Iodine Hall Thruster Propellant Feed System for a CubeSat

Kurt A. Polzin* and Steven Peeples†

NASA-Marshall Space Flight Center, Huntsville, AL 35812

The components required for an in-space iodine vapor-fed Hall effect thruster propellant management system are described. A laboratory apparatus was assembled and used to produce iodine vapor and control the flow through the application of heating to the propellant reservoir and through the adjustment of the opening in a proportional flow control valve. Changing of the reservoir temperature altered the flowrate on the timescale of minutes while adjustment of the proportional flow control valve changed the flowrate immediately without an overshoot or undershoot in flowrate with the requisite recovery time associated with thermal control systems. The flowrates tested spanned a range from 0-1.5 mg/s of iodine, which is sufficient to feed a 200-W Hall effect thruster.

I. Introduction

CubeSats are relatively new spacecraft platforms that are typically deployed from a launch vehicle as a secondary payload,[1] providing low-cost access to space for a wide range of end-users. These satellites are comprised of building blocks having dimensions of 10x10x10 cm^3 and a mass of 1.33 kg (a 1-U size). While providing low-cost access to space, a major operational limitation is the lack of a propulsion system that can fit within a CubeSat and is capable of executing high Δv maneuvers. This makes it difficult to use CubeSats on missions requiring certain types of maneuvers (i.e. formation flying, spacecraft rendezvous).

Electric thrusters, with their high specific impulse, offer a path to CubeSat propulsion, but there are some general challenges to integrating an electric thruster into a CubeSat platform. Even small or scaled-down electric thrusters often require more power than the steady-state power that can typically be produced by the small solar arrays of the spacecraft. Packaging of an electric thruster is also difficult owing to the occupied volume and inherent mass of the thruster system [thruster, tankage and valves, power processing unit (PPU)]. These issues are compounded by thermal issues associated with a thruster that is mounted within the CubeSat and potentially radiating heat to other systems (avionics, power system, flight computer). In addition to these operations issues and integration challenges, many thrusters require propellant stored at a high pressure, but CubeSats are often launched as secondary payloads and high pressure systems are typically not permitted by the primary payload launch customer.

Recently, work has been performed investigating the use of iodine as a propellant for Hall-effect thrusters (HETs). [2] Iodine stores as a dense solid at very low pressures, making it acceptable as a propellant on a secondary payload. It has exceptionally high $\rho I_{\rm sp}$ (density times specific impulse), making it an enabling technology for small satellite near-term applications and providing the potential for systems-level advantages over mid-term high power electric propulsion options. Iodine flow can also be thermally regulated, subliming at relatively low temperature (<100 °C) to yield I_2 vapor at or below 50 torr (see Fig. 1).[3,4] At low power, the measured performance of an iodine-fed HET is very similar to that of a state-of-the-art xenon-fed thruster. Just as importantly, the current-voltage discharge characteristics of low power iodine-fed and xenon-fed thrusters are remarkably similar, potentially reducing development and qualifications costs by making it possible to use an already-qualified xenon-HET PPU in an iodine-fed system. Finally, a cold surface can be installed in a vacuum test chamber on which expended iodine propellant can deposit. Referring to Fig. 1, the temperature doesn't have to be extremely cold to maintain a low vapor pressure in the vacuum chamber (under 10^{-6} torr at -75 °C), making it possible to 'cryopump' the propellant with lower-cost recirculating refrigerant-based systems as opposed to using liquid nitrogen or low temperature gaseous helium cryopanels.

An iodine-based system is not without its challenges. The primary challenge is that the entire feed system must be maintained at an elevated temperature to prevent the iodine from depositing (transitioning from the gas phase back into

*Propulsion Research Engineer, Propulsion Research and Technology Applications Branch, Propulsion Systems Department. Associate Fellow AIAA.

