Development and Characterization of a Miniature Hall-Effect Thruster using Permanent Magnets

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Abstract: With the advent of low-power Hall-effect thruster (HET) development in the last 20 years, important research on efficient designing and scaling of HETs has been conducted. In this context, a low-power HET – the TUD-H3-P – has been developed and tested at the Institute of Aerospace Engineering at Technische Universität Dresden. The TUD-H3-P serves primarily as a laboratory thruster and test bed for a university-built thrust balance and hollow cathode. The application of the thruster and its derivatives as propulsion for small satellites is a long-term goal. The thruster is designed to operate at a nominal discharge power of 200 W, and therefore provide a thrust of approximately 10 mN at a specific impulse ($I_{sp}$) in excess of 1000 s. Thus, it can be an attractive candidate for applications like drag compensation for small and micro-satellites. Though small-scale HETs suffer from high power losses to the discharge channel walls, specific means to counteract overheating and erosion have been implemented to increase the overall thrust efficiency. A brief description of the design process will be presented. Initial characterization tests were carried out using a small-scale torsional pendulum thrust balance in combination with a Kaufmann & Robinson, Inc. LHC-1000 hollow cathode. The thruster was primarily tested using krypton and xenon as the propellant.

Nomenclature

$B$ = magnetic flux density
$d_m$ = mean channel diameter
$E$ = electric field
$F$ = thrust
$F_L$ = Lorentz force
$g$ = gravitational acceleration
$I_d$ = discharge current
$I_{sp}$ = specific impulse
$I_{sp,a}$ = anode specific impulse
$L_c$ = channel length

$m$ = particle mass
$\dot{m}_a$ = anode mass flow
$P_d$ = discharge power
$q$ = particle charge
$U_d$ = discharge voltage
$v$ = particle velocity
$v_e$ = drift velocity
$w$ = channel width
$\eta_a$ = anode efficiency

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I. Introduction

In order to provide well-matched and sophisticated propulsion systems for spacecraft with lower power supplies, HET miniaturization has emerged as a promising field of research. The relatively simple and low-cost designs enable research institutes and universities to participate in that research process. However, miniaturization of HETs poses several challenges. The increased surface-to-volume ratio of the discharge channel of small-scale thrusters increases the plasma-wall interaction and thereby leads to significant power losses to the walls, resulting in overheating, decreased thruster efficiencies, and lifetime degradations.

The design and experimental investigation of low-power HETs has been a field of research at Technische Universität Dresden since 2015. The TUD-H1-S technology demonstrator with a nominal discharge power range of 50 W to 150 W was developed by Hock as part of his diploma thesis. In that thruster, one single outer coil concentric to the discharge channel was implemented to generate the magnetic field. The thruster’s performance was, however, poor due to errors in the magnetic field topology and damage during the assembly process. A new approach was conducted by Gondol in 2018 with the 200 W TUD-H2-S. In this device, one inner and four distinct outer coils were installed. This thruster proved operation using argon as propellant but a lower anode efficiency than predicted by the applied scaling method. Additionally, high power losses to the channel wall led to an impractical increase in the thruster temperature. The TUD-H3-P is the third iteration of HETs developed at the Institute of Aerospace Engineering with the goal to increase thrust efficiency compared to its predecessors and was designed for a nominal discharge power of 200 W. It represents a classic SPT-type HET with dielectric channel walls made of borosil and uses permanent magnets to establish the magnetic field.

II. Hall Thruster Theory

The basic underlying physics of HETs has been extensively described in publications and literature (see for example Ref.4–6). A mostly radial magnetic field $B$ is established near the exit plane of an annular channel. An exterior hollow cathode serves as the source of electrons, which stream along the potential difference of several hundred volts that is generated between the anode that is located at the bottom of the discharge channel and the cathode into the channel. As they move toward the anode at the bottom, they are deflected by the Lorentz force given by:

