Further Development of the TIHTUS Test Facility at IRS

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The Thermal-Inductive Heated Thruster of the University of Stuttgart (TIHTUS), combines the complimentary operations of arcjet and inductive plasma sources in order to generate a flexible, high-performance propulsion test platform. Since its initial development, the system has meed modified with a number of new measurement tools, allowing passive data collection within the thruster whilst plume diagnostics are conducted. Present investigative campaigns include the use of alternative propellants as well as geometric optimisation of the thruster stages. Additionally, an improved design of the inductive stage is intended to increase the total obtainable data from the system.

Nomenclature

f	= Inductive generator operating frequency [Hz]
H	= Magnetic field strength [A/m]
I	= Current [A]
p	= pressure [Pa]
$\dot{Q}$	= Heat flux [W]
U	= Electrical potential [V]
ΔV	= velocity increase/decrease required to execute orbital manoeuvre

Subscripts

A	Inductive stage power supply anode
DC	Arcjet
DC, n	Arcjet segment number
RF	Inductive generator stage
$tank$	Test chamber (ambient reference)
z	Thruster (discharge tube) central axis

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I. Introduction

In order to increase the range and flexibility of future space operations, efforts must be made to decrease dependence on Earth-exclusive and production-intensive propellants. A number of naturally-occurring compounds such as water, methane, and carbon dioxide are available at locations of interest throughout the solar system.[1–10] Similar compounds are also presently ejected as waste from crew life support systems.[11] The capacity to capitalise on such sources can build towards extended scientific campaigns. Specifically, the use of these propellants may act to mitigate orbit degradation in satellites and space stations, providing increased on-site research opportunities. To understand the applicability of these compounds for thrust generation, they must first be investigated in a relevant and compatible propulsion environment.

When selecting a propulsion platform, consideration must be given to the nature of the intended propellant and it's applicability to the three families of electric propulsion: electrothermal, electromagnetic, and electrostatic. Electrothermal thrusters remain highly relevant in the field of electric propulsion, despite being the predecessor to modern electrostatic and electromagnetic propulsion. Whilst the latter classes exhibit higher specific impulses required for long-duration and high-ΔV trajectories, the high-thrust characteristics of electrothermal thrusters make them better suited for shorter duration, more impulsive manoeuvres where an exhaust velocity above conventional chemical propulsion is required. Furthermore, electrothermal systems make use of neutral species as well as charged species. This is beneficial when assessing gases requiring large energy inputs for ionisation.

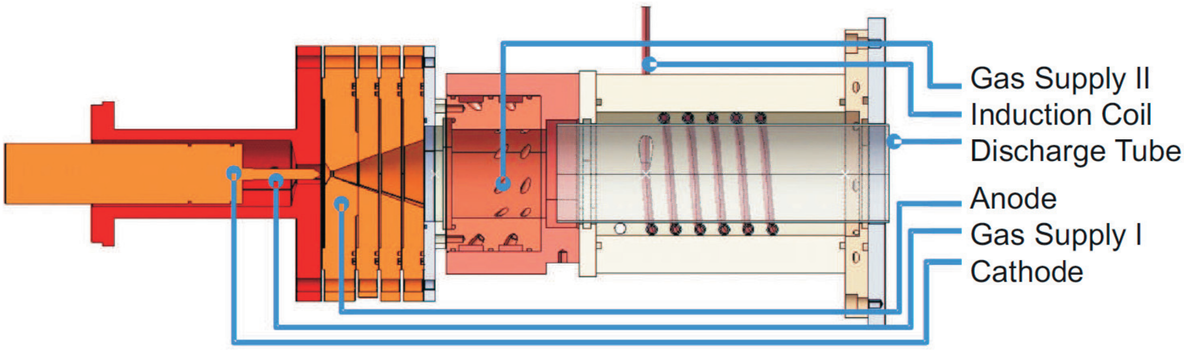

Figure 1. TIHTUS systematic layout[12]

To this end, the TIHTUS (Thermal-Inductive Heated Thruster of the University of Stuttgart) facility at the Institute for Space Systems (IRS) has been repurposed to conduct an investigation of alternative propellants. Originally designed for pure hydrogen operation, TIHTUS combines a segmented arcjet (HIPARC) and inductive plasma generator (IPG) in series, as displayed in Figure 1. The two stages use complimentary heating process, with the IPG used to increase thermal energy in the otherwise cooler arcjet outer-plume region, thus increasing the average flow temperature.[13] Between the two stages, additional gas may be added to the flow. This secondary injection allows more aggressive species such as CO_2 to be tested, without compromising the integrity of the arcjet electrode arrangement. Furthermore, the ability to regulate the ratio of power and propellant flow between the two stages allows an extensive database to be collected and preferable combinations discerned.