†Electrical Engineer, Digital Systems Design Team, Avionics Design Division.

the solid phase), which will block the propellant feed lines. Furthermore, deposition will occur unless the temperature in the lines is not greater than the temperature of the propellant reservoir. The flow rate can be controlled by adjusting the heating applied to the reservoir, but as with any thermal control there is a relatively slow response to changes in the heating rate.

In this paper, we outline what would be needed for a feed system for, the iodine satellite (iSAT) technology demonstration mission,[5] which aims to fly 200 W iodine-fed HET installed within a 12-U (20x20x30 cm ^{3}) CubeSat. In Sect. II we focus on describing the function of each of the components needed for a precision system that would operate in a microgravity environment. A discussion of an auxiliary control board that was designed and fabricated to accept commands from a flight computer and operate the iodine feed system components follows in Sect. III. Finally, in Sect. IV results are presented from laboratory testing performed to validate a control methodology that uses the reservoir temperature and a variable-position valve to precisely control the iodine flowrate.

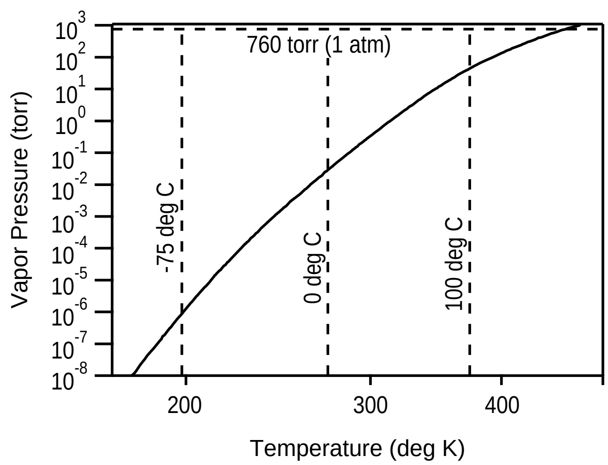


Figure 1. Vapor pressure curve for molecular iodine (I_2). After Refs. [3, 4]

II. Feed System Components

The propellant feed system for an iodine-fed HET consists of several components, as illustrated schematically in Fig. 2. In this section we described these components and their function in the feed system.

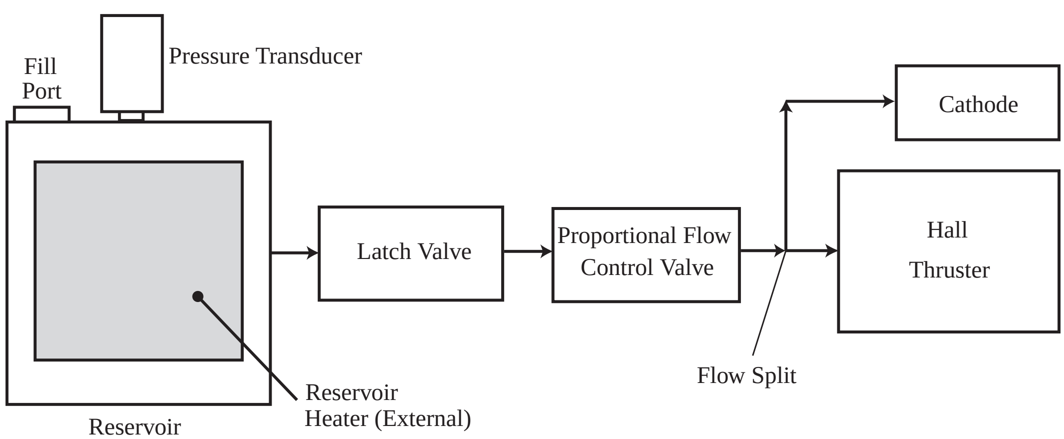


Figure 2. Schematic illustration of a flight-like iodine propellant feed system.

A. Propellant Reservoir

Iodine is stored in the propellant reservoir as a solid and sublimes directly to the gas phase through the application of heat. This produces a gas with a pressure corresponding to the vapor pressure given in Fig. 1, which is typically below 50 torr ($\approx$ 1 psi) in the iodine-fed HET application. The gross propellant flow rate can be controlled by varying the temperature of the reservoir. In both the present work and in Ref. [2] the response of this method is on the timescale it takes to heat and cool the reservoir, which is relatively slow.

