Characterization of a Fixed-Volume Release System for Initiating an Arc Discharge in a Heaterless Hollow Cathode

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Ryan K. Ham[1] and John D. Williams[2,3]
Colorado State University, Fort Collins, CO, 80523, USA

Scott J. Hall[4]
Vantage Partners, LLC, NASA Glenn Research Center, Cleveland, OH, 44135, USA

and

Gabriel F. Benavides,[5] and Timothy R. Verhey[6]
NASA Glenn Research Center, Cleveland, OH, 44135, USA

Abstract: Heaterless hollow cathodes may provide improved reliability, simplicity, and portability when compared with traditional heater-equipped hollow cathodes, traits which are well suited for low-power Hall-effect thrusters that are currently being developed for small satellite propulsion. Despite the advantages, there are concerns that the ignition process in heaterless hollow cathodes may impose an excessive burden on the propellant feed and/or electrical systems of a small satellite. To address this concern, a fixed-volume release flow protocol, which can be used to temporarily increase the propellant mass flow rate, was developed, modeled, and experimentally evaluated. The new protocol allowed for a heaterless hollow cathode to be ignited reliably with a moderate bias voltage and a minimal electrical power requirement. Specifically, a xenon fed heaterless hollow cathode was ignited with a 375 V bias using 17.3 mg of propellant. Repeating the tests with krypton showed that ignition could be achieved in the same heaterless hollow cathode assembly with a 300 V bias using 13.1 mg of propellant. We judge that a fixed-volume release system could be implemented in a satellite feed system while introducing minimal additional complexity.

Nomenclature

γ = heat capacity ratio
d = diameter
$\dot{m}$ = propellant mass flow rate
P = propellant gas pressure
R = gas specific gas constant
T = gas temperature
V = volume

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[1] Graduate Research Assistant, Department of Mechanical Engineering, rkham11@gmail.com.
[2] Associate Professor, Department of Mechanical Engineering, drjohndarrylwilliams@gmail.com.
[3] Technical Director, Plasma Controls, LLC, drjohndarrylwilliams@gmail.com.
[4] Research Engineer, Electric Propulsion Systems Branch, scott.j.hall@nasa.gov.
[5] Research Engineer, Electric Propulsion Systems Branch, gabriel.f.benavides@nasa.gov.
[6] Senior Research Engineer, Electric Propulsion Systems Branch, timothy.r.verhey@nasa.gov.

I.Introduction

HOLLOW cathodes are used in several common types of plasma thrusters to provide a continuous flow of plasma electrons that are used to sustain the main discharge and/or to neutralize the ions in the exhaust plume of the thruster. In addition to enabling steady state operation, a hollow cathode is also used to initiate the plasma discharge in the propellant gas, and essentially "start" the thruster. Serving such essential roles, the failure of a hollow cathode means the end-of-life of a thruster. One well-known premature failure mode of a hollow cathode is failure of the cathode heater element. Because the electron emission current from the cathode is predominantly thermionic, it is typical for cathodes to operate at moderately high temperatures of 1100 °C or more when equipped with a barium-based or lanthanum hexaboride insert. As a consequence, a cathode heater is commonly used to thermally prime the cathode to thermionic emission temperatures before a plasma discharge is initiated.[1] In doing so, ignition (i.e. the initiation of a plasma arc discharge) can typically be achieved by applying a modest bias, often less than 50 V, between the cathode and nearby keeper electrodes while propellant gas is flowing at a nominal flow rate. After ignition, the cathode heater is usually unpowered because the cathode is sufficiently self-heated by the nearby plasma via ion bombardment and ion recombination processes. While modern hollow cathodes have shown lifetimes in the tens-of-thousands of hours,[2–4] their lifetime can be drastically reduced by premature failure of the cathode heater. This mode of failure results from thermal fatigue caused by a high number of heating cycles and is a higher risk in missions that require many thruster ignition cycles. Because the cathode heater is a single-point failure mechanism of a thruster, heaters are subject to strict flight qualification requirements, which can add significant cost to the development of a hollow cathode.[5,6]

In addition to their cost, cathode heaters can be undesirable because they add to the overall size of a hollow cathode assembly. Furthermore, an auxiliary power supply circuit is required to power the heater, which adds to the complexity of the thruster power processing unit (PPU). One way to circumvent these issues is to remove the cathode heater entirely. Several studies, dating back to the 1980s, have shown that igniting a plasma discharge in a hollow cathode is possible without the use of a heater, however significantly elevated propellant flow rates and cathode-keeper bias voltages were typically necessary and cathode erosion was documented in some cases.[7–13] If these ignition difficulties can be addressed, and it can be proven that heaterless hollow cathodes can be ignited reliably with minimal complexity, then it is likely that many modern plasma thruster concepts would adopt heaterless hollow cathode technology. The reduced size, cost, and complexity of heaterless hollow cathodes make them well suited for efforts in miniaturizing Hall-effect thrusters for small satellite propulsion.[13–23] In this study, a propellant flow mechanism is investigated, which is designed to provide the propellant flow condition necessary to ignite a heaterless hollow cathode with minimal burden on the ignition circuit and minimum damage to the cathode.