$$\mathbf{F}_L = m \frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

where $\mathbf{F}_L$ is the Lorentz force vector, $m$ is the particle mass, $\mathbf{v}$ is the particle velocity vector and $q$ is the electric charge of the particle. Without an electric field, Eq. 1 shows that a charged particle is deflected orthogonally to the B-field lines on a circular motion whose radius is called the Larmor radius, given that the initial velocity vector of the particle and the B-field vector are orthogonal. The presence of an axially oriented electric field, however, deflects the gyrating electrons. As they approach the anode, the electrons are accelerated toward it, and as they move away, they are decelerated. Thus, the resulting motion of the electrons is the superposition of the gyration and an azimuthal drift in $\mathbf{E} \times \mathbf{B}$ direction with the drift velocity $v_e$:

$$v_e = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

The confined electrons describe a distinct area of high electron density near the exit plane called the ionization layer. From the bottom of the channel, the neutral gas propellant is injected. Most commonly, xenon is used as the propellant because of its high atomic mass and low first ionization energy, but other noble gases such as krypton and argon have also been investigated; these gases, however, result in a decrease of efficiency due to their lower atomic weights and higher ionization energies. As the neutral gas atoms approach the ionization layer, they collide with the electron cloud and become ionized. One major advantage of HETs is their very high mass utilization, wherein up to 90% of the propellant mass flow is converted into ion mass flow. The ions are then electrostatically accelerated in the axial direction resulting in an $I_{sp}$ that can exceed 2000 s.
A. Challenges of Low-Power Hall Thruster Design

Small-scale HETs often show a decreased efficiency and lifetime compared to larger kW thrusters and need sophisticated thermal control mechanisms in order to prevent overheating. As the size of the thruster is reduced, the surface-to-volume ratio of the discharge channel increases with $2/w$, with $w$ being the channel width. As a consequence, the power that is lost to the channel walls due to ion and electron bombardment increases and sputter erosion is promoted. As mature thrusters achieve lifetimes on the order of 7,500 up to 10,000 hours, small-scale thrusters are often limited to lifetimes below 3,000 hours. This power loss mechanism can be significantly reduced by altering the magnetic field configuration. Instead of allowing the magnetic field lines to penetrate the walls, so-called magnetically shielded thrusters provide a specific magnetic topology in which the field lines pass the walls tangentially. This arrangement produces a layer of low energy electrons in the proximity of the walls and significantly reduces the radial electric field component. This functionality has been demonstrated, for example, by Conversano et al. with their low-power MaSMi-60 HET that allows a 10–100-fold increase in discharge channel lifetime. However, this approach requires thorough and extensive design and measurement capabilities and was considered out of the scope for the TUD-H3 P.

III. Design of the TUD-H3-P

The design process of the TUD-H3-P was based on the application of scaling laws from literature to an optimized reference thruster in order to obtain first-order estimates of the thruster dimensions as well as operating conditions for a given power level. Although scaling is a less predictable and sufficient approach to designing a HET, the computational effort is significantly reduced compared to extensive plasma modelling. Scaling has been a topic of research since the 1970s; however, most of the work on scaling has been published since the 1990s. Numerous analytical and semi-empirical approaches from the literature were evaluated and compared in order to find the necessary geometric parameters of the discharge channel—i.e., mean channel diameter $d_m$, channel length $L_c$, and gap width $w$—and the nominal operational parameters such as discharge voltage $U_d$, peak magnetic flux density $B$, thrust $F$, and $I_{sp}$. The Russian SPT-100 by FAKEL served as the reference thruster during the scaling process. The results of the applied scaling laws showed deviations mainly in the channel length; the mean diameter and channel width were in the same range. For the TUD-H3-P, it was therefore decided to implement a variable channel length with a maximum of 25 mm in order to test different configurations and examine the influence. It was also decided to use the average of the $d_m$ values, which is 36 mm. Research at CNRS on the impact of channel width on the performance of the 200 W PPI thruster demonstrated a significantly improved propellant utilization efficiency and a decrease in wall power losses at higher values of $w$ than proposed by the scaling method, i.e., deviating from the proportionality condition of $w$ and $d_m$ that is often an underlying assumption of scaling methods. Moreover, a decrease in wall temperature of 100 K was observed for larger values of $w$. This was related to a decrease in surface-to-volume ratio for higher $w$ and a stronger magnetic mirror effect due to the channel walls being closer to the magnets that improves the electron confinement and magnetic field gradient toward the anode. Thus, it was decided, for the TUD-H3-P, to widen the channel width to 12 mm. For the magnetic field of the TUD-H3-P, an adjustable margin in the range of 0.015 T and 0.030 T of peak magnetic flux density was considered. The final design parameters of the TUD-H3-P are summarized in Table 1.