A propellant fill port is provided to load the reservoir for flight. In ground testing, the iodine is always settled on the bottom of the reservoir and in thermal contact with the heated interior surfaces. However, in flight there is a question as to whether the propellant will remain in contact with the reservoir sidewalls as the iodine sublimes and furthermore it is not known whether the iodine in the reservoir will be as the same temperature as the sidewalls. The pressure transducer on the reservoir is meant to monitor the sublimation of the solid iodine by measuring the vapor pressure directly to compare with the value that would be expected based upon Fig. 1. In previous ground testing, the predicted and measured pressures have been well-matched, which would lead us to conclude that a mismatch during flight would indicate poor thermal conduction from the reservoir walls into the propellant in the microgravity environment. Since it will be in contact with iodine vapor, the pressure transducer must be heated to a temperature greater than the reservoir to keep iodine from depositing on the transducer and rendering its measurements unuseable.

B. Latch Valve

The latch valve, shown in Fig. 3A, is in the feed system to provide a way to fully isolate the reservoir from the remainder of the feed system, especially during the launch phase of the mission when the secondary must be totally inactive and benign. This valve, manufactured by Vacco Industries, can be repeatedly opened and closed during a mission to contain the iodine vapor. It possesses its own internal heater to keep iodine from depositing within the flow channel. The specifications for the latch valve are given in Table 1.

Table 1. Specifications for the latch valve.

Mass	< 250 g
Volume	< 100 cm^3
Voltage	28 VDC, 20 ms pulse (open & close)
Proof Pressure	35 psig GHe, 5 mins
External Leakage	20 psig GHe, 6 mins, 4.6×10^{-9} sccm
Internal Leakage	20 psig GHe, 6 mins
	none indicated at 22 and 150 deg C
Flow Capacity	20 psid GHe
	27,448 sccm at 22 deg C
	19,500 sccm at 150 deg C

C. Proportional Flow Control Valve

The proportional flow control valve (PFCV), shown in Fig. 3B, is also manufactured by Vacco Industries and has the same footprint as the latch valve. Its purpose in the system is to provide accurate, fast response feedback control of the iodine flowrate. Unlike thermal control methods, such as heating the reservoir to sublime more propellant, the PFCV responds quickly to changes in the applied voltage, making it possible to quickly vary the flowrate and also to control the flowrate for changing conditions within the system (for example, a changing reservoir pressure arising from heating or cooling cycles). A PFCV was previously used to control the flowrate in an iodine feed system in the work of Ref. [2], but for that valve the pressures required for flow rates of interest were roughly 100 torr, creating condensation problems at the valve and requiring significant heating of the feed system to prevent deposition. The PFCV shown in Fig. 3B is internally heated to maintain the wetted surfaces at a temperature greater than the deposition temperature of the gas. It also has been shown to be capable of passing flowrates of interest at upstream pressures below 50 torr. In the flight configuration feed system, feedback control of the PFCV can be employed to maintain constant HET discharge current, which at a given discharge voltage correlates well with the anode flow rate.[2] Finally, if the valve completely seals when driven to the fully-closed position then it may provide the means to isolate the reservoir from the rest of the system and completely obviate the need for a latch valve. The specifications for the PFCV are given in Table 2.