II.Background

Paschen's Law shows that the electrical bias required to breakdown a gas and form a plasma discharge between two electrodes is a function of the product of the gas pressure and the distance between electrodes.[24,25] A plot of this relationship, typically called a Paschen curve, reveals that there is a pressure-distance product at which the breakdown voltage is at a minimum. An example of these data are shown in Fig. 1 (left), which shows experimentally measured Paschen curves for two common electric propulsion propellants, xenon and krypton.[7] In preliminary ignition testing of a 3.2 mm diameter heaterless hollow cathode, the ignition voltage was determined for a range of xenon propellant mass flow rates (see Fig. 1 (right)). The downward sloping trend in these data indicate that at xenon mass flow rates up to 50 sccm—significantly higher than the nominal flow of 1-2 sccm for this cathode—the conditions within the hollow cathode assembly correspond to a region of the Paschen curve that is to the left of the minimum. This trend is common to nearly all hollow cathode assemblies in this range of propellant flow rates, and is the reason why many have observed that heaterless hollow cathodes require elevated propellant flow and a much larger bias for ignition when compared with heated cathodes. The data shown in Fig. 1 demonstrate that, to achieve ignition at a minimal voltage, an extremely high propellant mass flow rate is necessary.

In a laboratory gas feed system, the mass flow rate is usually controlled with a closed-loop, thermal mass flow controller, or similar technology. These flow controllers allow for a broad range of propellant mass flow rates to be tested easily, and they allow for heaterless hollow cathodes to be ignited in a high-flow condition, and then operated in a nominal low-flow condition. While it is possible to implement this type of mass flow control system in a satellite propellant feed system, the cost, mass, complexity, and inherent risk is prohibitive in many applications, especially in small satellite propulsion systems. In this paper, an alternative flow mechanism, called a "fixed-volume release," is presented. A fixed-volume release system can provide a significantly elevated propellant mass flow rate for a period of time using only a few simple components, facilitating the ignition of a heaterless hollow cathode with minimal burden on the electrical system.

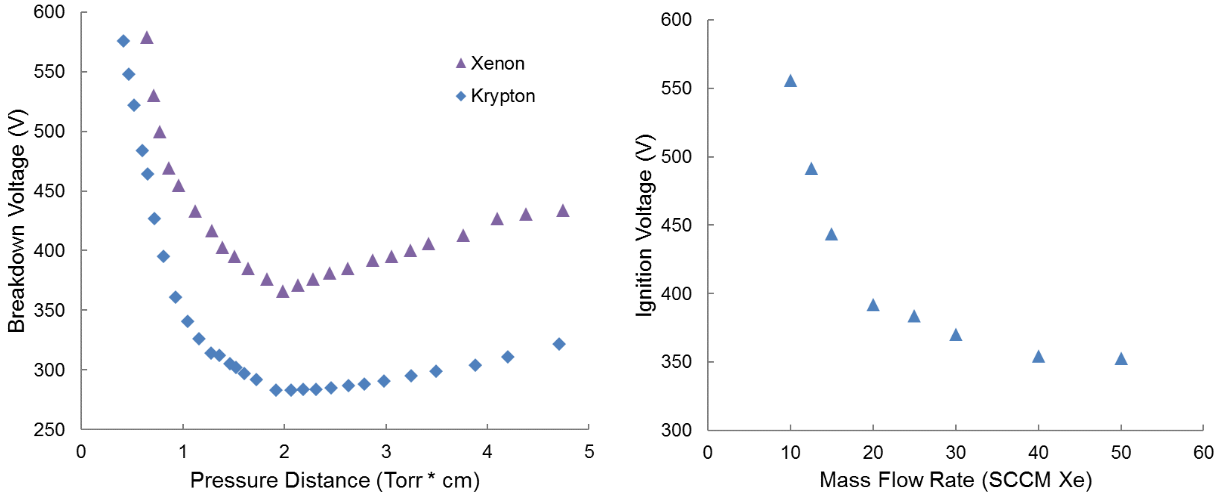

Figure 1. Experimentally measured Paschen curves for xenon and krypton (left), and ignition voltage for a heaterless hollow cathode as a function of xenon propellant mass flow rate (right).[7]

III.Testing the Fixed-Volume Release Concept

The fixed-volume release concept presented herein was devised to be suited for integration into a small-satellite propellant feed system. In small-sat systems, a fixed flow control (rather than a closed-loop mass flow controller) is the preferred flow control mechanism given its low cost, mass, and complexity. A fixed flow control, such as a precision micro-orifice or a porous metal flow restriction, is effective for maintaining a propellant flow rate during normal cathode operation; however it does not allow for the propellant flow rate to be increased to levels that are required for ignition of a heaterless hollow cathode.

