The Effect of Magnetic Shielding on H6 Hall Thruster Performance and Erosion Rates

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Abstract

This study focuses on the magnetic shielding (MS) effect in the 6kW Hall Thruster (H6) performance. By method of systematic literature review, differences in specific impulse and rate of erosion between magnetically unshielded (US) and shielded Hall Thrusters (HT) were investigated. Following analysis suggests that the MSH6 can operate at similar specific impulses to that of the USH6 while significantly reducing erosive factors.

Introduction

One obstacle hindering space related advancements is the costly process of producing and researching aerospace technology. As the focus of space travel shifts from scientific to financial motives, monetary corporations and government research facilities alike are less willing to spend unnecessary expenses on space travel as a whole, especially when it comes to chemical propellant rockets. Consequently, new plasma-based models of rocket ships are primarily used for deep space missions to increase fuel efficiency, extend durability, and decrease unnecessary costs. Despite the exceptional performance of various Hall Thruster models within the last 50 years, complications with channel erosion reduce their overall efficiency (Conversano et al., 2017). To minimize erosion from the plasma fuel's force, magnetically shielded models protect Hall Thruster walls from such damage.

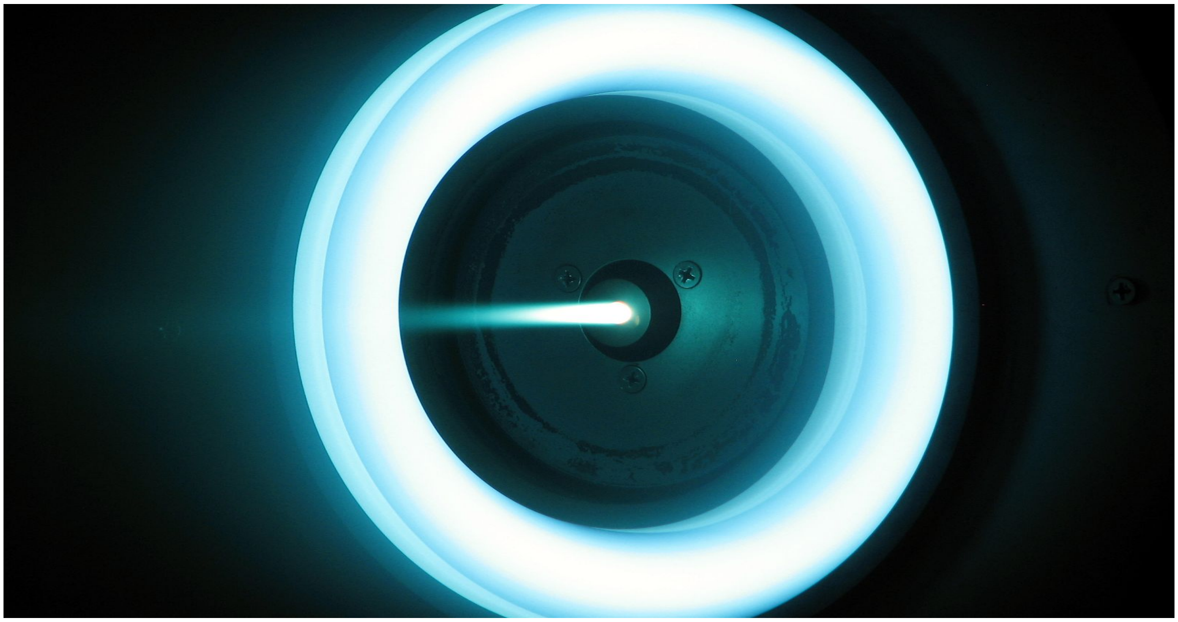

Fig. 1: An image of a mid-operation 6kW Hall Thruster taken at JPL.

