Versatile Xenon Flow Controller for Extended Hall-Effect Thruster Power Range
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Maxar is currently developing the electric propulsion system required by the NASA mission to reach the metallic asteroid (16) Psyche. The electric thrusters are expected to operate over a five-fold power range, spanning 0.9 kW to 4.5 kW, due to the limited availability of power in the main asteroid belt which is over three times further away from the sun than Earth. The wide range of power span during the Psyche mission requires a broad control of the xenon propellant flow rate. Besides the anode flow, the cathode flow control is critical for the healthy operation of a Hall-effect thruster, because it guarantees a timely ignition, a stable discharge and it limits the potential difference between cathode emitter and system ground. Especially at the lower powers it has been confirmed that the Lanthanum Hexaboride (LaB₆) emitter performs better with additional cathode keeper current and cathode flow than that supplied by the nominal discharge between anode and cathode. Therefore, a higher cathode-to-anode flow ratio of 9% compared to the nominal 5% has been selected for operation at discharge powers below 1.5 kW. Maxar developed a new Xenon Flow Controller (XFC) that is able to: 1) extend the range of flow rates; and 2) switch between two different cathode flow fractions. The new XFC, developed in conjunction with Moog, is configured also to leverage the Maxar heritage and limit the re-qualification of any other component of the EP sub-system. The XFC leverages the extended flow rate range of the proportional flow control valve (PFCV), already successfully flight-qualified and manufactured by Moog. The PFCV controls the total flow proportionally to the thruster discharge current, through a closed-loop feedback control loop. A normally-closed solenoid valve is placed upstream the PFCV simply to provide a second level of isolation. The two different cathode flow fractions are achieved with two distinct sets of orifices specifically designed to provide a cathode-to-anode ratio of 5% when operating at high flow rates, and 9% when operating at low flow rates. The control orifices are set on parallel lines, one of which is isolated by a latch valve. Both unit level and system level test demonstrate the control of the flow rate over the required range with required accuracy.

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1. Introduction

Electric Propulsion (EP) is steadily becoming the system of choice to propel commercial spacecraft for orbit raising as well as for station keeping in Earth orbit. International and Governmental Space Organizations are also leveraging the benefit of electric propulsion for space exploration and discovery missions. NASA’s planned Psyche mission will use electric propulsion to rendezvous with and orbit the asteroid (16) Psyche to study this unique world. This asteroid is composed almost entirely out of metal, and could be the bare core of a planetesimal that was stripped of its mantle during collisions early in solar system formation. It is located in the asteroid belt between Mars and Jupiter, and the spacecraft will arrive when it is about 2.7 AU from the sun. In order to reach Psyche, the spacecraft will rely on a Mars gravity assist and the steady propulsion guaranteed by the Hall Effect Thrusters (HET), which will also be used for orbital maneuvers and orbit maintenance around the asteroid. Psyche will be the first mission that uses an HET beyond cis-lunar space.

The Psyche spacecraft leverages the long heritage of the Maxar (formerly SSL) 1300-Class platform. In its 60 years long and successful history Maxar built and launched 280 spacecraft with a combined 2,200 years on-orbit service. Maxar also pioneered the use of electric propulsion, as it first introduced the use of the Hall Effect Thrusters on Western commercial spacecraft. In the last 15 years Maxar launched 35 EP-based spacecraft cumulating over 100,000 hours of active thruster operation, without experiencing any EP system failure. The Psyche spacecraft is an all-electric spacecraft based on the SPT-140 (HET manufactured by EDB Fakel, Russia) that is currently used by multiple Satellite Prime manufacturers, and started active operation on Maxar’s platform in 2018, after an extensive qualification campaign. Further details on the EP subsystem can be found in a companion paper.

The Maxar EP system to be used on the Psyche mission differentiates from the typical operations in Earth orbit due to the available power range. Geostationary telecommunication satellites use the full power thruster power (4.5kW) for orbit raising and a lower power level (3.0 kW) for station keeping. However, as the Psyche spacecraft travels to (16) Psyche at about 3.3 AU from the sun, the available electrical power on the spacecraft will decrease to the point where the thruster discharge power will be reduced to as low as 1.0 kW. As the discharge power decreases, so does the propellant (xenon) flow rate, which scales almost linearly with the discharge current (at constant discharge voltage). The Maxar heritage EP system implements a flow controller based on the thermostrottle, which has a limited 2-fold throttling range; the fluid properties (viscosity and density) are modified by heating up the fluid that flows through a capillary.

