A Low Power Proportional Flow Control Valve for Electric Propulsion Systems for Satellite Applications

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Abstract: The regulation of satellite propulsion systems is rapidly moving away from preset mechanical valves to active electronic control valves achieved through either bang-bang control or proportional flow systems. Cobham recently developed a proportional flow control valve specifically designed for low power consumption and low mass to provide a solution for this growing demand. The new valve can be configured for low or high pressure flow control as well as primary pressure regulation, and is controlled by either built in closed loop control or customer supplied electronics. Low mass and power consumption are achieved by the use of piezo actuators that consume virtually no power at steady state metering conditions. Under transient conditions the associated electrical current is proportional to the charging/discharging of the piezo capacitance. The valves are highly flexible and able to provide proportional flow control with inlet pressures up to as high as 5000 psig and regulating pressure with inlet pressures up to 3000 psig.

Nomenclature

Ps	=	supply pressure (psia)
P2	=	outlet pressure (psia)
Po	=	ambient pressure (psia)

I. Introduction

COBHAM developed a proportional flow control valve (PFCV) as an alternative to the traditional mechanical regulator, and on/off solenoid and plenum flow regulation systems that are typically referred to as bang-bang solenoid systems. The Cobham design is shown in Fig. 1. A recent review of satellite propulsion system specifications determined that there are two basic types of proportional valve applications, pressure control and flow control. The pressure control (reducer) applications use a proportional valve to control the pressure downstream of the valve in place of a typical mechanical pressure regulator, and is often supplied with full tank pressure. A closed loop control system is required and typically uses a downstream pressure transducer to provide the pressure feedback signal. Xenon flow ranges for the pressure control applications can be as high as several hundred mg/sec.

Figure 1. Cobham proportional flow control valve

The Xenon flow control applications use proportional valves to meter flow to thrusters by using an appropriate feedback signal. In this case the inlet pressures are relatively low (<3 bar) and the Xenon flow rates are in the mg/sec range.

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II. Design Overview

A. Target Performance Parameters

Table 1 below contains the performance parameters that were targeted during valve development for the pressure and flow applications. These requirements were determined from a review of past satellite propulsion system (large and small) requirements thus the listed requirements are not specific to one application.

Table 1. Valve requirements

Specification	Xenon Pressure Regulation	Xenon Flow Proportional Flow Control
Mechanical Interface	316L CRES Tubing	316L CRES Tubing
Filtration, Integrated	2 micron	2 micron
Operating Pressure Range [psia] (Inlet)	100 - 2700	5 - 60
Flowrate [mg/s]	0 to 200	0 to 22
External Leakage [scc/s Ghe] between 0.0 and MEOP	1.0E-6	1.0E-6
Internal Forward Leakage [sccs Ghe] between 0.0 and MEOP	1.0E-4 at MEOP	1.0E-4 at MEOP
Cycle Life	100,000	100,000
Design Life	22.5 years after 5 years storage	22.5 years after 5 years storage
Maximum Input Current [mA]	25 mA at 32.0 VDC	25 mA at 32.0 VDC
Valve Response	<= 10 ms	<= 10 ms
Operational Temperature Range [deg C]	15 to 60	15 to 60
Non-Operational Temperature Range [deg C]	-34 to 71	-34 to 71
Random Vibration - [Grms]	21.6	21.6

B. Valve Configuration

As satellites become smaller and lighter the available electrical power for thruster systems decreases as well. Minimizing the valve actuation power is a key goal to accommodate these lower power systems and was a main driver in the valve design. After the consideration of many alternative actuators, it was decided to pursue the use of piezo actuators because they have extremely low power requirements particularly when used in low frequency applications like when used in a proportional flow valve.

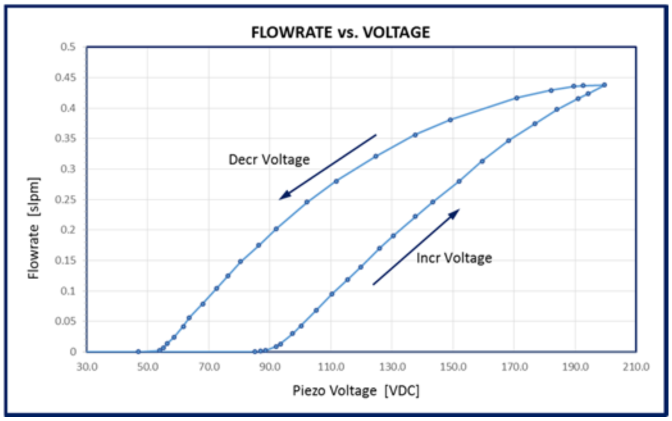

Figure 2. Typical Hysteresis Characteristic

Piezo actuators come in two basic configurations, benders and linear stacks. The benders tend to have large displacements and low force output while the linear stacks have large force outputs but very small displacements. The small displacements require mechanical amplification to actuate a valve mechanism.