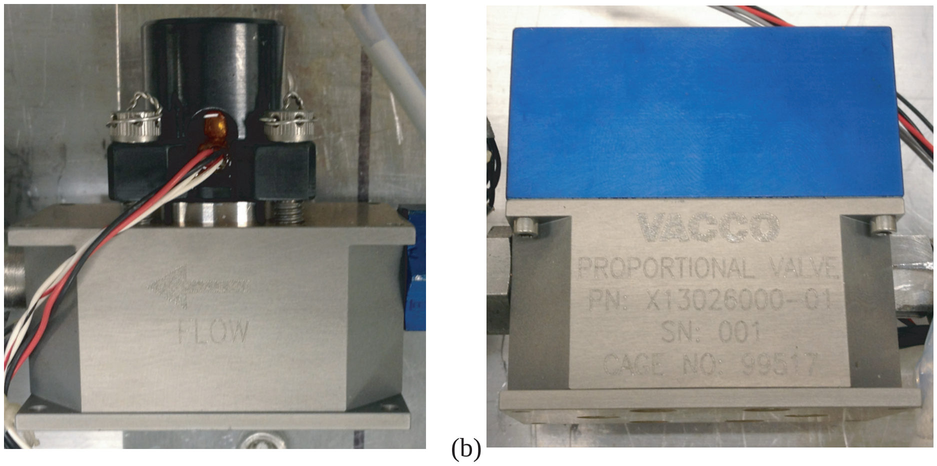
(a) (b)


Figure 3. Photographs of the Vacco Industries (a) latch valve and (b) proportional flow control valve.

Table 2. Specifications for the proportional flow control valve.

Mass	< 250 g
Volume	< 100 cm^3
Voltage	0-130 VDC (adjustable)
Power	5.2 μW at 22 deg C
Proof Pressure	35 psig GHe, 5 mins
External Leakage	20 psig GHe, 6 mins, 6.8×10^{-9} sccm
Internal Leakage	20 psig GHe, 6 mins
	none indicated at 22 and 150 deg C
Flow Capacity	20 psid GHe, 130 VDC applied
	27,448 sccm at 22 deg C
	19,664 sccm at 150 deg C

D. Line Heating

The wetted surfaces in the lines and connectors between the various components in Fig. 2 must be heated to maintain iodine in the vapor phase throughout the system. An approximate rule-of-thumb is that the line temperature at all locations should be greater than the reservoir temperature. This is understood using Fig. 1, where we observe that if the temperature in the line is lower than the reservoir temperature, then the gas could deposit on the cooler walls to lower the vapor pressure to the level commensurate with that temperature. Eventually this process will cause enough iodine to deposit on the walls and completely block the flowpath.

III. Auxiliary Control Board

An auxiliary control board has been developed to operate a latch valve, up to two (2) PFCVs and heaters for the reservoir, feed lines and valves. It also is used to measure feed system pressures, temperatures, and the actual applied voltage to the PFCVs. An onboard field-programmable gate array (FPGA) provides a serial link to accept commands and handle all lower level input/output functions. A block diagram showing the high-level hardware interfaces with the auxiliary control board is given in Fig. 4.

A. Latch Valve

The latch valve is either opened or closed when the FPGA provides a 20 ms pulse to a 28 VDC MOSFET-switched circuit. The advantage of the latch valve is that power does not need to be applied to hold the valve open or closed,

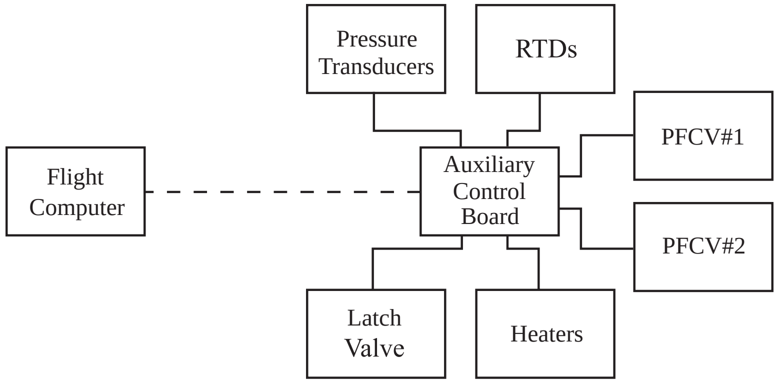


Figure 4. Block diagram showing the high-level hardware interfaces with the auxiliary control board.

reducing the overall power draw substantially. The valve can be commanded to open or close through the serial link.

