slightly differ from P_{REG} (reduced and regulated pressure immediately downstream the Pressure Regulator), due to the slight pressure drop across the MFS device, it is convenient to introduce a LPT downstream the MFS. The PGD is, in this case, composed by the MFS itselt + the additional LPT.

$\dot{m}_{PR}$ is measured by the mass flow sensor and $\dot{m}_{CP}$ can be deduced by using the above introduced relationship. By integrating this latter versus time it is therefore possible to estimate the consumed chemical propellant.

For the application relevant to the Propellant Gauging for Chemical Propulsion the MFS developed for GAIA program has to be upgraded for operation with He and at a higher input pressure (up to 30 bar)

VI. Conclusion

The fundamental fluidic components /elements for the implementation of the fine flow regulation in different satellites propulsion application areas have been presented. These components have achieved the qualification status (most of the activities performed within GAIA program). Different arrangements of this components have been identified and implemented to realize Cold Gas finely throttleable micro Thruster, Flow regulators for electric thrusters and Propellant gauging devices. For each application a specific review is presented in the paper. For what concern Propellant gauging using the qualified Mass Flow Sensor a possible application scenario including Chemical Propulsion, has been also identified (a delta development for the developed MFS design is however necessary for this specific application).

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