This report discusses the original TIHTUS establishment conducted by Böhrk (2009), as well as improvements and modifications to reach the current system configuration. The new operational window resulting from these modifications is also presented, followed by a comparison of the original inductive stage (IPG3) with its successor (IPG7).

II. Experimental Facility

The TIHTUS facility arrangement is displayed in Figure 2. The thruster is mounted on the exterior of the tank lid in order to avoid possible discharges to the tank walls caused by the high operating potentials

of the IPG. The tank itself possesses an effective internal volume of 9.4 m^3 and is connected to the IRS main facility vacuum. This vacuum system is capable of suction rates of 6000 m^3/hr at atmospheric pressure or 250,000 m^3/hr at 10 Pa. This results in a minimum pressure of 3.0 Pa without propellant flow through the thruster(s). While this is certainly high for an electric propulsion test facility, the design mass flow rates for HIPARC and IPG are several hundred l_n/min, corresponding to several grams of air per second. Hence very low background pressures are not feasible for such a large-scale system. Later work may address the scaling of such a system in the interest of optimisation, though for now the influence of background pressure on desired measurement parameters will be monitored and accounted for.
Power for the system is supplied by two independent sources. HIPARC is connected to the IRS main high-current system and may be operated up to 100 kW (as per its design). The IPG is supplied by a separate matching network power station, with an operable maximum of 180 kW. Previous campaigns on TIHTUS have been largely focused on the 50 kW combined power level, for reasons explained in Section III.

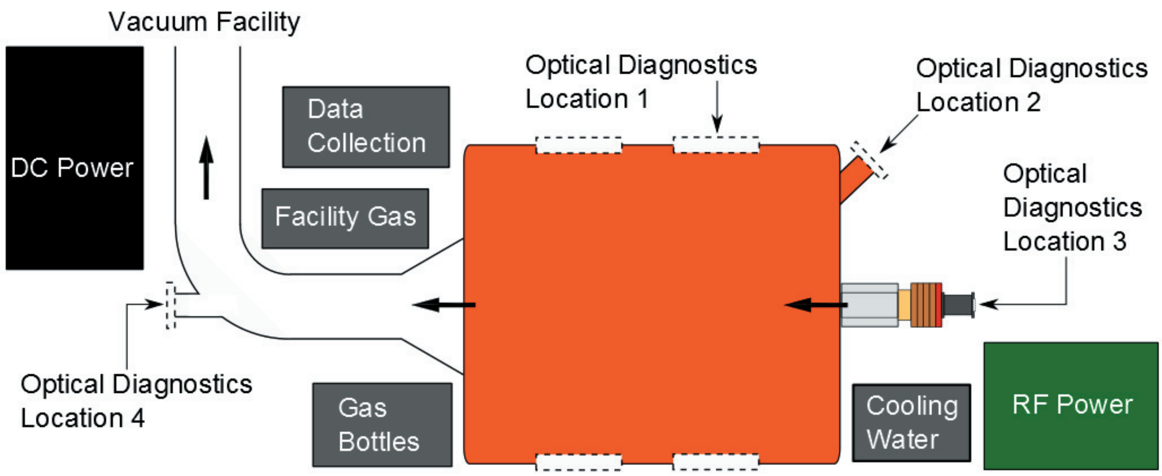

Figure 2. TIHTUS test facility

Modifications to the TIHTUS facility have acted to extend the measurement capacity of subsequent campaigns. As seen in Figure 2, optical measurements are now possible at three locations about the facility. Location 1 is primarily focused on interaction between the flow and measurement probe, while Locations 2 and 3 are intended for radial-distributed observations of the flow. Location 4 has limited applications, but may be used to observe the arcjet discharge which is otherwise obscured by the IPG body.
A number of passive measurements are taken during each test, with their respective tools and applications listed in Table 1.

While independently useful, a number of these measurements may be combined in order to provide a deeper understanding of interaction between the two stages; in particular how conditions generated in the arcjet influence the second stage and resultant plume. For example, given its reasonably weak magnetic field strength ($H_z \approx 2.8 \times 10^4$ A/m), the IPG relies on electrons in order to Ohmicly heat the gas flow. Hence combined values of arcjet potential, pressure, and wall heat flux may assist in clarifying whether inflow conditions to the IPG are favourable, or whether the optimal point has been passed and no further performance gain is observed with increasing power in the first stage. Additionally, many of the measured values may be used with the in-house numerical tool, SINA (Sequential Interative Non-equilibrium Algorithm)[14] to model. Of particular interest are the wall heat fluxes, as well as the IPG coil current.