B. Proportional Flow Control Valve

The FPGA provides a pulse width modulated (PWM) signal to a DC/DC boost converter to produce the variable 12-120 VDC required to open the PFCV. The output voltage is proportional to the PWM input duty-cycle. The control on the board is open loop and it is left to the flight computer or another serial-linked controller to close the control loop. While there are many integrated circuits that can locally (on-board) close the control loop, because the piezo actuator in the PFCV has a high impedance there is no way to quickly bleed off the excess voltage when a reduced PFCV output voltage is needed (i.e. when partially closing the PFCV). A separate MOSFET-switched load is used to perform this bleed-off task. The duty cycle and load control is set through the serial link. The output to each of the PFCVs is passed through a voltage divider and fed into the analog-to-digital converter (ADC). The digital value is a feedback measurement that is made available to the flight computer through the serial link.

C. Heating

There are six MOSFET-switched heating circuits. Heaters are 12V or 28V and located in the latch valve, PFCVs, propellant reservoir, and propellant feedlines. The FPGA creates a one-second period, programmable duty-cycle control for the heaters. The duty cycle during the one-second period is set through the serial link.

D. Temperature Monitoring

The latch valve and PFCVs have thermistors built in for temperature sensing. In addition, the auxiliary control board can accept inputs from up to three resistance temperature device (RTD) circuits, which could be used for measuring the temperature in the reservoir, at a representative location on the propellant line, and potentially at a location on the thruster. Thermistor and RTD outputs are conditioned and sent to an ADC which is directly commanded and controlled by the FPGA. The FPGA makes the digital values corresponding to each temperature measurement available to the flight computer through the serial link.

E. Serial Communications

The serial interface uses a universal asynchronous receiver/transmitter (UART) protocol operating at 9600 baud with 8 bits and one stop bit. The auxiliary board can perform serial communication through any of the on-board jumper-selectable methods: RS-232, RS-485/422, TTL and Xbee wireless communication. The FPGA does not transmit unless a command has been issues by the flight computer. All responses are followed by an ASCII “ACK” for acknowledge of command or “NAK” for not acknowledged. For ADC value request commands “ACK” follows the output of the requested value.

IV. Laboratory Testing

In this section we describe a laboratory test setup, the results of checkout testing with N_2, and testing performed with iodine vapor aimed at demonstrating the functionality of the feed system components needed for an iodine-fed HET in which flowrate is controlled using the reservoir temperature and a variable position valve.

A. Test Layout

A diagram of the system is given schematically in Fig. 5. The entire setup is located outside of a vacuum facility with the exhaust directed into the chamber. This test setup can support either iodine vapor sourced from the propellant reservoir or other gases (such as N_2) supplied to the system through the MKS1479 flow controller. Either input can be isolated using the hand valves. The gas flows through the latch valve and the PFCV before it enters the MKS1152 vapor phase flow meter. There are 0-258 torr (0-5 psia) pressure transducers upstream and downstream of the PFCV, but these failed when heated to above 115 deg C during iodine testing. The wetted surfaces in the MKS1152 are internally heated to keep gases from recondensing within the flowmeter. The flowrate measurement is accomplished by measuring the pressure at each end of a fixed viscous laminar flow tube and then correlating the flowrate as [6]

$$Q = K\left(p_1{}^2 - p_2{}^2\right) \tag{1}$$

where Q is the mass flow rate, p_1 and p_2 are the upstream and downstream pressures across the laminar tube, and K is a proportionality constant that should remain relatively fixed for a given gas type and inlet temperature. Gas is then exhausted into a vacuum chamber, where in future work it can be used as a calibrated gas source for the cathode and anode. During iodine testing, the lines are wrapped with heater rope while the reservoir is independently heated with a pair of cartridge heaters aligned with the centerline of the tank and inserted into the sidewalls.