Table 1: Design Parameters of the TUD-H3-P

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TUD-H3-P</th>
</tr>
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<tbody>
<tr>
<td>$P_d$ in W</td>
<td>200</td>
</tr>
<tr>
<td>$U_d$ in V</td>
<td>250</td>
</tr>
<tr>
<td>$I_d$ in A</td>
<td>0.8</td>
</tr>
<tr>
<td>$d_m$ in mm</td>
<td>36</td>
</tr>
<tr>
<td>$w$ in mm</td>
<td>12</td>
</tr>
<tr>
<td>$L_c$ in mm</td>
<td>15-25</td>
</tr>
<tr>
<td>$B$ in T</td>
<td>0.015 - 0.030</td>
</tr>
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A. Magnetic Circuit

The magnetic circuit of a HET serves the purpose of generating the required radial magnetic field near the channel exit plane and conducting the magnetic field from the source to the front part of the channel.

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Furthermore, it provides a mechanism for adjusting the peak magnetic flux density in the channel. For the TUD-H3-P, permanent magnets were used in order to decrease weight and volume compared to electromagnets. Axially magnetized sintered SmCo magnets were chosen for the thruster. The magnet configuration consists of an inner ring magnet concentric to the channel and a configuration of 47 SmCo bar magnets that are concentrically arranged to the channel on the outside. Contrary to electromagnets, permanent magnets provide a fixed magnetic field. Thus, it is not trivial to adjust the field to a certain value and requires an additional mechanism. For this purpose, a magnetic shunt ring was implemented that can be slipped over the outer bar magnets, as shown in Figure 1. The closer the shunt is moved to the pole piece, the more flux is redirected through the shunt and therefore the peak flux density in the channel decreases. This method provides a margin for adjusting the magnetic field to the point of best operation. The magnetically conductive path is made of magnetically annealed soft-iron that shows a saturation flux density of \( >2 \text{T} \).\(^{21}\) A magnetic screen was additionally implemented in order to increase the gradient of the magnetic flux density toward the anode and thereby increase electron confinement in the front of the channel and promote the ionization process.\(^{22}\) A COMSOL Multiphysics\(^{\text{®}}\) simulation was used to evaluate the radial magnetic flux density in the channel. Several values of the gap width between the shunt and the outer pole piece were simulated. In Figure 2, the radial component of the flux density along a line parallel to the center axis at a distance of \( \frac{d_{\text{m}}}{2} \) is shown for shunt gaps of 8 mm, 1 mm and 0.5 mm. As expected, the maximum flux density decreases in the channel as the shunt is moved closer to the outer pole piece.

![Figure 1: Cross-Section of the TUD-H3-P](image)

![Figure 2: Comsol plot of radial magnetic flux density for a 0.5 mm, 1 mm and 8 mm shunt gap. The anode surface is at \( z=10 \text{ mm} \) and the exit plane is at \( z=35 \text{ mm} \).](image)
B. Thermal Design

As stated in Section I.A, a thorough thermal design is crucial in order to keep the temperature within operational limits of sensitive thruster components such as electrical connections in the back of the thruster and the magnets. The thermal conductive path was designed to efficiently evacuate the heat from the channel walls and the anode to the back of the thruster. Two copper components were implemented directly into the thruster design. At the center, a 6 mm diameter copper cylinder supports heat transport from the inner wall to the back. The cylinder is in direct contact with the inner ring magnet and crucial for the inner thermal conduction. Concentric to the channel, a cylindrical copper shell with a closed bottom serves the same purpose for the outer channel wall and the anode by surrounding the outer and bottom part of the channel.