A good compromise between the typical bender and linear stack is the circular disc type piezo actuator. The circular piezos flex upward in the middle of the actuator when an electrical potential is applied, and the displacement is large enough to allow the valve mechanism to be directly driven. The force output is sufficient to overcome required seal off preloads. The circular shape also allows the piezo to be constrained in a manner that leads to excellent vibration/shock robustness. These reasons drove Cobham to choose this style element to actuate the valve.

The nature of piezo actuators means there is a significant hysteresis bandwidth associated with their use as shown in Fig. 2, as well as a tendency for the valve to drift slightly because of the capacitance "charging" effect shown in Fig. 3.

These characteristics make piezo actuated valves difficult to use for open loop flow control. However, when a well-designed closed loop controller is available to accommodate the piezo characteristics it a piezo actuated valve offers excellent response characteristics and very low power consumption across a wide range of temperatures and pressures.

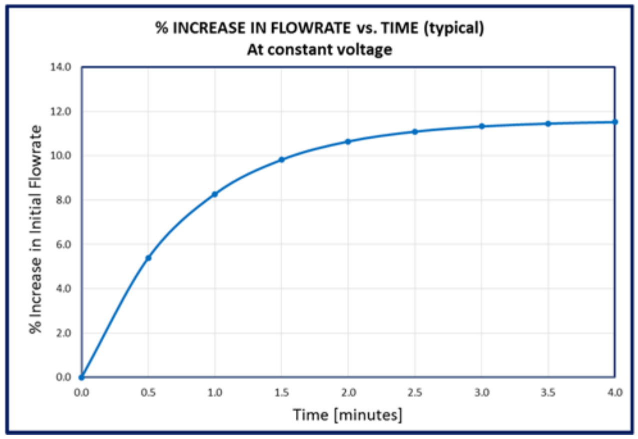

Figure 3. Typical Piezo Charging Effect

III. Testing

Preliminary development testing has been run on the lower inlet pressure flow control version of the proportional valve to determine its operational characteristics with respect to the expected pressure and temperature ranges.

A. Test Facility and Equipment

All testing was performed within the Space assembly and test area in the Cobham facility in Orchard Park NY. Thermal testing consisted of placing the valve in a thermal chamber and instrumenting and monitoring of the test unit temperature. A typical test set-up is shown in Fig. 4 and the schematic for the flow tests is shown in Fig. 5.

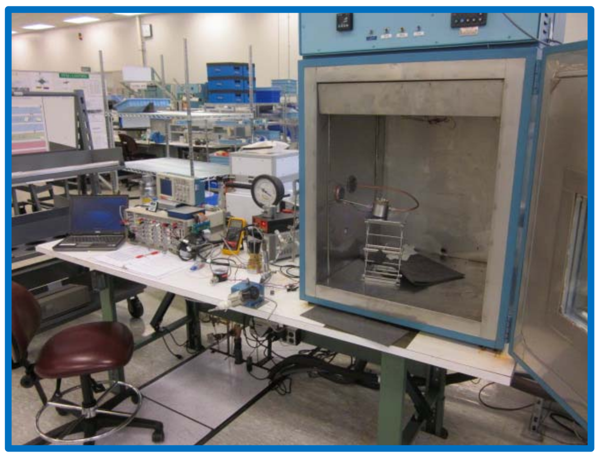
Figure 4. Steady State flow test set-up

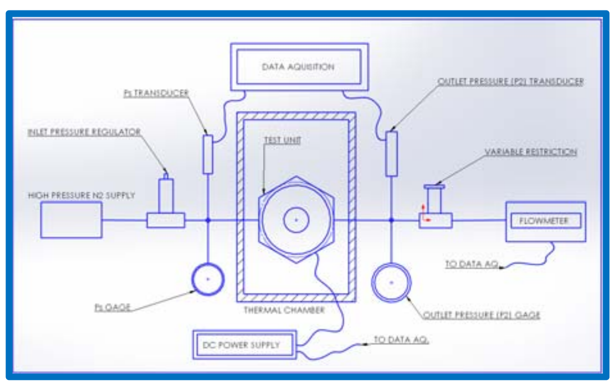

Figure 5. Test Schematic

B. Observations

The valve has been shown to perform well over a temperature range of 0.0 C to 75 C. The typical effect of temperature on flow vs. piezo voltage (Vp) is shown in Fig. 6. When used in a propulsion system with closed loop control, the system can easily compensates for any shift in flow as a result of temperature changes.