To achieve the high propellant mass flow rate necessary for heaterless hollow cathode ignition, a fixed-volume release system can be implemented with the addition of a single valve as shown in Fig. 2. The fixed-volume release system, located upstream of a heaterless hollow cathode assembly, (see Fig. 2 (right)), consists of three components: a flow restriction, a valve, and the volume contained between the two. The flow restriction at the upstream end of the volume is meant to be sized such that a nominal propellant mass flow rate is maintained during normal cathode operation (e.g. 1 sccm Xe). The purpose of the valve at the downstream end of the volume is to shut-off propellant flow to the hollow cathode. By closing the shut-off valve, the gas pressure within the volume is allowed to rise and may eventually equalize with the supply pressure upstream of the restriction given enough time. Upon opening this valve, the pressurized propellant within the volume is released through the hollow cathode, providing a significantly elevated propellant mass flow rate for a period of time, and thus enabling the ignition of a heaterless hollow cathode.

A. Fixed-Volume Release Hardware and Layout

To test this concept, an experimental fixed-volume release system, shown in Fig. 2 (left), was constructed and integrated into a vacuum facility for testing with a heaterless hollow cathode. This system was designed to be operated in vacuum so that it could be located as close to the hollow cathode as possible, minimizing the volume of propellant feed line downstream of the solenoid valve. A motorized needle valve was used at the upstream end of the fixed-volume, which allowed for the inlet flow rate to be adjusted as necessary. A solenoid valve was used at the downstream end. To monitor the behavior of the fixed-volume release system, a pressure transducer was attached to the section of propellant feed line located between the needle valve and the solenoid. An arbitrary length of feed line could also be attached to the volume to allow for the size of the volume to be adjusted if necessary. For the research presented in this paper, the volume of the fixed-volume release system was selected to be 13 cm^3. The volume was calculated using Eq. (1) after closing the valve and measuring the time rate of change of pressure in the volume. In Eq. (1), V is the volume, $\dot{m}$ is the mass flow rate into the volume which was measured using a thermal mass flow controller, R is the gas specific gas constant, T is the temperature, and $\dot{P}$ is the measured time rate of change of pressure within the volume.

$$V = \frac{\dot{m}RT}{\dot{P}} \tag{1}$$

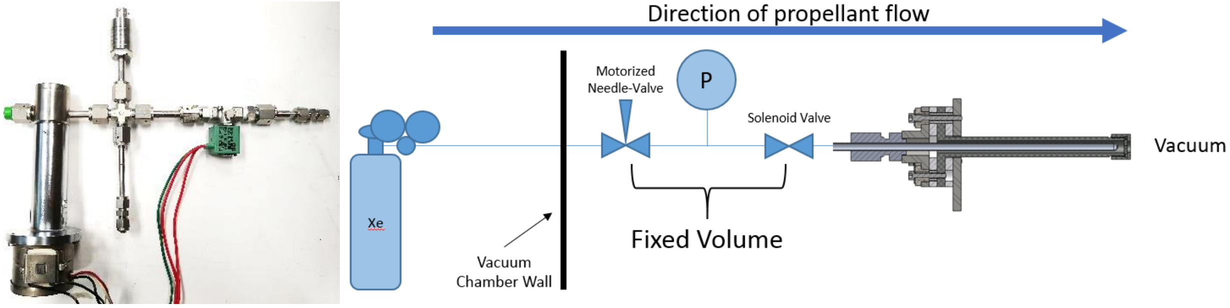

Figure 2. Photo (left) and schematic (right) of an experimental fixed-volume release system that can be used to provide elevated propellant mass flow rates during heaterless hollow cathode ignition without using a mass-flow controller.

B. Heaterless Hollow Cathode Test Articles

The fixed-volume release system was tested in heaterless hollow cathode ignition experiments at both NASA Glenn Research Center and at the Center for Electric Propulsion and Plasma Engineering (CEPPE) at Colorado State University. Separate hollow cathode assemblies were used at each location, with each manufactured to the same specifications by Plasma Controls, LLC.[26] A 3.2 mm diameter cathode was used in this research. Given its small size and the capability to operate at discharge currents up to 3 A, this cathode is suitable for low power Hall-effect thrusters, a thruster class which could benefit from heaterless hollow cathode technology. The cathode is made from a tantalum tube with a formed hemi-spherical tip terminated with a 0.5 mm orifice. A porous tungsten barium oxide emitter is housed within the tube. Because of its compact size, the emitter used in this cathode was not manufactured with an inner diameter feature, which causes the propellant gas to flow around and/or through the semi-porous emitter itself. The hollow cathode assembly, shown in Fig. 3, has an enclosed keeper made from graphite, which was designed with a slender profile so that it could be easily integrated into a Hall-effect thruster in a center-mounted configuration. This evaluation unit was designed with an additional feature that allowed for different keeper orifice plates to be installed and tested. For this study, 1.4 mm diameter graphite keeper orifice plate was used, and the cathode tip was positioned at an axial distance of 1.3 mm upstream of the keeper orifice plate.