The thruster is additionally mounted onto a copper plate that serves as a heat sink. In order to promote heat radiation from external surfaces, a cylindrical aluminum alloy radiator was installed at the back of the thruster mounting and covered with a varnish provided by Airbus Defence and Space Friedrichshafen that increases the thermal emissivity. The thruster is covered with an aluminum top that is slipped over the assembly and also varnished. This cover holds the outer pole piece in place and protects the thruster from spark discharges. For a thermal simulation, the power losses were estimated based on the calculation of the sheath potential that drives the wall power loss and the anode power loss, according to Ref. 4 Other power loss mechanisms were neglected for simplicity. The most critical temperature of the inner ring magnet is 217.6 °C for an input power of 200 W and below the maximum operating temperature of 350 °C.

IV. Characterization Tests

Initial performance characterization tests were conducted at the Institute of Aerospace Engineering. The tests were carried out using krypton and xenon as the propellant for the TUD-H3-P. Most HETs are optimized for the use of xenon in terms of discharge channel geometry and magnetic topology. The utilization of krypton is currently of high interest in the community and mainly financially motivated, since costs are significantly lower for krypton than for xenon. This publication will be mainly limited to the krypton test data, the xenon data will be part of a further publication. 23

Four different peak magnetic flux densities were tested: 17 mT, 22 mT, 25 mT and 28 mT. The channel length was held constant at 25 mm. Tests with shorter channel lengths are topic of future work. The tests were mainly intended to obtain performance measurements, and thus the different operating points were only maintained for several minutes.

A. Test Facility

The tests were carried out in a cylindrical vacuum chamber with a diameter of 0.5 m and a length of 1 m. A primary multi-stage Roots vacuum pump and a second stage cryopump with a total pumping speed of 10,000 l/s enabled a vacuum regime of approximately 1E-7 mbar during the tests without mass flow from cathode or thruster. With an additional mass flow through the thruster of 30 sccm that was used for the ignition procedure, the chamber pressure increased to 2-3E-4 mbar. A torsional pendulum thrust balance developed by Neunzig et al. 24 was used to take thrust measurements during operation. The thruster was mounted onto a pivoted aluminum frame that allowed rotation around a vertical axis and was balanced by an assembly of counterweights. A thrust thereby led to a rotatory motion of the thruster and a reaction of a torsion spring of known spring constant, which served to translate the deflection into a distinct force value, i.e., thrust value. The deflection was measured using a laser interferometer. Prior to each test cycle, the thrust stand was calibrated by applying a defined force using a voice coil. Uncertainties of the thrust measurements are primarily due to the calibration process and increase with the force according to the voice coil current. The electrical connections of the anode and cathode keeper were realized through two liquid metal reservoirs filled with Galinstan along the thrust balance axis, enabling a frictionless connection.

Figure 3 shows the thruster mounted on the thrust stand. During the calibration of the thrust balance with the TUD-H3-P, anomalies occured that were not noted with the predecessors of the thruster. These were operated using electromagnets, and thus it is likely that the anomalies were due to the interaction of the thruster’s magnetic field with the voice coil. Therefore, the test data presented below must be taken with caution and might show a significant uncertainty of up to 15 %.
B. Hollow Cathode

A Kaufman & Robinson, Inc. LHC 1000 hollow cathode with an emission current of up to 20 A was utilized for the test cycles of the TUD-H3-P. The hollow cathode was mounted onto the same aluminum frame as the thruster. Typically, the ratio of the anode mass flow to the cathode mass flow is on the order of 10 to 1. However, the LHC 1000 was slightly oversized for the application with the TUD-H3-P. As a consequence, the cathode mass flow was at times close in magnitude to the anode mass flow during operation and was held constant at 10 sccm krypton. Using xenon, the cathode mass flow was lowered to 5 sccm.