The wider five-fold flow rate throttle range encouraged the use of a proportional flow control valve (PFCV, manufactured by Moog Inc., NY USA) to regulate over the required range, as demonstrated in preliminary tests. In this case the flow rate is changed by adjusting mechanically the opening of the valve.

One more feature that is required when throttling the SPT-140 over a wider range is the ability to change the flow rate ratio between cathode and anode. It has been shown that a higher cathode-to-anode flow ratio is required when operating in the lower power range (<1.5 kW). This feature together with operation of the cathode in keeper mode mitigates the relatively large cathode-to-ground voltage observed during the low power test, so that it is always higher than -30V. However the heritage flow controller used on Maxar EP systems is based on a fixed flow split and it cannot be adjusted depending on the power level of operation. Therefore the new flow controller to be used on the Psyche mission implements the proper versatility to change the cathode flow split between 5% and 9%, used at high and low power respectively. A discrete set of orifices in parallel paths, one with an isolating latch valve, is used to achieve the correct cathode-to-anode flow split.

Moog has played a significant role supporting the space industry’s electric propulsion (EP) community in Japan, Europe, and the US, for over 20 years with the delivery of more than 500 EP components, and nearly 100 EP subassemblies, used for satellite and deep space missions. Moog’s flight proven components delivered to date cover a wide suite of applications including; mechanical regulation, bang-bang regulation, proportional flow control regulation, isolation and flow control valves, fill and drain valves, and xenon cold gas thrusters. Three of these flight proven components will be utilized for use on the Psyche XFC.

This article will present the development of a new Xenon Flow Controller (XFC) manufactured by Moog based on Maxar’s configuration in order to span a wide range of flow rates (more than ten-fold) and guarantee a dual cathode-to-anode flow split for operation at low power (<1.5kW) as well as high power (up to 4.5kW). The article will go into some of the details of the flow controller configuration as well as individual valve design. The results of unit level development testing are reported herein. Finally the performance of the flow controller in an integrated test with the thruster will be presented.


II. Xenon Flow Controller Design Overview

A. Xenon Flow Controller Configuration

The design guidelines that drove the configuration of the flow controller (Figure 1) are multiple. As mentioned in the introduction the most critical feature is the ability to span a wide range of flow rate to cover the full power range. The highest versatility across multiple HET operational points is achieved with flow rates that vary from 4 to 20 mg/s of Xenon; that shall be expanded from 3 to 23 mg/s after adding at least a 15% margin. Such wide operational range can only be achieved with the proportional flow rate valve, which can actually operate from as little as a fraction of mg/s, and up to the limit of the orifice when fully open.

Two different cathode to anode flow split ratio are required. This functionality could be achieved in multiple ways. Two PFCV could be implemented in parallel in order to constantly adjust the flow rate across anode and cathode line; however the complication of using two controller that would depend on each other as well as on the thruster operation would have required more component (such as pressure transducers) introducing a higher level of complication in the power processing unit, as well as in mass and volume that would have heavily affected the development of the whole EP system. Another variation of the flow controller could have been the implementation of two different solenoid valves with well defined orifice sizes located in parallel on the cathode line. Only one solenoid valve at the time would have been actuated depending on the required cathode flow rate. However this configuration would have required the ability to actuate multiple solenoid valves independently, each of which requires a peak-hold circuit; moreover these valves require more power than the heritage valve, and therefore the power processing unit would have required a major redesign.

Finally the configuration locked on a fixed set of orifices (Figure 1): one on the anode line and another two in parallel on each cathode line. Since relatively less flow through the cathode line is required when the total flow is higher (high Power mode), it is sufficient to use only one orifice on the cathode line, by blocking the other. When in low power mode, there is higher demand of flow through the cathode line (higher cathode to anode flow split), therefore the passage through both cathode orifices is allowed; the design principle of the orifice size is described in the next sections. In order to achieve this functionality a miniature latch valve is introduce on one of the cathode line and actuated only when operating in HET low power mode. The selection of this specific latch valve is driven by its size and simplicity of operation. Indeed the latch valve has similar size of the other valves and only require one 28V pulse to open it or close it. These valves are already implemented on the EP system\textsuperscript{12, 13} and therefore commands and power sources already exist in the system with minimal to no impact to the overall system. Indeed also the flow controller latch valve is powered directly by the spacecraft and not by the power processing unit.

A solenoid valve is also included at the inlet of the flow controller, right upstream of the PFCV, to provide the required second line of gas isolation from vacuum. Also in this case a Moog valve is used, instead of the heritage Fakel valve. Even if the Moog valve require a higher power there is no impact to the power processing unit which was designed to operate 3 valves in parallel with the same peak-hold circuit. Therefore the selection of such valve was straightforward.