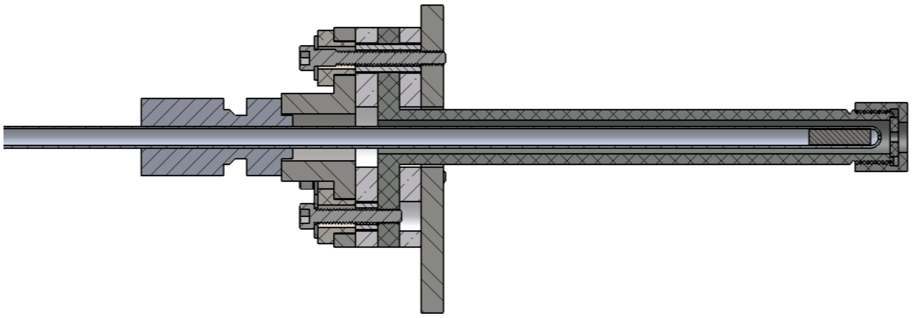

Figure 3. Cross-section view of the heaterless hollow cathode that was used in this research.

C. Vacuum Facilities and Equipment

Two vacuum facilities were used to perform this research: Vacuum Facility 17 (VF-17) at NASA Glenn Research Center, and the Gemini vacuum chamber at Colorado State University. Both vacuum chambers are very similar in geometry and capability. Each vacuum chamber is a non-magnetic, stainless steel cylinder, with a diameter of approximately 1 m, and a length of approximately 2 m. VF-17 uses a cryogenic pump capable of pumping room temperature xenon at a speed of approximately 2000 L/s.[27] The Gemini vacuum chamber at Colorado State University is equipped with a turbomolecular pump, which pumps xenon at a rate of 1800 L/s. Each facility was outfitted with a laboratory gas feed system, and a high-voltage DC power supply capable of supplying the bias necessary to perform heaterless hollow cathode ignition experiments and to operate a cathode in diode mode. To simplify the ignition process, an auxiliary anode was not used in this testing. A 100 Ω ballast resistance was used in the cathode-keeper circuit to limit the peak current during ignition and protect the cathode and other electrical equipment during ignition testing. An oscilloscope was used to monitor and record the voltage and current flow between the cathode and keeper electrodes during ignition tests.

IV.Fixed-Volume Release Flow Model

To explore the flow conditions that can be achieved with a fixed-volume release system, a simple gas flow model was developed to predict the propellant flow rate through a hollow cathode as a function of time. The model was made to represent the experimental setup used to evaluate the fixed-volume release concept, so that its predictions could be compared with experimentally measured data to evaluate its accuracy. In the model, a control volume is used to represent the volume between the fixed flow control and the shut-off valve. In the model, the hollow cathode assembly is assumed to be located immediately downstream of the shut-off valve, with a negligible volume of propellant feed line between the control volume and the flow restriction at the cathode tip. Due to inherent complexities that are beyond the scope of this study, the effects of a plasma discharge were ignored, and a temperature of 300 K was assumed in the flow calculations. This assumption is inaccurate because testing of the fixed-volume release showed that the temporal flow behavior is altered by the ignition of a plasma discharge within the hollow cathode assembly. This is likely because the formation of a plasma, and subsequent gas heating in the cathode orifice, results in an increased flow impedance. Additionally, plasma production just downstream of the cathode orifice may cause some mass flow to occur in the upstream direction due to ion motion.[28] These effects were ignored because the model is currently only being used for qualitative purposes and is only being compared to experimental results recorded when a plasma is not ignited. Further details are presented in the discussion section (section VI) below. The model allows for various parameters to be adjusted such as the size of the volume, the charge pressure, and the flow restriction created by an un-operated hollow cathode at the outlet of the volume. It was found that by adjusting these parameters, a wide range of temporal flow behaviors can be achieved.