In contrast to the last 50 years of traditional chemical propellant use, electric propulsion engines function by releasing accelerated ionized gas in form of plasma. Generally, inert Xenon gas is fed into a cylindrically shaped fuel chamber to be bombarded by electrons released from a cathode, ionizing Xenon atoms (Goebel & Katz, 2008). Upon gaining such positive charge, Xenon gas takes form of plasma substance. Simultaneously, magnetic coils surrounding the acceleration chamber impose electric fields that spur ions into movement at rates of 50km/s around the cylindrical chamber (Mikellides et al., 2013). Releasing the accelerated ions in the opposite of the desired direction creates thrust, in a similar fashion to that of chemical rocket's combustive methods to accelerate gas. This typically occurs at mass flow rates of 20 mg/s (Conversano et al., 2017). However, both methods of propulsion show significant differences in performance as chemical propellant combusts large amounts of low molar mass fuels in short bursts compared to Hall Thruster's continuous propellant discharge. In terms of physics, a spacecraft's thrust is directly proportional to mass, so Xenon with a high molar mass of about

131 amu would provide more thrust than that of conventional liquid oxygen or hydrogen (Pote & TeDrake, 2001). This means that plasma rockets would require much less propellant to reach the same velocity of chemical rockets. Consequently, Hall Thrusters are able to carry more thrust per unit weight of propellant, largely attributing to their candidacy for deep space missions.

Mission studies within the last few decades report sizeable changes in velocity and fuel efficiency between electric and combustion based propulsion. Generalizing their performances, chemical rocket exhaust show velocities of 3 to 4 km/sec, while the electric engines emit exhaust velocities of about 10^3 km/sec (Goebel & Katz, 2008). When it comes to thrust and fuel efficiency, operation levels of Hall Thrusters show much promise in the application of long term space travel. Recently, these have been developed to reach extremely high power levels while maintaining high specific impulse while keeping fuel consumption low, appealing to the needs of aerospace corporations as a promising candidate for deep space missions (Brown et al., 2017). As corporate motives for space propulsion continues to increase, the demand for high power Hall Thrusters to become even higher power have risen. Essentially, a decrease in the operating costs of a rocket is demanded with the ever-present desire for increased thrust (Cusson et al., 2017 (b)).