Table 1. TIHTUS facility passive measurements

Measurement	Probe/system	Application
HIPARC anode segments heat flux ($\dot{Q}_{DC,1-4}$)	PT100, Siemens Flowmeter	Distribution of plasma temperature within HIPARC (combined with cathode heat flux for arcjet thermal efficiency)
IPG discharge tube heat flux ($\dot{Q}_{RF}$)	PT100, Siemens Flowmeter	IPG thermal efficiency and discharge tube wall temperature
HIPARC injector head pressure (p_{DC})	Pressure gauge	Arcjet gas behaviour
IPG injector head pressure (p_{RF})	Pressure gauge	Combined gas interaction in IPG
Tank pressure (p_{tank})	Pressure gauge	Pressure ratio with plume
HIPARC anode segment current ($I_{DC,1-3}$)	Isolation transformer	Distribution of diffuse arc within HIPARC
HIPARC cathode current ($I_{DC,k}$)	Isolation transformer	HIPARC total applied power
HIPARC potential (U_{DC})	Isolation transformer	HIPARC total applied power and arcjet gas behaviour
IPG anode current and potential (I_A, U_A)	Isolation transformer	Combined gas interaction in IPG
IPG coil current (I_{RF})	HOKA	IPG operating frequency and plasma conductivity behaviour

III. TIHTUS Development

Since the last campaign conducted by Böhrk (2009), a number of modifications have been made to the experimental set-up. As previously mentioned, TIHTUS has only yet been operated at a total of 50 kW between both stages. This is primarily due to material limitations of cooling water sealing at the IPG exit. During the Böhrk campaign, hydrogen acted as the thruster propellant, with silicon and Viton® used to contain the discharge tube cooling water. For comparison, Figure 3 displays IPG discharge tube cooling heat flux for hydrogen, argon, and nitrogen at a number of operating conditions.

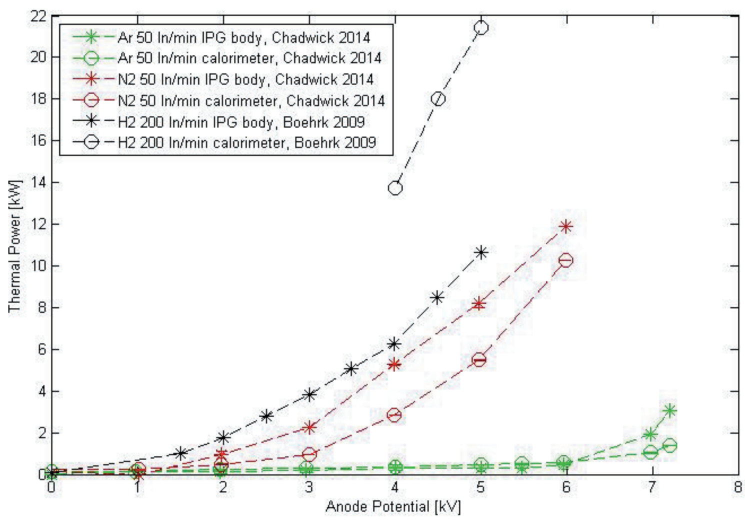

Figure 3. Discharge tube heat flux during operation

Even with the reduced input power, the temperatures experienced by the discharge tube limited possible testing time with the solicon sealing to approximately 10 minutes during the hydrogen campaign. In addition to limiting the amount of data able to be collected in a single test, reducing the input power severely restricts the investigative ability of the set-up. This is particularly evident in the case of the IPG, where transitions between capacitive, first inductive, and second inductive operating modes are clearly observed.[15] For this reason, the near-exit water sealing has been changed to a graphite design, greatly increasing the maximum operating temperature for this region of the thruster. An example of heat damage on the previous silicon sealing, as well as an assembly of the new graphite design are displayed in Figures 4 and 5 respectively.