To properly model the propellant mass flow rate exiting the control volume and flowing through the hollow cathode as a function of time, it was necessary to precisely quantify the flow restriction caused by the geometric features of the hollow cathode. This was accomplished by using a capacitance manometer to measure the propellant gas pressure just upstream of the hollow cathode as a function of propellant mass flow while the hollow cathode was at room temperature. This relationship, plotted in Fig. 4 (left) for xenon and krypton gasses, was observed to be slightly non-linear, indicating that the discharge coefficient is not constant for all flow rates. To account for the this, an effective choke diameter was computed for each data point using the equation for choked flow, Eq. (2); in which $\dot{m}$ is the mass flow rate, d is the effective choke diameter, P is the pressure upstream of the restriction, T is temperature, γ is the heat capacity ratio, and R is the gas specific gas constant. The resulting data, shown in Fig. 4 (right), were then curve fit so that effective choke diameters could be estimated for a continuous range of values.

$$\dot{m} = \frac{\pi d^2 P}{4\sqrt{T}}\sqrt{\frac{\gamma}{R}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{2}$$

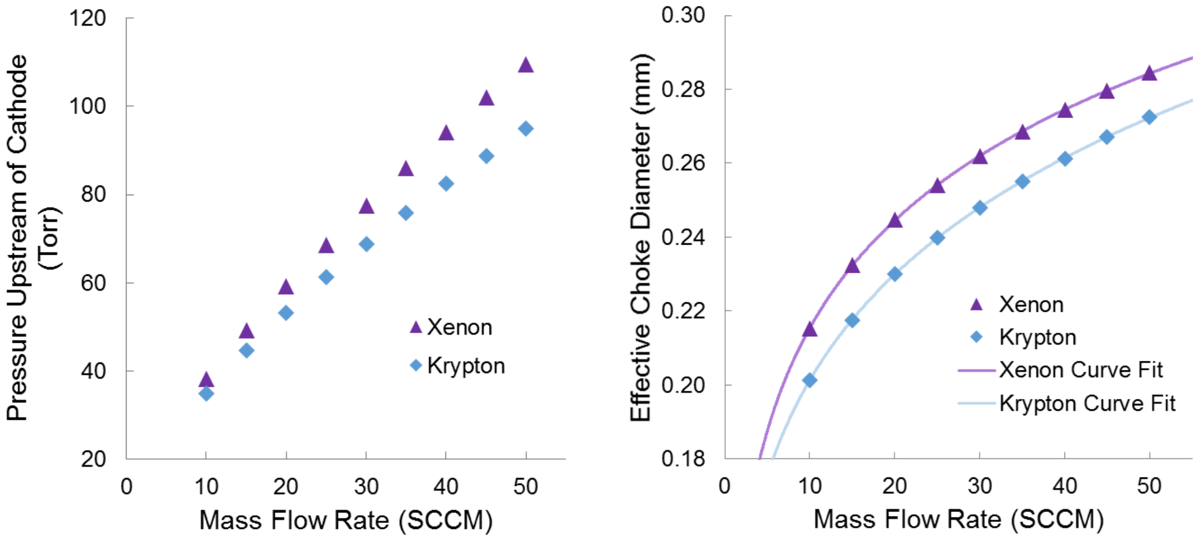

Figure 4. The propellant gas pressure upstream of the room temperature hollow cathode as a function of propellant mass flow rate (left), and the effective choked orifice diameter for each of these data points (right).

Using the cathode flow restriction values described above, the propellant mass flow rate through the hollow cathode was predicted as a function of time using Eq. (2) and employing a finite difference time-stepping method. Fig. 5 shows two different flow behaviors that can be achieved with a 20 mg charge of xenon propellant. The flow rate values were plotted on a logarithmic scale so that the two curves can be clearly differentiated. The smaller, 10 cm^3 volume corresponds to a higher initial charge pressure than the larger, 20 cm^3 volume using the given mass of the propellant charge. Because of this, the smaller volume produces a greater initial flow rate; however, because the smaller volume also discharges more quickly, the elevated flow rate is not maintained for as long of a duration. By adjusting the charge mass and volume, a wide range of temporal flow behaviors can be explored. Further adjustments can be made by including additional flow restriction to the outlet of the volume. This sort of modification would likely be necessary for larger heaterless hollow cathodes that do not provide sufficient flow restriction. By fine-tuning these parameters, a fixed-volume release system can be tailored to provide a specified temporal flow behavior to meet the ignition requirements of any heaterless hollow cathode.

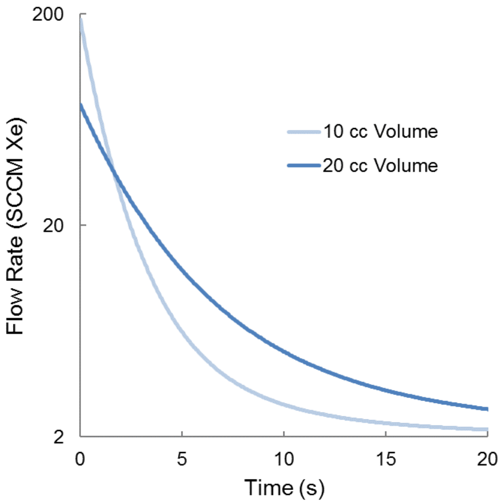

Figure 5. Comparison of two different propellant charge volumes. The curves represent the predicted flow produced by a fixed-volume release system using a 20 mg charge of xenon propellant.