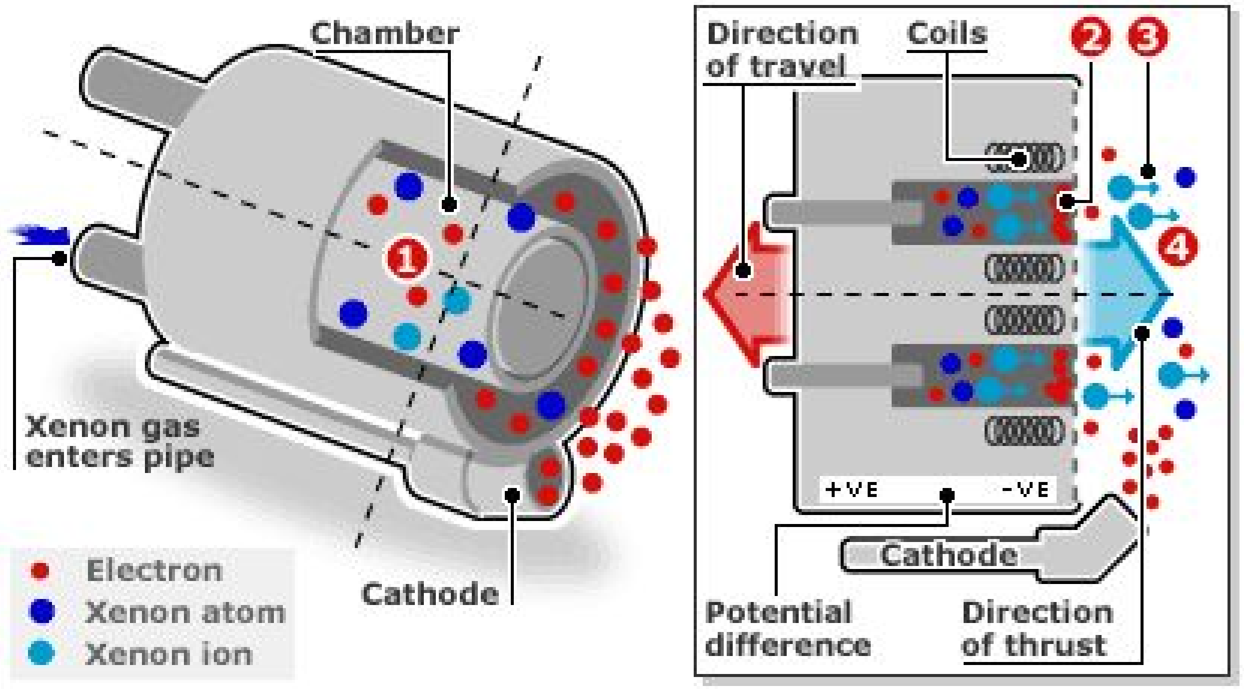

Fig. 2: The inner workings of a typical Hall Thruster. In the left hand figure, creation of Xenon plasma can be observed by electrons released by the cathode bombarding Xenon gas. The right hand figure shows the acceleration and release of Xenon ions by electrostatic properties.

The ions within a Hall Thruster's has been known to cause decomposition on the insulating walls of its plasma acceleration chambers. The high temperatures and overwhelming kinetic forces generated by the accelerated Xenon ions create abrasion against the channel walls, limiting the lifespan, and therefore reusability in Hall Thrusters (Hofer et at, 2014 (b)). Because HTs are designed for deep space travel purposes, an extended service life is an essential element for its practicality. In the recent years of aerospatial findings, topographic countermeasures known have been proposed to reduce HT's internal erosive forces (Longmier et al, 2013). A method known as magnetic shielding has shown practically erosion less performance levels under power emissions at 300V in some case studies.

Fig. 3: Above two images show the respective before and after images of a <20 hour long operation test on the MaSMi Miniature Hall Thruster.

Magnetically shielded Hall Thruster models show similar performance to unshielded models but are expected to have longer service lives (Grimaud & Mazouffre, 2017). Conventional HT models generate imbalances of electrons in a channel's magnetic-force-line equipotentialization due to inconsistent deviations of electron density, especially near the positively charged anode walls (Cusson et al., 2017 (b)). Magnetic shielding addresses the electron density discrepancies by reverting the direction of the accelerated ions away from the channel sides. In doing so, the magnetism imposed by MS keeps Xenon away from the walls to reduce degradation. Magnetic topography shows a typical electric field's area of influence is strongest along the walls of the chamber, potentially reducing the spacecraft's exhaust velocity with the application of MS. (Hofer et al., 2015). However, various operation tests within the last three years show little deviation from the specific impulses of shielded and unshielded thrusters.

Essentially, it can be asserted that shielded HTs will maintain similar ionization power while obtaining elongated lifespan.

Experimental Hall Thrusters and the Magnetic Shielding Effect

Today's state of the art Hall Thrusters are capable of maintaining over 60% efficiency from 300-800V while achieving specific impulses at over 3000s (Cusson et al., 2017 (a)). For clarification means, specific impulse is a measure of fuel efficiency, as it measures how much thrust is produced per unit of propellant. Compared to the performance levels of combustible rockets, Hall Thrusters are undoubtedly an upgrade. However, critical wear processes exist in a HT's fuel channel which shorten the service life and inhibit their long term practicality. In a 2010 wear test conducted on the BHT 4000 Hall Thruster, decomposition was noted to disappear after 5,600 hours of running (De Grys et al., 2010). Extensive research on the findings Haag et al. lead to the conclusion that the channel ring's insulators were able to run without erosive interference three main changes were identified for the reduction of discharge chamber erosion: configuration changes of certain magnetic fields which repelled ions away from chamber walls, less deviation between ion densities in between the inner chamber walls and chamber walls near the exit, and the even distribution of ion potential levels throughout the channel to lower temperature discrepancies (Hofer et al., 2014 (a)). Topographically, the magnetic shielding effect extends the range of electric field lines deeper into the exhaust chamber, which allows for ions of different temperatures to intermingle, thus reducing discrepancies in temperature (Boyd et al, 2008). Similarly, areas of differentiating propellant density are evened out as these longer ranged electric fields have greater ability in transporting ions from high to low concentrations. Furthermore, electric fields in the MSHT are parallel to the chamber walls (Mikellides et al, 2013). Because electric fields dictate the direction of ion pathing, these electric fields that do not intersect the walls prevent ions from colliding with the wall, further reducing erosive forces within an HT (2013). Current magnetic shielding methods aim to produce these same changes by altering the geometric configurations of magnetic field lines near the chamber exit.