For the low pressure flow control applications (Ps<200 psig) there is no discernable change in flow control capability over the inlet pressure range as shown in Fig. 7. Obviously flow gain changes with inlet pressure, however a robust control algorithm should easily compensate for inlet pressure effects.

Internal leakage throughout the temperature range was well within design goals as tabulated in Table 2.

A complete development testing program is scheduled to be carried out in the last quarter of 2017. Planned tests include vibe, shock, thermal and pressure cycles, operational cycles (100,000+ cycles) and dynamic testing.

IV. Conclusion

The PFCV desig presented in this paper offers propulsion system integrators a low power and flexible option. Test results to date are promising and the testing of the design will continue with results being presented in a later paper. While we chose this particular requirement set for this initial development activity, the PFCV design is easily modified to achieve application specific requirements. Finally, the PFCV presented here is only one of several PFCV configurations that Cobham is developing, and plans to develop new proportional flow control products and demonstrate their robustness through an extensive testing program.

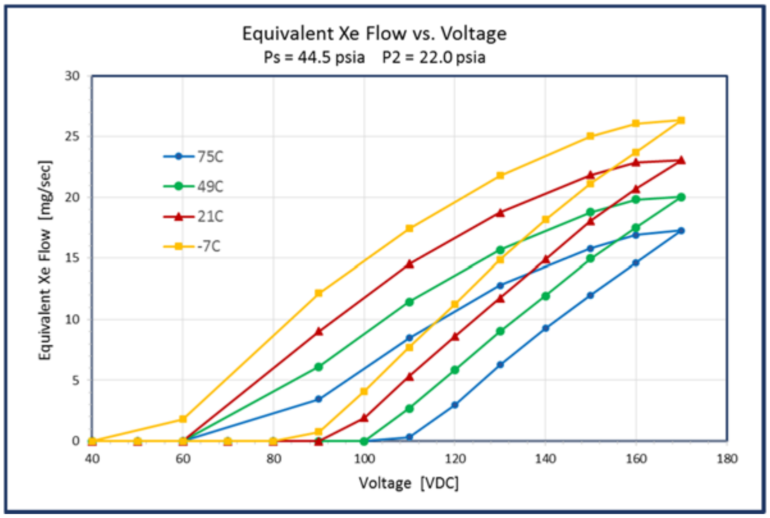

Figure 6. Flow vs. Voltage and Temperature

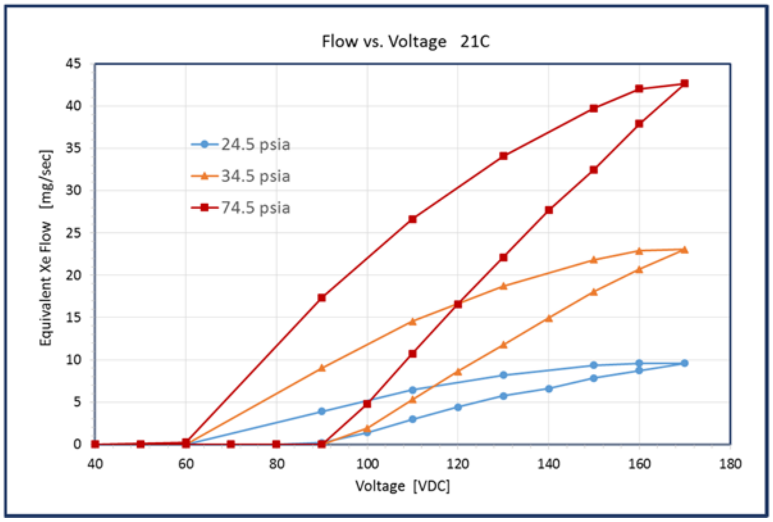

Figure 7. Flow Gain vs. Inlet Pressure

Table 2. Leakage Table

Internal Leakage	
Ps = 74.5 psia	
Temperature [deg C]	**GHe Leakage** [GHe sccs]
-7	3.9×10^{-9}
21	3.3×10^{-9}
49	1.4×10^{-8}
75	3.6×10^{-8}