V.Results

Experimental testing performed with a room-temperature cathode, with no ignition operations performed, showed that the fixed-volume release system produced the expected propellant flow behavior. The propellant mass flow rate through the hollow cathode during a propellant release was calculated by measuring the gas pressure within the fixed-volume as a function of time and using Eq. (3); where $\dot{m}_{out}$ is the mass flow rate out of the fixed-volume, $\dot{P}$ is the time rate of change of pressure within the volume, V is the volume, R is the gas specific gas constant, T is the temperature, and $\dot{m}_{in}$ is the mass flow rate into the control volume which is a constant value, provided the inlet is in a choked flow condition. The pressure data were curve-fit to eliminate excessive fluctuations that would otherwise be present in the derivative of the pressure with respect to time. Fig 6. (left) shows both the measured pressure and the calculated flow rate through the hollow cathode as a function of time. Upon opening the valve at time t = 0, a significantly elevated propellant flow rate is achieved. The flow rate then decays and eventually approaches a steady flow rate, which is metered by the inlet flow restriction (1.75 sccm Kr in this case). Fig 6. (right) shows these results compared with the flow model. The model predictions agree well with the experimental results.

$$\dot{m}_{out} = \frac{-\dot{P}V}{RT} + \dot{m}_{in} \tag{3}$$

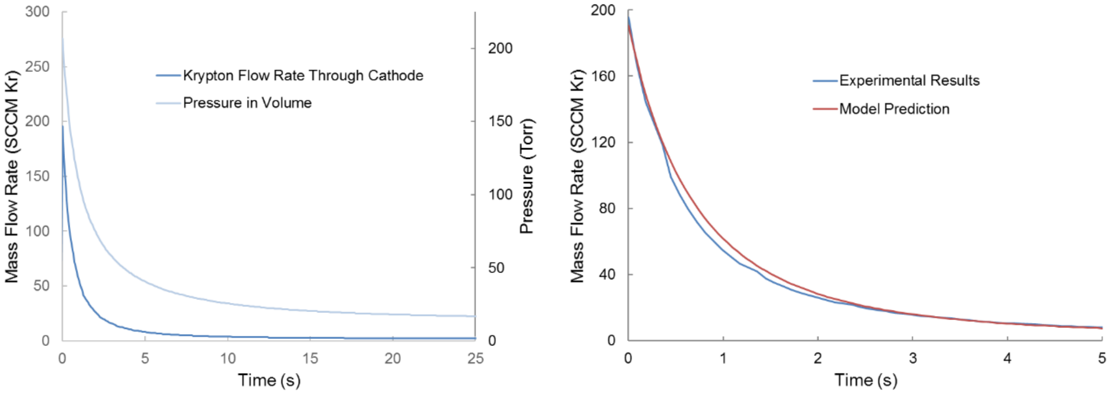

Figure 6. Experimentally measured fixed-volume pressure and calculated flow rate as a function of time (left), and comparison of experimental results and flow model (right). Time t = 0 corresponds to the valve opening, releasing approximately 13 mg of krypton propellant from a 13cm^3 volume.

In performing ignition tests with the above described 3.2 mm heaterless hollow cathode, it was found that the fixed-volume release was capable of providing the flow conditions necessary to facilitate fast, reliable ignitions at a minimal bias for both krypton and xenon propellants. The volume of the fixed-volume release was approximately 13 cm^3 in all of the tests performed. With xenon, ignition could be achieved with a 375 V bias and approximately 17 mg of propellant. With krypton, the heaterless hollow cathode could be ignited with a 300 V bias and approximately 13 mg of propellant. In either case, over 10,000 hollow cathode ignitions could be performed with 200 g or less of propellant.

Fig. 7 (left) shows the voltage and current flow between the cathode and keeper electrodes during an ignition test that was performed with a fixed-volume release system and a room temperature cathode. In this example, a 375 V bias was applied between the cathode and keeper. At time $t = 0$, the valve of the fixed-volume release was opened, and a 17.3 mg charge of propellant was released through the hollow cathode. The ignition of a plasma arc discharge is evidenced by the sudden rise in current and simultaneous drop in voltage that occurs at time $t = 0$. The initial inrush current is followed by an exponential decay in current flow, which is characteristic of a resistor-capacitor circuit. In this case, the capacitance is provided by the output capacitance of the laboratory power supply, and the electrical resistance is provided by both the plasma and the 100 Ω ballast resistance, which was added to the cathode-keeper circuit. Fig. 7 (right) shows the average electrical power consumption during the ignition. Initially, the electrical power is provided by the energy stored in the power supply output capacitance. In this case, the peak power consumption was approximately 60 W. At a time of approximately, $t = 0.1$ s, the current flow settled to the 1.5 A current setting, at which time the electrical power consumption stabilized to approximately 20 W. We believe that this type of “instant start” behavior is desirable in heaterless hollow cathode ignition because it does not require high electrical power for a significant period of time.