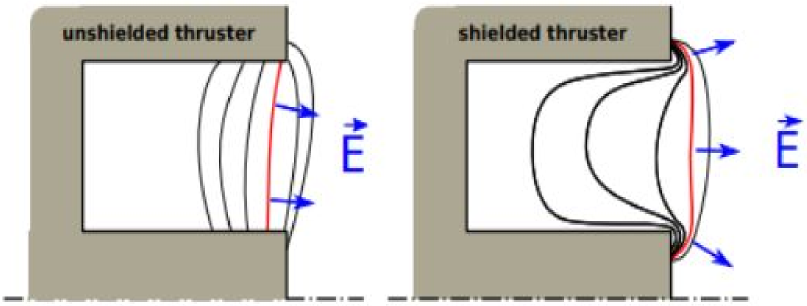

Fig. 4: Magnetic field topology and of US (left) and MS (right). Red line shows the imposed magnetic field. Black lines show the extent of the electric fields. Notice that the electric fields in the MSHT extend deeper into the chamber without intersecting the walls.

The chamber walls of Hall Thrusters are generally composed of insulating material that shield the rocket itself from damage (Grimaud & Mazouffre, 2017). If Hall Thrusters are to prove viable as transportative agents for deep space propulsion, it is essential to elongate its service life to a feasible degree. However, as long erosive forces continue to prove a problem in the long term architectural stability of HTs, their viability in the field will be greatly hindered. Recurrent factors contributing to the increase in erosion rate are correlated with entropy increase in electrons: increased temperature, increased ion current density, etc (Hofer et al, 2014 (a)). The consideration of these factors are relevant to the analyzation of Hall Thruster longevity. 6kW HT walls are made of Boron Nitride (BN), BNSiO2, or other ceramic insulators that contribute to the protection of the H6 as a whole by shielding ion impact (Dotson et al., 2013). Essentially, their inclusion in the H6 chamber wall allows for a more controlled ion flow by:

1. Reducing ion bombardment on channel walls
2. Further minimizing electron discrepancies
3. Acting as ion resistant material

As an HT's forces of internal wearing stem from high energy of the ions and the flux of ions onto the surface, magnetic shielding can elongate the service life of a given HT by preserving the insulating material itself (Cusson et al, 2017 (a)).

Purpose

In the past few years, the H6 and H9 Hall Thrusters have shown improved operation levels with the implementation of magnetic shielding. However, continuing to maintain adequate thruster efficiency is crucial in evaluating the applicability of Hall Thrusters. Furthermore, as internal erosion continues to be a prevalent issue for HT's, increased service lifetime will greatly bolster their candidacy in field missions. Considering its core performance metrics, this study aims to investigate magnetic shielding's effect on both HT channel erosion and operation levels. Presented at the 35th International Electric Propulsion Conference, unshielded 9kW laboratory grade HTs have shown state of the art operation levels of 2950 Isp under 800V while maintaining over 60% efficiency and a 2.6% difference in anode flow rate (Cusson et al, 2017 (b)).

A concept study to evaluate the effectiveness of MS in reducing channel erosion using previous published data from literature while maintaining feasible operation levels for field use.

Since Hall Effect Thrusters were designed to address the lack of reusability of combustion type rockets, it is absolutely imperative to eliminate factors that unnecessarily reduce the lifespans of HTs. This study proposes that plasma propellant erosion against channel walls shortening the service life of HTs can be mitigated with the application of magnetic shielding. Magnetic shielding's success on diminishing ion interactions against ceramic insulators on channel walls can allow for reusability and elongated service lives of HT. Additionally, the higher control on ion acceleration posed by MS can lead to a higher capacity for operation voltages and implementation of fully fledged conductive walls (opposed to the current use of semiconductors) which will increase the thrusts and specific impulses that current HTs can achieve.

Research question

How does Magnetic Shielding change Hall Effect Thrusters in terms of Electron Transport and Erosion rate?

Hypothesis

Alternate: Magnetic Shielding will reduce channel erosion while maintaining near identical rates of electron acceleration.

Null: Magnetic Shielding does not change or increase channel erosion while unchanging or reducing electron transport rates.