B. XFC Design Overview

The Moog Xenon Flow Controller (XFC) for the Psyche mission is an all welded, stainless steel assembly that controls the flow of xenon gas (propellant) from a low pressure regulated source, to the anode and cathode input lines of a Hall Effect Thruster (HET). Two nominal flow split ratios of the cathode to anode are possible, across the entire operating flow range, with the use of two cathode lines and the option of latch valve isolation on one of two cathode lines. The latch valve is open for lower flow operations (9% nominal flow split ratio) and closed for higher flow operations (5% nominal flow split ratio) in order to provide improved operational efficiencies.

As depicted in Figure 2, the XFC assembly consists of one normally closed solenoid isolation...
valve (SIV), one proportional flow control valve (PFCV), one cathode isolation latch valve (LV), and integral flow control orifices in each of the downstream flow lines (1 anode, and 2 cathode). Component brackets, tubing, fittings, and an integral flight plate are also part of the overall assembly. Each valve also contains an integral inlet filter to mitigate potential contamination risk. 

The normally closed SIV provides propellant isolation. The PFCV provides propellant isolation in the closed position, and controlled throttling of propellant in proportional to the amount of input current within its operating range. During operation the PFCV will adjust to the desired set point in relation to the downstream demand in a closed loop feedback system. The LV provides propellant isolation in the closed position for one of the two cathode flow lines. The orifices are sized to meet the overall flow range in relation to the PFCV operating range, and the operational flow range desired for the mission, and to provide the desired flow split ratio across this same operational range. Although currently planned for a maximum expected operating pressure (MEOP) of <50 psia, the XFC design is capable of a MEOP of up to 2700 psia (186 bar). Maximum steady state power of the XFC under ambient thermal conditions is <3W.

All XFC components are based on qualified, flight heritage designs, and the overall XFC assembly is based in principle on the Moog heritage XFC12. Flow control orifices are similar to flight heritage designs13 except for the size change to meet the specific requirements of the current program. Orifice sizes were initially determined based on predicted pressures across the XFC assembly and the use of textbook mass flow equations for a sharp edged orifice. Verification and adjustment of the orifice sizes were then realized during subsequent development testing on a flight like XFC.

III. Xenon Flow Controller Development Testing

A. Test Article – Development Unit

Development testing was performed on a flight like XFC as shown per Figure 3 using the same/similar component designs that are planned for flight, except for the flight plate, brackets and orifices. Orifices for the development unit were integrated using a mechanical connection (VCR type) in lieu of a welded connection to facilitate easy exchange of different sizes, as required.

Figure 2. Moog XFC CAD schematic, Isometric and Top Views

Figure 3. XFC Development Unit and XFC Development Unit with Thermocouples

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B. Test Set-up and Results

The development test setup recreated flight conditions with a regulated inlet pressure and downstream near vacuum conditions, in a closed loop feedback control system using the anode flow for the XFC control. A data acquisition system recorded results for pressures, flows, PFCV current and temperatures throughout the development testing, as typical.

Xenon flow testing was conducted at ambient, cold (-10°C), and hot (50°C) environmental thermal conditions, and over a total flow range of 3.0 mg/s to 23.0 mg/s xenon. Inlet pressures where maintained at 37±1.45 psia (2.55 ±0.1 bar) throughout all testing conditions. Total flow rates of 6.3 mg/s xenon or lower were operated with the XFC LV open for a targeted cathode to anode (C:A) flow split ratio of 9%, and total flow rates of 6.9 mg/s or higher were operated with the XFC LV closed for a targeted C:A flow split ratio of 5%. The minimum inlet pressure to the XFC was also determined at the maximum flow rate conditions to identify margin for end of life (EOL) conditions. For comparison purposes, testing for each operating condition was repeated with the use of argon except with mass flow rates adjusted to equate to the mass flow rate of xenon for each operating point. For each gas and temperature condition, the flow rate and flow split ratio were determined by stepping through the flow rate range using the anode flow rate requirement as the control command for the XFC.

Graphical results of the XFC development testing at Moog, presented in Figures 4 through 6, indicate consistent results over the temperature range (-10°C to 50°C), with C:A flow split results within expected tolerance ranges as compared with the nominal target C:A flow split ratios.

Anode and cathode flight like orifices were also manufactured and tested for verification of performance in comparison with the XFC development unit orifices made with the VCR interface. Results of the flight like orifices indicated no significant deviations as compared with the VCR orifices, as expected.

Overall results of the XFC development testing verified the design was operating as predicted and within requirements in support of the program.