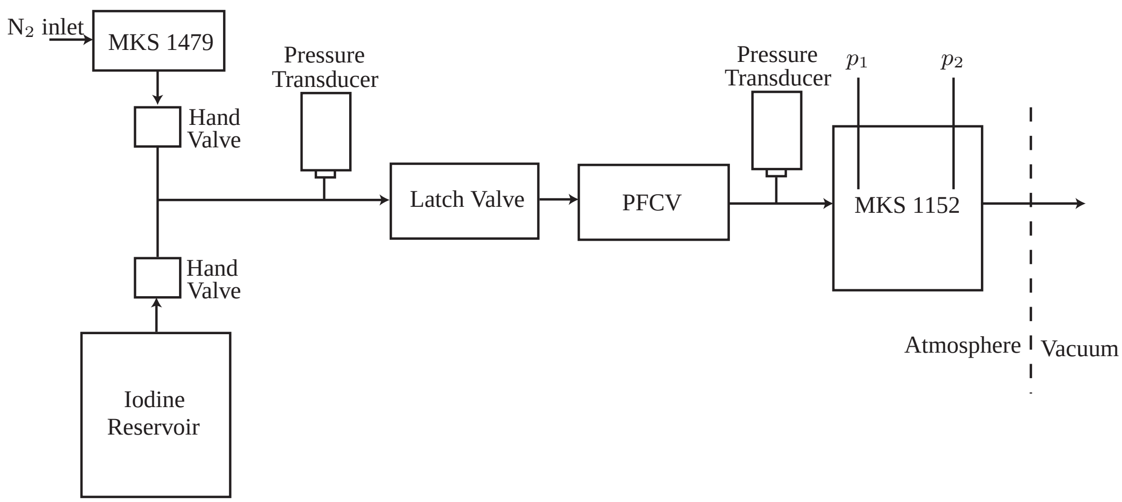


Figure 5. Schematic illustration of a flight-like iodine propellant feed system.

B. Operational Checkout on N_2 gas

Unlike operation on iodine, where the pressure in the reservoir is fixed by the temperature, in the checkout testing the *flowrate* is controlled to a fixed value by the MKS1479 unit. However, in our checkout testing we used the constant flowrate source to show that the PFCV was operating (producing a variable pressure drop across the valve as it was opened or closed) and that the achievable pressures at a few sccm of N_2 were within the same regime as those given in Fig. 1 for iodine reservoir temperatures below 100 deg C.

A sample of the data at a constant MKS1479 setpoint of 5 sccm N_2 is given in Fig. 6. As the PFCV is incrementally closed, the downstream pressure reduces for a time as the pressure upstream of the PCFV grows to support the same flowrate at the new, smaller opening size. Eventually these values reach a new steady-state value corresponding to the internally-consistent pressure drops for the given flowrate and PFCV opening size. A contour plot showing the steady-state pressure values measured upstream of the PFCV as a function of the PFCV voltage (opening size) and the volumetric flow rate of N_2 is given in Fig. 7. This figure shows that the PFCV can be dynamically exercised to provide a flowrate over a wide range of upstream pressure values. Said another way, for a given upstream (reservoir) pressure value, the PFCV can be varied to yield a wide range of flowrates.

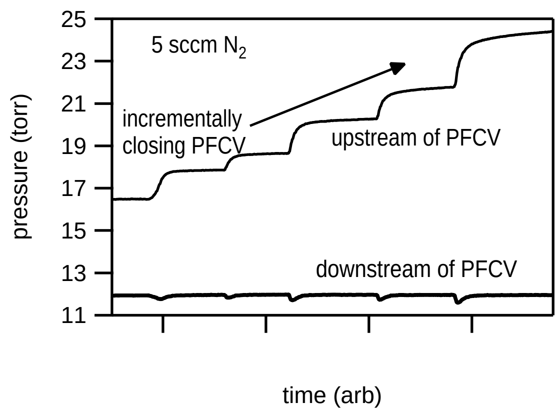


Figure 6. Pressure measured upstream and downstream of the PFCV at a constant MKS1479-controlled N_2 setpoint for an incrementally-closing PFCV.