Methods

Literature Search: This study was conducted by method of systematic literature review in which academic, peer reviewed articles were compiled as means of data. Papers were collected via electronic databases, namely Google Scholars, Research Gate, Science Direct, University of Michigan's Plasmadynamics and Electric Propulsion webpage, EBSCOhost, etc. Though all papers regarding Hall Thrusters were collected, papers including the performances of the 6kW Hall Thruster were the priority search target. The H6 is laboratory grade HT meant for research purposes. Additionally, references from certified electric propulsion professors from various research facilities were considered usable. All numerically significant papers were accessed in English from American journals. Furthermore, a vast majority of collected papers were published within a four year range, especially those relating to magnetically shielded H6 models. Search terms for the collection of such academic papers included "Hall Thrusters", "6kW Hall Thruster", "Magnetic Shielding."

All progress regarding data collection and analysis were conducted at Thousand Oaks High School or in a private environment. In accordance with the Thousand Oaks High School Center for Advanced Studies' safety policy, lab generated data is forbidden which largely attributed to the choice of systematic literature review.

Data Collection: For the sake of accuracy, only papers that focused on the 6kW HT's performances on specific impulse and rate of erosion within operation ranges 300V to 800V were included as numerically significant data. Appropriately, papers on USH6 that tested the same specific impulse and erosion rate parameters were compiled. To conduct the necessary statistical analysis tests on the evaluation of magnetic shielding's effect on Hall Thrusters, the appropriate measures that each quantitatively significant paper included:

1. Performance numbers on the 6kW Hall Thruster
2. Independent variable as Voltage
3. Dependent variables for specific impulse (s) or erosion rate (mm/kh)
4. Scholarly and peer reviewed

Statistical Analysis: By method of t-test, both averages and standard deviations for values of the specific impulses of the USHT and MSHT were calculated as two seperate t-values then compared to show if statistical significance existed or not. By doing so, a systematic method of evaluating if MS shows change in rate of erosion was employed in this study.

Results

Table 1: Between two studies evaluating exhaust chamber diametrics for the US and MS H6, the current density, electron temperature, and rate of erosion were recorded between shielded and unshielded models' inner (farthest from chamber exit) and outer layers (closest to chamber exit).

Unshielded Outer Layer

Ion Current Density (mA/cm^2)	27	17	15	14	12
Electron Temperature (eV)	11.4	28.1	31.5	30.8	26.5
Erosion rate (10^-6 m/h)	0	9.8	15.6	16.1	15.0

Unshielded Inner Layer

Ion Current Density (mA/cm^2)	54	24	21	15
Electron Temperature (eV)	24.8	31.1	32.3	25.2
Erosion rate (10^-6 m/h)	0	20.3	21.1	19.7

Shielded Outer Layer

Ion Current Density (mA/cm^2)	25	12	11	9	5
Electron Temperature (eV)	6.1	6.7	7.1	8.3	9.3
Erosion rate (10^-6 m/h)	0	0	0	0	0

Shielded Inner Layer

Ion Current Density (mA/cm^2)	15	7	8	4
Electron Temperature (eV)	6.2	7.0	10.2	13.3
Erosion rate (10^-6 m/h)	0	0	0.0004	0.02

In an evaluation of both a shielded and unshielded 6kW laboratory grade Hall Thruster under a 300V level of power, engines were left running under a operating times of about 117 hours . A coordinate measuring machine was used to record the channel walls' dimensions before and after testing to find rates their respective erosion rates. It was found that the complete mitigation of chamber wall deterioration was correlated with high ion current density and low electron temperature. These two factors contribute to a more controlled environment for the anode to accelerate the Xenon ions and therefore lower discrepancies that prevent the plasma from behaving ideally. Both trends were found consistently in both the unshielded and shielded models, but ion current density and electron temperature deviations varied differently. Between the outer layers of both controls, unshielded models showed 108% higher ion densities and 218% greater temperatures in the plasma propellant, which translated to the existence of erosion. Heightened operating conditions within the exhaust chambers of the USH6 group are due to the absence of deep electric fields that even out ion discrepancies in density and temperature, contributing to higher rates of erosion as the Xenon propellant is to behave less ideally. Contrarily, both the CMM detected decomposition in both inner chambers, but with drastic deviation. When erosion was detected, unshielded models were found to have sustained internal erosion of 985% to 52,750% to that of magnetically shielded models. Data suggests that unshielded Hall Thrusters operate at higher ion densities and temperatures, promoting higher rates of channel degradation, but the magnetic shielding group shows almost nonexistent erosion rates with low levels of transport intensity.