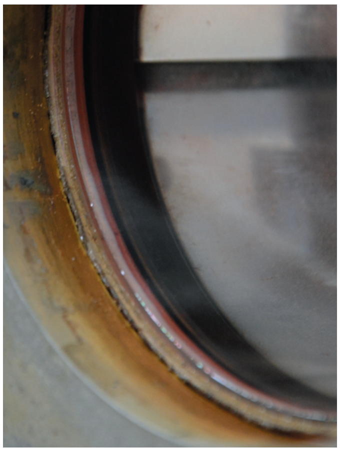

Figure 4. Damaged silicon sealing post N_2 50 l_n/min, 100 kW

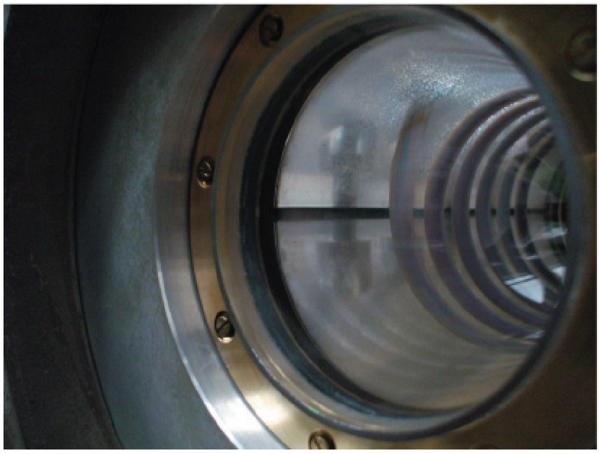

Figure 5. Graphite sealing assembly

By increasing the possible operating temperature at the thruster exit, the experimental method hence becomes more flexible. Of particular interest is the prospect of hysteresis. Hysteresis, being a retarding effect for the transition to capacitive operation once the inductive mode has been reached, is known to occur in such systems as the IPG.[16] It is thus expected that investigations of such a phenomenon will be possible with the new set-up.

IV. New Inductive Stage

In addition to the improvements made to the current IPG model (IPG3), a new model, IPG7,[17] is planned for installation and integration into the TIHTUS system. The major differences between the two, seen in Figures 6 and 7, are the water-cooled body and inductive coil.

Whilst operating in the same water-cooled fashion as IPG3, IPG7 features a more easily accessible discharge tube, allowing broken tubes to be replaced significantly faster than previously. This is an additional bonus when considering some of the current projects discussed in Section V. Other components such as connections from the inductive coil to the water cooling system have been made reusable to reduce repair times after component failure and hence increase total testing time.

In addition to the body, the inductive coil itself has been slightly modified to display a larger cross-section and wall-thickness, while maintaining the previous water-cooling channel dimensions of IPG3. Additionally, the IPG7 coil couples with a discharge tube of outer diameter 90 mm, in contrast to the 88 mm of IPG3. Therefore, the combination of lower coil resistance (from the increased current-carrying cross-section) and an increased total current path (due to the increased diameter requiring more copper to form) will affect the operating frequency (f) of the IPG7 in contrasting ways. These resulting frequencies should be compared to those of IPG3, in order to assess the impact on previously characterised conditions and results. Such measurements are possible through the use of the HOKA probe.

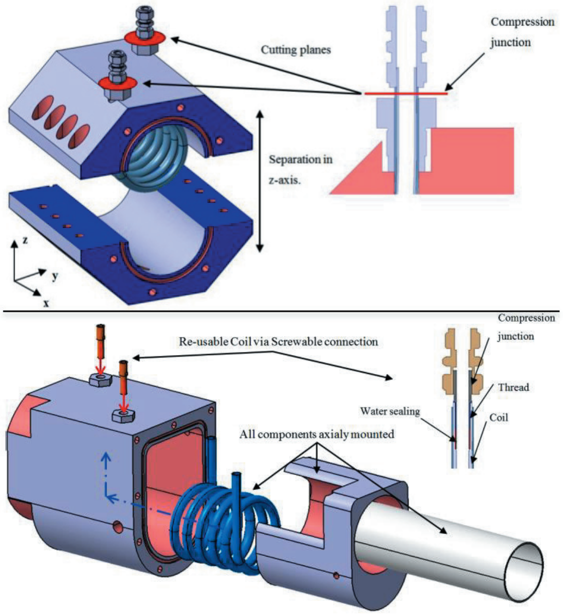

Figure 6. IPG3 (above) and IPG7 (below) assembly schematics[17]