![Figure 4. XFC Development Test Flow Results – Ambient Temperature](image)

![Figure 5. XFC Development Test Flow Results – Hot Temperature](image)

![Figure 6. XFC Development Test Flow Results – Cold Temperature](image)
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IV. Xenon Flow Controller Integrated Testing

A. Test Set-up

The flow controller was integrated within the full EP system (Figure 7) to confirm its performance when running the thruster SPT-140 and controlled by the power processing unit. The test has been performed at JPL in the 3m wide and 10m long Owen vacuum chamber that has a pumping speed greater than 200 kL/s during thruster operation. The test was divided into two different activities with different set-up configurations: 1) the flow controller outside the vacuum chamber; 2) flow controller inside the vacuum chamber.

In the first configuration (Figure 8.a) two flow meters are located downstream both cathode and anode line in order to measure the cathode to anode flow split. The flow meters UFM-1661 are in the 0-50sccm and 0-300sccm range and both calibrated on Xenon. The pressure upstream the flow controller is fixed with a mechanical regulator within the range of 37 +/- 2 psia. The vacuum chamber is at high vacuum with a base pressure always lower than 5e-7 Torr (Xe).

The Thruster, the SPT-140 QM002 5,8, is installed in the vacuum chamber with two 50-psia Taber pressure transducer right upstream to verify the static pressure in each line during operation. Filters are installed to prevent any particulate to backflow into the flow controller. Gas isolators are required to provide electrical isolation. These components together with the lengthy facility line (several meters of ¼" tube), generate a pressure drop of about 1-2psia between the xenon flow controller and the thruster, which is on the same order of magnitude of the flight configuration. The XFC valves are operated by laboratory 32V power supply. The PFCV position is driven by adjusting the current supply to a maximum of 150mA (12V maximum), or alternatively the voltage; the solenoid valve require a peak voltage of 28V for a fraction of a second and then kept open with a 10V supply (with a max current of 0.15A); the latch valve required one 28V pulse (~0.5A). One thermocouple is placed on the body of the PFCV to monitor temperature shifts of the valve

In the second configuration (Figure 8.b) the XFC is placed into the vacuum chamber behind the thruster, with the 1/8” tubing to be 1-2 m long in flight-like configuration. In this case it is not possible to install the flow meters on each of the anode and cathode lines, instead one UFM-1661 flow meter, in the 0-300 sccm(Xe) range, is placed upstream the line outside of the vacuum chamber to measure the total flow rate. Because of the lengthy line several seconds (up to 1 minute) is needed to stabilize the flow rate reading, especially at the lowest flow rates. The pressure transducer is checked both at the same location as the first configuration (Figure 8.a) as well as right downstream of the XFC to verify the pressure at the outlet of each line (Figure 8.b). The PFCV can be either powered in open loop by the PPU or an external power supply, while only the PPU can control the XFC in closed loop. The Solenoid valve is powered by the power processing unit. The latch valve is operated with an external power supply as in the first test set-up configuration. When inside the chamber the flow controller may be exposed to a much lower temperature (down to -50 °C), and therefore it has been isolated thermally from the thrust stand and a 10W heater has been mounted on

![Figure 7. XFC development unit setup inside the chamber](image)

![Figure 8. Integrated test setup with the XFC placed: a) outside the chamber; b) inside the chamber.](image)
the base plate with the objective to control the PFCV body temperature between 10 and 30 °C. Two thermocouples are placed on the baseplate and the PFCV body to monitor the temperature during each phase of the test. Finally a polyamide sheet cover the whole unit to avoid any coating with backspattering material.

B. Test Results

The main characteristics of the XFC to be verified are: the relationship between the PFCV current and the total flow rate; and the ability to provide the required cathode-to-anode flow split ratio at every operating flow rate. As explained in the previous section these parameters may depend on how the unit is operated and in which environment it functions. The main feature to be characterized for open loop control is the hysteresis (Figure 9). This repeatable behavior manifests as the PFCV is powered continuously throughout the range of allowable currents. When the PFCV valve is initially powered by increasing the current from zero to a specific set value, it requires a different current to actuate the moving components of the valve and achieve a certain flow rate as compared with reducing the current to a set point from an existing energized state after the initial energization. A higher flow rate for the same PFCV current is therefore possible depending on the starting operating condition and direction of operation. This is a well known characteristic of the PFCV as documented in a previous IEPC paper8. Figure 9 shows the full envelope of the hysteresis. That is achieved by continuously increasing the PFCV current starting from “I_{max}”, moving along the “lower boundary” up to the maximum flow rate “I_{max}”, at which point the valve is fully open and more PFCV current does not affect the unit anymore, thus the plateau. When decreasing the PFCV current, it is now possible to verify that the same flow rate achieved on the lower boundary can be now attained at a lower PFCV current (to a shift on the order of ~1mA), as compared with reducing the current to zero (Figure 10). This if the worst case scenario, while in reality it is not as critical when operating in open loop because the initial flow rate needs to be accurately known in order to start the thruster at the expected discharge current, that is directly correlated to the flow rate.