Table 2: Erosion Rates from various US and MS 6kW Hall Thruster studies under operating condition of 300V

Source	Magnetically Shielded?	Erosion (mm/kh)
(Goebel et al, 2012)	No	10
	Yes	6.8x10^-2
(Goebel et al, 2014)	No	9
(Hofer et al, 2012)	No	4.19
	No	4.75
	Yes	0
	Yes	2.4x10^-2
(Hofer et al, 2014)	No	6.37
	No	9.52
	Yes	0
	Yes	2.4x10^-2
(Mikellides et al, 2013)	No	8.7
	Yes	5.6x10^-1
(Jorns et al, 2015)	No	10
	Yes	7.78x10^-2

Six statistically valid studies involving the comparisons of 6kW Hall Thrusters show significant differences between the erosion rates of US and MS Hall Thrusters. In all studies involving the US linear rate of erosion against the channel walls, values were consistently above 4.19 mm/kh at a total average of 7.82 mm/kh. At a much lower magnitude, MS Hall Thrusters erosion rates were consistently below .56 mm/kh with a total average of 0.11 mm/kh. In terms of numerical difference, the difference of means between the US and MS H6 were at a magnitude of 73 times. To verify statistically if there was a significant difference between the rates of erosion between the US and MS groups, standard deviations were also calculated to conduct a two tailed test. In doing so, the computed t value was 9.17 under a significance level of .05.

In the two studies conducted by Hofer et al. in 2012 and 2014 (a), there are four data sets each opposed to the two sets commonly shared amongst the other studies. In his abrasion investigations, he monitored erosion rates along the inner and outer layers of both the US and MS Hall Thrusters, hence the total of four data values. Both data sets found that the outer layer of the MSH6 ran at an erosion less level as the ions existent in the propellent were successfully diverted from the walls by way of magnetic mechanics. Contrastingly, the MSH6 inner walls both yielded values of 2.4x10^-2 mm/kh due to subjection in more abrasion intensive environments as the this is where most ion pathways lie. Though at higher magnitudes, this similar trend was found in the USHT, as the greatest rates of erosion were found near the thruster exits at averages of 7.135 mm/kh while lower average rates of 5.28 mm/kh were recorded in the deeper parts of the exhaust chamber. It can thus be noted that the channel exits of HT exhaust chambers receive the most amount of abrasion. To preserve statistical integrity in the t tests, an average was taken for both Hofer studies' separate inner and outer erosion values, making its data value equal to that of the other studies. However, from surface level observation based on averages, it can be presumed that the MSH6 is more effective than the USH6 in reducing internal erosive forces.