C. Current-Voltage-Characteristics

Figure 4 shows the current–voltage–characteristics (CVCs) during the four test cycles for different magnetic configurations and thruster mass flow rates of 20 sccm krypton and below. A typical CVC of a HET shows a characteristic shape. At a specific discharge voltage, the electrons obtain enough energy to ionize the neutral gas. The succeeding avalanche ionization results in a rapid increase in current. As soon as the ionization reaches its maximum, the current stays relatively constant independent of the applied voltage. In the CVC plots, the discharge current shows a steep increase at discharge voltages in the range of 100 V for mass flow rates above 13 sccm and all magnetic field configurations. This increase shifts to higher voltages for lower mass flow rates. At a constant mass flow rate, the voltage at which the current increase appears also rises slightly with the magnetic field. After the rapid incline, the current flattens out as the voltage is further increased. At magnetic flux densities of 0.025 T and 0.028 T, the thruster was mostly operated at the adjusted anode current limit, ranging between 1.0 A and 1.6 A. Higher current limits were deemed impractical due to the increase of discharge power at low voltages. The constant current section at higher voltages can only be obtained in voltage-controlled mode and was therefore not achieved. Merely with peak magnetic flux densities of 0.017 T and 0.022 T and by reducing the gas flow to 14 sccm and below it was possible to lower the current below the adjusted current limit of 1.4 A and therefore reach a voltage-controlled operation with a relatively constant discharge current. At 0.017 T, the current could be lowered to approximately 0.9 A, which is only slightly higher than the nominal current of 0.8 A.
Figure 4: Current-Voltage-Characteristics of the TUD-H3-P for different magnetic field configurations and mass flow rates

D. Thrust

In Figure 5, the thrust is plotted over the discharge voltage for the four test cycles and anode mass flow rates of 20 sccm krypton and below. The data is corrected for ingested neutral gas atoms from the chamber background.
The thrust shows a steep initial increase and then relates linearly with the discharge voltage. For voltages up to 300 V, a maximum thrust of 17.35 mN was measured at 0.017 T, 288 V, 1.36 A, and 15 sccm. At the nominal voltage of 250 V, thrusts exceeding 10 mN were reached at 0.017 T and 0.022 T. For magnetic fields higher than 0.022 T, the small voltage range only covers a relatively narrow thrust span from 3 mN to 11 mN. Again, it must be emphasized that uncertainties are high due to the imperfect calibration process. Moreover, the large cathode mass flow provides additional neutral gas that can be ingested into the thruster.
and artificially increase the thrust.

E. Specific Impulse

The anode specific impulse $I_{sp,a}$ – i.e., the specific impulse calculated using only the thruster mass flow; the cathode mass flow is neglected – at each individual operating point was derived from measured values of the thrust and the anode mass flow rate corrected for the background pressure. The $I_{sp,a}$ is hence calculated as follows:

$$I_{sp,a} = \frac{F}{\dot{m}_a g}$$ (3)

with $F$ being the thrust, $\dot{m}_a$ the anode mass flow rate and $g$ the gravitational acceleration. Due to the dependence on the thrust measurements, high uncertainties are to be expected. In Figure 6, the $I_{sp,a}$ is plotted over the discharge voltage for the four test cycles and anode mass flow rates of 20 sccm and below. At the nominal voltage of 250 V, anode specific impulses above 1500 s were achieved at 0.017 T as well as 0.022 T. At 0.017 T, decreasing the mass flow rate results in a slightly decreased $I_{sp,a}$ at a constant voltage. The same applies to 0.022 T at voltages between 280 V and 300 V. At equal voltages, the $I_{sp,a}$ stays relatively constant, independent of the magnetic field. Increasing the magnetic flux density further limits the $I_{sp,a}$ to 1400 s and below with the exception of one rather unstable operating point at 0.025 T and 15 sccm, because the accelerating voltages are not sufficient and higher currents were not tested.

F. Anode Efficiency

The anode efficiency is often used to evaluate the thruster performance. It relies on measurements of the thrust, anode mass flow rate, discharge voltage and discharge current, and is calculated using:

$$\eta_a = \frac{F^2}{2 \cdot \dot{m}_a P_d}$$ (4)

In Figure 7, the anode efficiency $\eta_a$ is plotted over the discharge voltage for the four test cycles and anode mass flow rates of 20 sccm and below. A maximum $\eta_a$ of 47.51% was reached at 0.017 T, 294 V, 1.24 A and 14 sccm. At the nominal voltage of 250 V, anode efficiencies exceeding 35% could be achieved at 0.017 T and 0.022 T. For a magnetic field of 0.025 T, shown in Figure 7, efficiencies up to 30% were reached below 200 V and at a maximum current of 1.6 A. At the highest magnetic field of 0.028 T in Figure 7, the operating points are more widespread and only single operating points at $\eta_a$ in the range of 30% were reached at voltages below 200 V.