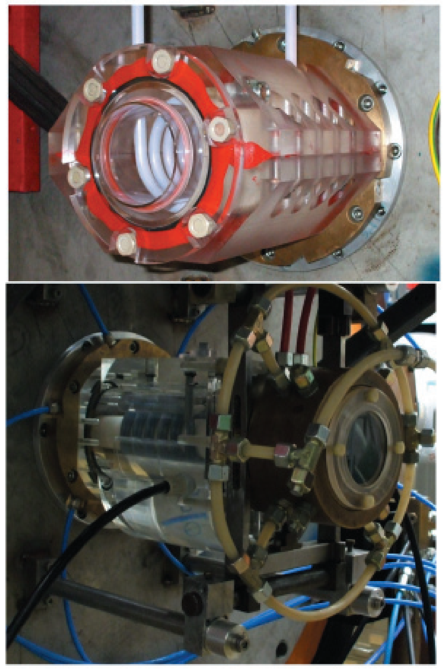

Figure 7. IPG3 (above) and IPG7 (below) mounted on test stand

V. Present and Planned Campaigns

Current research at the TIHTUS facility is focused around four major topics, being alternative propellants, variation of the arcjet anode segments, variation of the IPG discharge tube thickness, and measurements of the IPG discharge tube wall temperature.

As previously discussed, the flexibility of the TIHTUS system makes it ideal for the implementation of naturally-occurring gases such as CO_2 and water for the purpose of propulsion. However, the implementation of such gases benefits greatly from general optimisation of the system. This is approached through variations of the arcjet anode arrangement as well as the IPG discharge tube wall thickness. The discharge of the arcjet can be significantly altered by varying which of the anode segments are electrically connected to the thruster circuit, as displayed in Figure 8. The discharge can then again be changed if the unconnected segments remain, acting as a cold expansion nozzle, or are removed, therefore decreasing the distance between the two stages (and hence the available space in which species may recombine). As previously mentioned, the electron number density plays a vital role in Ohmic heating within the IPG, and hence variations in the arcjet anode set will have a significant influence on the total thruster performance. The IPG itself may also have its discharge behaviour influences by varying the separation between the plasma and coil through means of the discharge tube wall thickness. Previous campaigns have shown that the benefits from varying the wall thickness were non-linear, with a reduction from 2.3 mm to 1.25 mm measuring more that double the plume thermal power.[18]

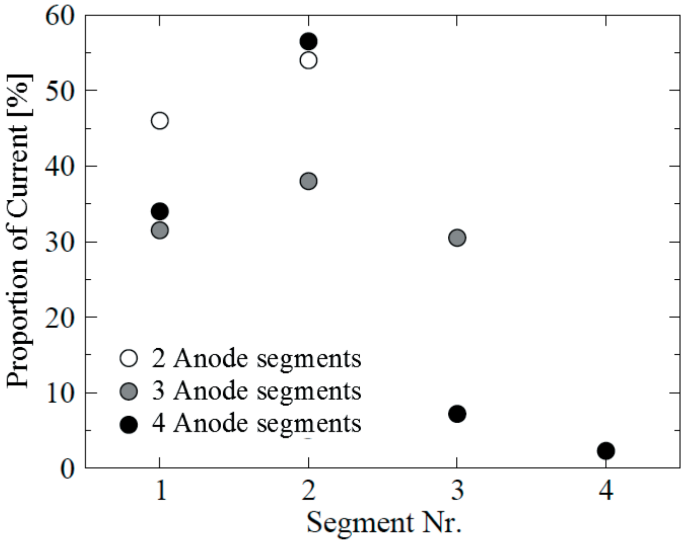

Figure 8. Distribution of anode current distribution as a result of electrical connectivity (adapted from Böhrk)[13]

Whilst propellant and geometric alterations assist in assessing gross system performance and interstage interaction, measurements of the discharge tube wall temperature cover other targets. Firstly, these may be used to assess material limitations of the quartz containment structure, complimenting the study of performance for different tube thicknesses. However, they may also serve another purpose of assessing near-wall temperatures of the plasma, therefore providing additional information for SINA as well as a chance to compare with other temperature measurement techniques.

VI. Conclusion

The TIHTUS system, initially developed to combine the complimentary operations of arcjet and inductive plasma sources, has now developed into a platform through which a number of isolated and complimentary performance phenomena may be investigated. The use of alternative propellants, obtainable from heritage and planned space locations as well as from crewed missions, may be investigated under a number of combinations and configurations. Further gains in performance may be obtained through modifications of the system's two stages in order to optimise coupling between the two. All of these campaigns are supported by a number of new passive and active measurement possibilities, as well as a new IPG design to increase to total data yield from the set-up. The end result of these modifications makes TIHTUS a flexible, comprehensive test stand through which a number of new research areas are possible.

VII. Acknowledgements

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