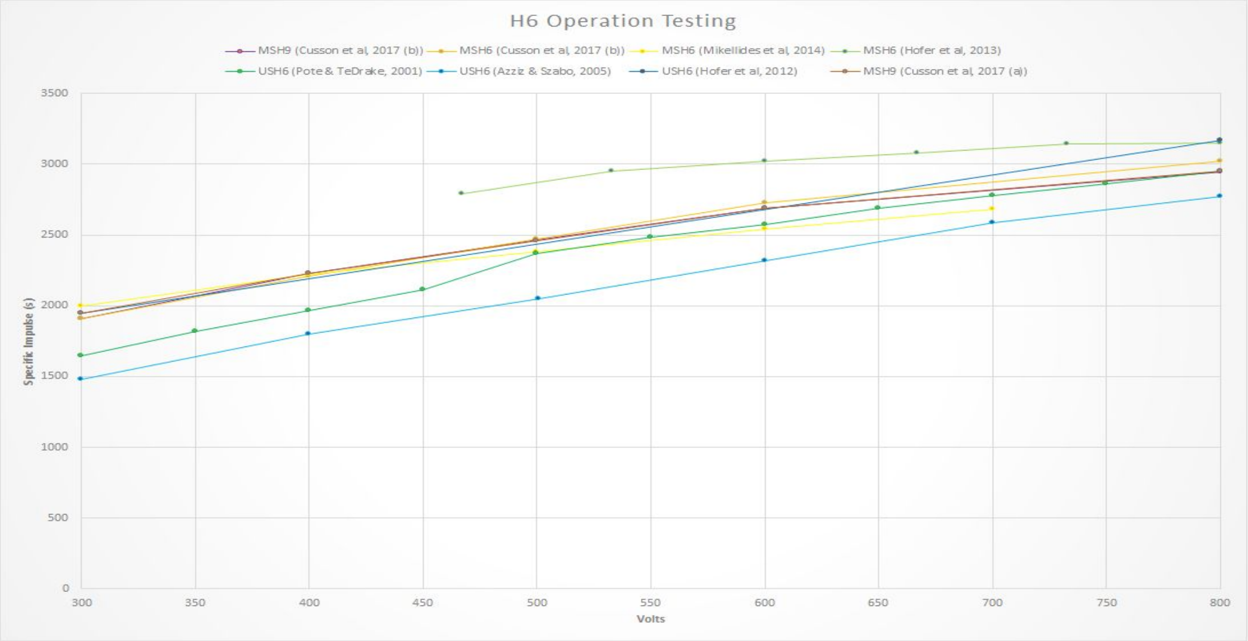

Fig. 5: Performance of the H6 in specific impulse (s) under various voltages (300V-800V).

A total of seven studies contained statistically significant data for the specific impulses for both unshielded and magnetically shielded H6 models by independent variable "Voltage." As voltage increases, all specific impulse points show an increase in value across US and MS models. Three data sets on the performances of the USH6 are shown with an average specific impulse of approximately 4.247 s per volt with a standard deviation of about 481. Considering the relatively large range between the dependent specific impulse values, the seemingly alarming standard deviation value does not invalidate the data. Similarly, the MSH6 demonstrated means of 4.74 s per volt with a standard deviation of 401.

To investigate if the MSH6 can maintain the already sufficient specific impulses of the USH6, t tests were also conducted for data shown in the graph above. With a significance level of .05 and degree of freedom of 7, the t value was found to be .013 In terms of averages, the MS group showed an 11% higher specific impulse output than the US.

Discussion

From wear testing conducted on a 6kW laboratory grade HT, results showed a thousandth of the original erosion rate under magnetic shielding. Under low power operations, erosion was completely mitigated as the CMM showed no volume changes before and after testing. As operating voltage increased, traces of chamber abrasion were detected on the walls of MS, but were reduced by factors of 73 times, ranging from 9.82 x 10 to 5.3x10^4 um/h (Hofer et al., 2014 (b)). Higher magnitudes of ion density and electron temperatures found in the USH6 were associated with higher rates of erosion due to discrepancies that made the Xenon propellant behave non ideally, resulting in backsputter against the channel walls.

Considering today's standards, a state of the art HT would require specific impulses of at 3000s and efficiencies of at least 60% (Cusson et al., 2017 (a)). The H6MS showed an Isp of 3020 seconds at 800V while maintaining a total efficiency of 63.6%, qualifying it as a high class Hall Thruster with the benefit of having a considerably longer service life. Other models, such as the H9, show a similar Isp of 2947 at 800V while maintaining a total efficiency of 62.1%. For comparison, Szabo and Azziz's performance testing on a laboratory BHT-1500 yielded a specific impulse of 3200s at 1000V while maintaining an efficiency of 60% (2005). Results between the HMS and BHT showed little characterization variation but radical difference in erosion rates.

Net efficiency percentages tend to increase as voltage increases, increasing specific impulse to power level ratios can be attributed to this trend (Hofer et al, 2015).

To evaluate if there was statistically significant changes between the performances of unshielded and magnetically shielded HTs, two tailed tests were the determining factor. With the prior mentioned standard deviation and means in Table 2 and Figure 5, t values of both were calculated to their sets' respective degrees of freedom. For linear erosion rates, the computed t value was 9.1678987 with a t critical value of 2.015. Because the t value is greater than the t critical value, this indicates a numerically significant change between the erosion rates of the MS and US H6. In this case, the t test advocates for the acceptance of the original alternate hypothesis: "Magnetic Shielding will reduce channel erosion while maintaining near identical rates of electron acceleration." In accordance to the requirements of accepting the alternative hypothesis, specific impulse values for the US and MS H6 need to have analytically similar results from the t test. The eight sets of data from graph 1 yielded a t value of .013 with a t critical value of 1.943 in respect to degrees of freedom. Because the calculated t value is below the t critical value, this shows that there is no statistically significant difference between the specific impulses of US and MS groups, further suggesting the validity of the proposed alternate hypothesis.