G. Continuous Operation Test

In order to investigate the thermal steady-state of the TUD-H3-P, an additional test cycle was carried out where the thruster was operated continuously at 200 W for 60 minutes. The temperature at the tip of the inner copper stem levelled at about 170°C, which is in good agreement with thermal simulation data.
Figure 6: Isp of the TUD-H3-P for different magnetic field configurations and mass flow rates
Figure 7: Anode efficiency of the TUD-H3-P for different magnetic field configurations and mass flow rates.
H. Performance Test Summary

Table 2 is a summary of the performance test data. The operating point of highest anode efficiency at voltages up to 300 V and the operating point of highest anode efficiency at a discharge power of 200 W are presented for both krypton and xenon.

Table 2: Summary of Selected Operating Points of the TUD-H3-P

<table>
<thead>
<tr>
<th></th>
<th>Highest Efficiency up to 300 V (Krypton)</th>
<th>Highest Efficiency at 200 W (Krypton)</th>
<th>Highest Efficiency at 200 W (Xenon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_d$ in W</td>
<td>366.3</td>
<td>202.5</td>
<td>199.1</td>
</tr>
<tr>
<td>$U_d$ in V</td>
<td>294.3</td>
<td>186.6</td>
<td>298.6</td>
</tr>
<tr>
<td>$I_d$ in A</td>
<td>1.24</td>
<td>1.09</td>
<td>0.67</td>
</tr>
<tr>
<td>$B$ in T</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>$F$ in mN</td>
<td>16.87</td>
<td>9.81</td>
<td>11.53</td>
</tr>
<tr>
<td>$I_{sp,a}$ in s</td>
<td>1965</td>
<td>1332</td>
<td>1594</td>
</tr>
<tr>
<td>$\eta_a$ in %</td>
<td>47.51</td>
<td>33.87</td>
<td>49.6</td>
</tr>
</tbody>
</table>

Efficiencies exceeding 40% of anode efficiency were only reached at discharge power levels exceeding 300 W. Since only short tests were carried out, long-term tests are necessary in order to verify that the concerning operating points comply with the thermal limitations of the thruster. Operation with xenon resulted in a significant increase in thrust and anode efficiency compared to krypton. Though krypton is a lighter gas than xenon and the $I_{sp}$ can therefore theoretically be higher, the $I_{sp}$ using xenon reached similar, if not higher values compared to krypton. This might be due to a higher propellant utilization. Figure 8 shows the TUD-H3-P in operation with both krypton and xenon.

![Figure 8: TUD-H3-P operating with krypton and xenon at 250 V discharge voltage.](image)

V. Conclusion

A low-power HET with a nominal discharge power of 200 W was developed and characterized at the Institute of Aerospace Engineering at Technische Universität Dresden. In order to counteract the typical overheating of small-scale thrusters, the channel width was widened to 12 mm compared to scaling results to decrease the surface-to-volume ratio of the discharge channel, and thereby reduce wall power losses. Copper components and radiating surfaces were additionally implemented to lower the steady-state temperature of the thruster. SmCo permanent magnets were used and in combination with a magnetic shunt mechanism, the peak magnetic flux density provided a range of 0.015 T to 0.030 T. The characterization tests were carried out using krypton and xenon and four different peak magnetic flux densities were tested: 17 mT, 22 mT, 25 mT and 28 mT. The thruster showed best operation at the lowest magnetic flux density of 17 mT with the
highest efficiency at 200 W reaching 33.87% for krypton. During the test cycles, the background pressure and the cathode mass flow rate were unfortunately high and increased the facility effect on the measurements. Tests using a university-built hollow cathode in a larger test facility are scheduled in the near future. The calibration process of the thrust balance that was used will be investigated and adjusted in the future in order to obtain more reliable test data.

References