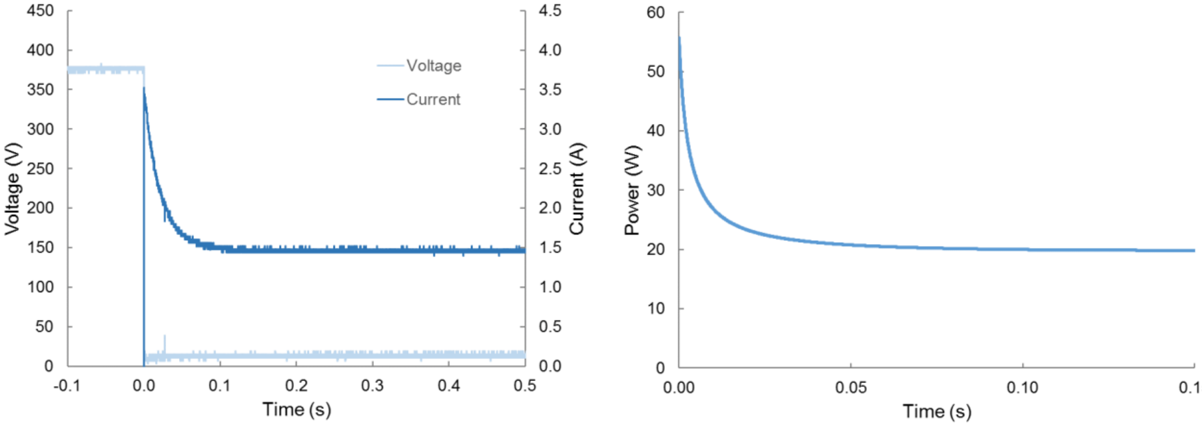

Figure 7. Voltage and current flow between the cathode and keeper electrodes during ignition of a heaterless hollow cathode using a 13cm^3 fixed-volume release system using a 17 mg charge of xenon propellant (left), and average electrical power consumption between electrodes (right).

VI.Discussion and Future Work

To successfully ignite a heaterless hollow cathode, it is necessary that the propellant mass flow rate be great enough to produce a pressure condition between the cathode and keeper that is sufficient for an arc discharge to be formed by the applied electrical bias. After a plasma discharge is initiated and the cathode temperature is still low, we hypothesize that the discharge is mostly maintained by volumetric ionization processes in which plasma electrons (released via ionization) flow to the keeper and ions (created via ionization) flow to the cathode where they are neutralized by electron current from the cathode. We believe it is important that the propellant mass flow rate remains sufficiently high for a time to sustain this volumetric ionization process while the cathode is being heated by ion bombardment and recombination processes. When the cathode reaches thermionic emission temperatures and the discharge transitions to predominantly thermionic electron emission, the propellant flow rate can be reduced to the nominal steady-state operating value. A fixed-volume release system is well suited for heaterless hollow cathode ignition because it can provide the necessary flow conditions with very minimal complexity.

The propellant mass flow rate as a function of time immediately after opening the valve of a fixed-volume release is analogous to the transient electrical current that flows in a resistor-capacitor circuit immediately after a switch is closed. In a resistor-capacitor circuit, the discharge current behavior (i.e. the peak current value and the time-constant of the exponential current decay) is a function of the initial capacitor voltage, the capacitance, and the resistance.

These parameters are analogous to the propellant charge pressure, the charge volume, and the outlet flow restriction of a fixed-volume release. By changing one or more of these parameters, the temporal propellant flow rate behavior can be altered, and the fixed-volume release can be custom tailored to suit the flow requirements of a specific heaterless hollow cathode. This makes the fixed-volume release a versatile tool that could be used to simplify the ignition process in a heaterless hollow cathode of any geometry.

The experimental fixed-volume release that was used in this research could be made more versatile by adding an additional volume and a flow restrictor downstream of the valve as shown in Fig. 8. In this configuration, the valve can be closed for an indefinite amount of time, and the charge volume can be allowed to charge up to the supply pressure upstream of the flow restrictor. The charge volume and the additional volume downstream of the valve can be sized such that the desired initial volume and pressure is attained upon opening the valve. The downstream flow restrictor can be sized such that the desired flow behavior is achieved. The addition of the downstream flow restrictor would likely be necessary for larger hollow cathodes that do not provide significant flow restriction from their orifice or insert geometry. Overall, the fixed-volume release could likely be packaged in a very small volume that could be easily integrated in a spaceflight propulsion system.