Conclusion

The magnetic shielding effect on the specific impulses and the rates of erosion in Hall Thrusters were evaluated to increase its reusability while maintaining its current performance levels. To implement such technology, the topography of existing electric fields are altered, rather than the structural components of the Hall Thruster itself. By employment of systematic literature review, Hall Thruster performance and erosion rate were evaluated and compared between MS and US by from various other academic studies.

From what the collected data shows, Hall Thrusters with magnetic shielding reach the current “state of the art” threshold for plasma rockets: 3000s Isp at 800V. While maintaining feasible the average rate of erosion across all magnetically shielded studies show a reduction by 73 times. In two tailed figure tests, the specific impulses for unshielded models with a degree of freedom of n=26 yielded a t value of 0.013, showing mathematical insignificance. Therefore, the performance levels of the US and MS H6 in terms of specific impulse can be considered numerically equal from 300V to 800V. With this, the alternate and null hypothesis of this study are both validated as they require similar base performances between both models. Calculations for the MSH6 with a degree of freedom of 7, yielded a numerically similar value of 9.16789877. USH6 Isp n=19, mm/kh n=8. Characterization of magnetically shielded Hall Thrusters show high performance in efficiency, electron acceleration, and degradation reduction, demonstrating a promising future for more efficient electron propulsion models and aerospatial advancement as a whole.

Limitations

In respect to the Thousand Oaks High School Safety Policy, no lab work or data was able to be implemented in this study, collecting data only from others’ findings. Furthermore, from a systematic literature review approach conducted at a student researcher level, the possibility of accuracy errors regarding concept and statistics may exist due to lack of understanding or sufficient data. Much information on Hall Thrusters conducted by private research facilities or monetary corporations were unavailable to the public and student researchers.

Due to the nature of systematic literature review from various research teams, controlled variables may slightly vary from paper to paper despite efforts to keep them consistent. Collected scholarly, peer reviewed papers may have had varying 6kW Hall Thruster diametrics such as different engine masses or net efficiencies that ultimately tamper the values for performance tests as thrust directly correlates with specific impulse (Goebel & Katz, 2008). All articles did not list the mass values for the tested HTs, so it was not possible to discern whether engine mass values were constant or not. For wear test values used to evaluate H6 erosion rate, all tests varied in time length, ranging from 80-117 hours. Although the data was taken in ratios (mm/kh) to keep controls consistent, extended time stamps can result in magnetic field changes similar to that of the 2010 wear test conducted by Haag et al in which the BPT-4000 reached an erosion less level.

Further Work

Magnetic shielding's ability to reduce channel erosion and reduce ion discrepancies constitutes much room for mechanical improvement. Presuming that MS will continue to divert ions away from channel walls, traditional insulator walls serve less of a purpose to protect the spacecraft from ion on wall abrasion (Grimaud & Mazouffre, 2017). Essentially, ion current's inability to reach the insulating material inside chamber walls suggest that the ceramic insulators are an unneeded component since magnetic shielding already provides sufficient containment measures. Instead, conducting walls consisting of metals that further support already existing electric fields are being proposed (Dotson et al, 2013). However, it is only possible with the success of magnetic shielding to negate the need for such Bi or BNSiO2 insulators. If the state magnetic shielded Hall Thrusters continue to prove more effective in the future, conductive wall Hall Thrusters are to be investigated as a potential aerospatial vessel.

Fig. 6: An image of an H6 with conductive graphite walls.

Considering the recent discovery of magnetic shielding, further development of the already seemingly successful technology could lead to the elimination of internal deterioration without consequential sacrifice. This effect in MSHT contributes to a more controlled ion flow and capacity to perform at higher operation levels exceeding 800V without excessive forces of internal abrasion which suggests the feasibility for even higher voltage Hall Thrusters in the future (Brown et al, 2017).

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