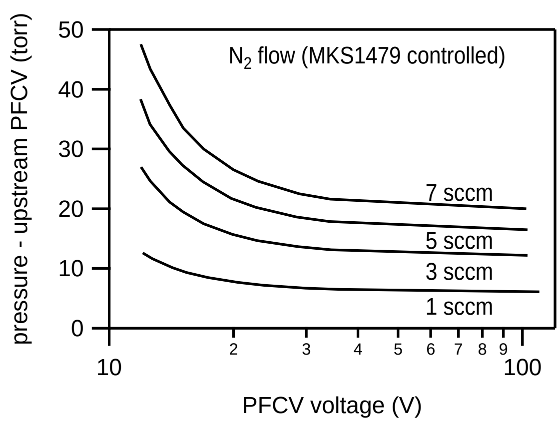


Figure 7. Contour plot showing the PFCV set voltage and the steady-state pressure measured upstream of the PFCV for constant MKS1479-controlled N_2 setpoints.

C. Operation on I_2 Vapor

For testing with iodine, the propellant lines are typically brought to ~115 deg C before heat is applied to the propellant reservoir. This ensures that the iodine in the reservoir is always at a temperature that is lower than the feed lines. Unless otherwise indicated, for the testing described in this subsection the reservoir was heated to 90 deg C and the flowrate was fully controlled using the PFCV.

1. Calibration

The output of the MKS1152 flowmeter was calibrated by bringing the system to a constant state (reservoir temperature of 90 deg C, constant PFCV position) and permitting iodine to flow at that state for several hours. A data set from one of these calibration tests showing the upstream and downstream pressures p_1 and p_2 and $K\left(p_1{}^2 - p_2{}^2\right)$ as a function of time are given in Fig. 8. Using the total mass expended during a test M, taken as the difference in the pre- and post-test reservoir masses, the value of K was determined using:

$$M = K \int \left(p_1{}^2 - p_2{}^2\right) dt \quad (2)$$

The data exhibit a slow drift because once the conditions (temperatures, PFCV voltage) were set, no further changes were made to the system to try and maintain a constant flowrate. The change in flowrate is almost entirely driven by variation in the upstream (reservoir) pressure over the course of the test.

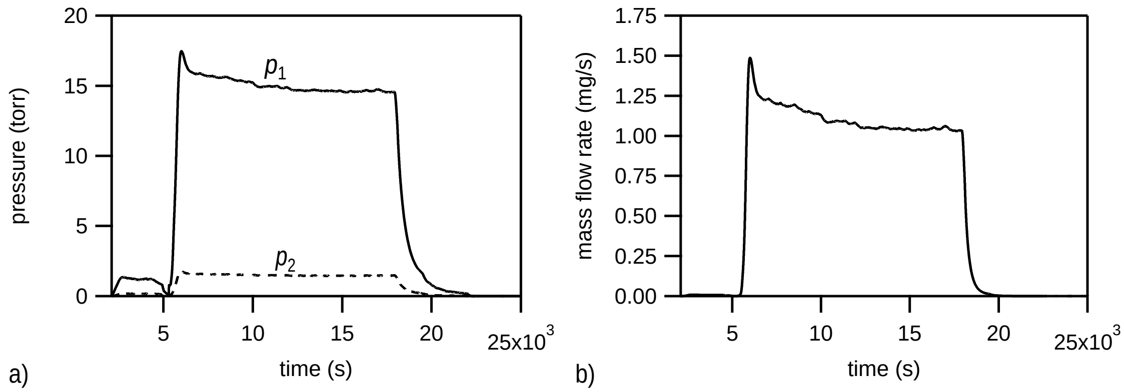


Figure 8. (a) Upstream and downstream pressures (p_1 and p_2) in the MKS1152 flowmeter and (b) the mass flow rate for the test calculated using Eq. (2)

Three calibration tests were performed to check the constancy of K under different flow conditions. In addition, a test was performed where the reservoir temperature was varied to change the upstream pressure and then the PFCV was exercised to show open-loop control of the flowrate. This will be described further in the following subsection, but the results of that test were also integrated and a value of K was determined from the mass loss. These calibration values are given in Table 3. In these calibration tests, the PFCV was shown capable of controlling the flowrate from a no-flow condition up to roughly 1.5 mg/s. This is not the upper limit on the capability of the feed system, but instead just the upper limit of what was achieved in these tests, and 50% higher than the approximately 1 mg/s anode flow rate needed for the 200-W thruster BHT-200.[2] We see that the value of K for the MKS1152 flowmeter is relatively constant over the flow conditions tested.