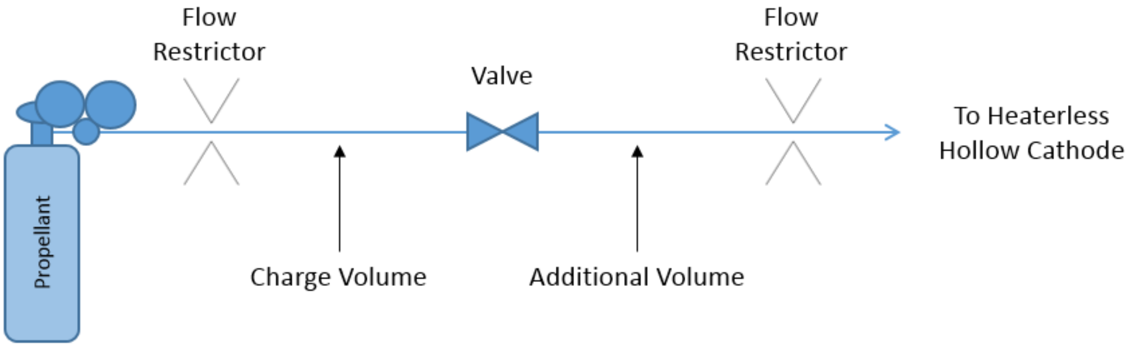

Figure 8. Schematic of a modified fixed-volume release design that includes several additional components that allow for greater versatility.

In modeling the propellant mass flow rate as a function of time, the effects of a plasma discharge were ignored, and a temperature of 300 K was assumed in the flow calculations. Because the temporal flow behavior is dependent upon the flow restriction of the cathode tip, this assumption is likely inaccurate if a plasma is created within the cathode and cathode orifice. By experimentally measuring the pressure in a fixed-volume release system as a function of time, it was found that the pressure does not discharge as quickly when a plasma discharge is ignited. In other words, the formation of a plasma discharge creates additional resistance to the flow of propellant. Data measured with and without discharge ignition are shown in Fig. 9. Because it is challenging to model the additional flow restriction caused by a plasma discharge, it becomes difficult to predict the exact flow behavior that a fixed-volume release will provide. This issue could be minimized by using an additional flow restrictor upstream of the hollow cathode as suggested in Fig. 8. This technique will be investigated in future studies.

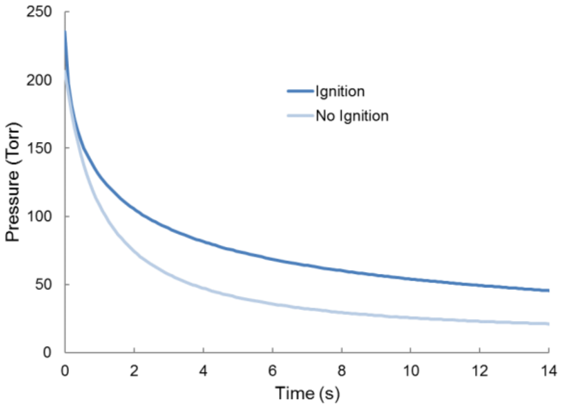

Figure 9. Comparison of fixed-volume release discharge with and without an ignition performed.

Although the fixed-volume release concept addresses concerns with providing the propellant flow necessary to ignite a heaterless hollow cathode with a moderate bias, there are still concerns that the ignition process may cause erosion and could possibly lead to premature failure of the cathode. It has been hypothesized that this would be caused by the development of a cathodic arc and subsequent ion bombardment upon the cathode in a localized spot during ignition, which could lead to ablation of the cathode due to sputtering and vaporization by extreme localized heating.[8,29] To investigate this in greater detail, a follow-on study is planned in which a fixed-volume release system will be used to perform 1000 or more ignition cycles in an automated test sequence. To quantify erosion effects, the cathode will be measured, weighed, and imaged before and after the test sequence to search for geometric and/or compositional changes.

VII.Conclusion

In this study, a fixed-volume release system was evaluated for facilitating the ignition of heaterless hollow cathodes. It was shown that a 13 cm^3 fixed-volume release system was capable of providing a temporarily elevated propellant flow rate and enabling reliable ignition of a 3.2 mm heaterless hollow cathode. Using krypton gas, the heaterless hollow cathode could be ignited with a 300 V bias by releasing a 13 mg charge of propellant through the cathode. The same heaterless hollow cathode could be ignited with xenon propellant using a 375 V bias and a 17 mg charge of propellant. The rate at which propellant flows from the fixed-volume depends upon the flow impedance created by the cathode and is affected by the ignition of a plasma. It is suggested that additional flow impedance be placed in the gas line feeding the cathode to avoid this dependence and also extend the period of time of elevated flow. The fixed-volume release system features identified in this paper enable one to tailor the temporal flow behavior so that ignition can be achieved in a given heaterless hollow cathode assembly and applied bias.

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