When operating the XFC together with the thruster it is critical to reliably set the initial flow rate, because it is commanded by an open loop controller. Indeed if the flow rate is too high, the discharge current of the thruster may overshoot and reach a current-limit mode, and eventually the controller would require longer time to achieve a stable final flow rate. Each PFCV is therefore tested to verify the characteristics of the flow gain curve and hysteresis, as shown in Figure 9.

To minimize hysteresis effects for a repeatable open loop flow rate selection it is recommended to operate on the upper boundary of the hysteresis curve. Figure 10 shows the maximum hysteresis on the upper boundary that is achieved when the PFCV current is fully applied and then decreased (‘open circle’ marker) to the point to have almost no flow and then increased back (‘triangle’ marker), which demonstrates a maximum PFCV shift of ~3mA as compared to a shift of ~10mA if starting from 0 mA. This if the worst case scenario, while in reality it was experienced to shift on the order of ~1mA, due to the tight control of the PFCV current. Figure 10 also shows the repeatability to open the valve at a specific flow rate when targeting a specific PFCV current (‘closed circle’ marker). By maxing out

Figure 9. Hysteresis of the PFCV (~10mA) measured during cold flow; PFCV body temperature is 40 +/-5 °C, with XFC place outside the chamber (configuration not more than 0.5ohm loss due to line resistance).

Figure 10. Hysteresis is limited (~3mA) when the PFCV current is set to max flow rate and then dialed down. PFCV body temperature at 20 +/-5 °C. XFC set up inside the vacuum chamber (Configuration #2).
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Figure 11. Cathode to anode flow split ration at different flow rates during cold flow and hot fire.

Figure 12. Pressure drop downstream the XFC. XFC temperature at 15 °C +/- 5 °C.

The PFCV current (e.g. up to 140mA) and then dialing back to a specific value it is possible to achieve a specific flow rate within an accuracy of ±1mg/s.

The other critical feature to be verified is the ability to change the flow split ratio depending on the flow rate that is required. Figure 11 shows that when the latch valve is closed, at a flow rate higher than 6.6mg/s, the cathode to anode flow split ratio is 5%. Instead at lower flow rate (<6.6mg/s) more flow through the cathode is required therefore the latch valve is actuated open so that the cathode to anode flow split ratio goes to 9%, as per design. The design requirement is met within 0.5% of accuracy. Figure 11 also shows that this condition is achieved for both cold flow and hot fire, therefore any partial change in pressure downstream the XFC does not affect the cathode to anode flow split.

The design of the XFC is dependent on the pressure drop across the orifices, therefore knowledge of these values is important. Figure 12 shows the pressure measured downstream the anode and cathode line (in Configuration #2, but without filter and propellant isolator). The pressure in the anode line increases linearly with the flow rate form 0.5psia up to 5.0 psia at the maximum flow rate, and it operates in the sub-sonic regime as expected; while the pressure in the cathode line increases as long as the latch valve is open at the lower flow rate, but it is always within 1-2psia when the latch valve is closed, operating in a choked configuration.

As described in the previous section, the closed loop operation of the PFCV valve is not affected by temperature as long as the valve is operated within its qualified thermal range. Additionally, the valve is operated at 20 °C ± 10 °C, and when at equilibrium the heat generated by the coil prevails, resulting in coil resistance change limited to ±1 ohm.

V. Conclusion

The XFC presented herein fully meets the design and performance requirements for the EP system to be used on the Psyche mission. The PFCV is able to cover a wide range of flow rates, as well as allow the cathode-to-anode flow split ratio for different power levels of the Hall Effect Thruster. Each PFCV will be tested to characterize its open loop performance in support of the operational requirements at the start up of the thruster.

The orifice design, supported by the operation of the latch valve, demonstrated the ability to achieve the cathode-to-anode flow split ratio required at every power level. Note that the flow split operation is “manual”, and therefore it is the operator’s (or software’s) duty to activate the latch valve when required.

Finally, the environmental conditions are of minor effect for open loop control as long as the XFC is operated within its designed range of at 20 °C ± 10 °C, and no effect for closed loop control across the entire thermal range of the XFC (-10°C to 50°C).

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