Table 3. Summary of calibration values.

Test	Mass Expended (mg)	K (mg/(torr^2 s))
Test #1	5.9	5.60×10^{-6} ($\pm$2.4%)
Test #2	6.3	5.05×10^{-6} ($\pm$2.2%)
Test #3	13.9	4.93×10^{-6} ($\pm$1.0%)
Average K		5.19×10^{-6} ($\pm$3.5%)
Varying PFCV	1.3	5.91×10^{-6} ($\pm$10.9%)

2. Open-Loop Testing

Open-loop testing was performed by varying the PFCV voltage at two separate reservoir temperatures (70 and 80 deg C), yielding flowrates spanning a range of values as shown in Fig. 9. We observe that it took 4-5 mins for the temperature to change from 70 to 80 deg C, but there was an additional 5-6 mins of recovery time because the temperature overshot the mark. While this is typical of a thermally-controlled system, the timescale on which the reservoir pressure and commensurate flow can be varied by increasing or decreasing the reservoir heating will always be at a minimum on the order of several minutes.

Exercising the PFCV produces the stairstep patterns in the flowrate. These changes in flowrate are relatively immediate in comparison with the flowrate change through variation of the reservoir temperature and there is no overshoot and recovery time when the valve is exercised. The flowrates exhibit drift in this data set owing primarily to changes in the upstream pressure conditions and, of course, the fact that the PFCV is not compensating for the changing upstream conditions to maintain a constant flowrate in this test.

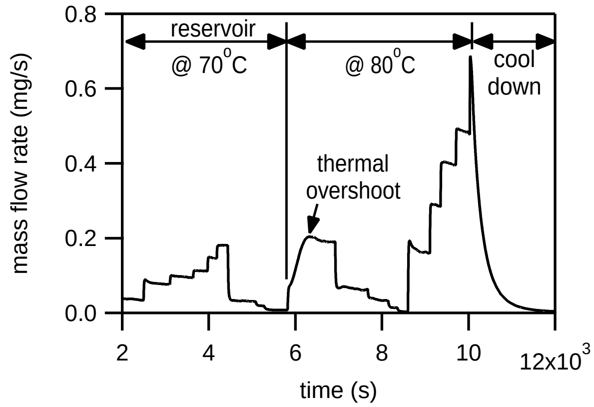


Figure 9. Flowrate measurements from open-loop testing where both the PFCV orifice size was intermittently adjusted (stair-step patterns) and the reservoir temperature was varied.

V. Conclusions

A Hall-effect thruster operating on iodine is attractive for CubeSat applications because it offers certain advantages related to the fact that iodine stores as a dense solid and can be sublimed to a low-pressure gas through the application of heat, obviating the need for high-pressure in the propulsion system. However, to operate in the microgravity environment, the system must be capable of containing the propellant and controllably subliming and feeding it to the thruster, while maintaining any wetted surfaces at elevated temperatures to keep iodine from redepositing back into solid form. An experimental feed system was fabricated to test the various components that would be required to provide precise, fast-response flow control in an iodine-based system. The gas flowrate can be controlled by adjusting the temperature in the propellant reservoir, but the response time for this type of control is on the order of minutes. A proportional flow control valve has been shown capable of controlling the flowrate over the range of interest for a 200-W HET. Unlike the thermal control method the response time on the valve is demonstrated to be relatively instantaneous, providing fast-response adjustment of the flowrate without the overshoot/undershoot associated with the thermal control method.

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