Abstract

The Institut für Raumfahrtsysteme (IRS) of the University of Stuttgart has been investigating magnetoplasmadynamic (MPD) thrusters for several years. These are operated in a steady state mode with currents ranging from 200 A to 8000 A and mass flow rates of different gases varying between 0.3 g/s and 2.0 g/s.

Results with hydrogen as propellant are compared to those with argon and nitrogen with higher molecular weights. The influence of throat geometry variation, i.e., on the one hand a shorter throat length and on the other hand a smaller throat diameter, is investigated.

In addition to the other characteristic data, the pressure in the arc chamber is measured.

The onset oscillations of the plasma, detected with an electrical probe, are analyzed by a Fast Fourier Transformation to get the frequency spectrum.

Parallel to the steady state thruster, a quasi-steady MPD thruster is investigated in order to determine the influence of the mode of operation on the performance. This thruster has the same geometry, electrode materials and gas injection system as the continuous one. The onset point, defined by the appearance of strong voltage oscillations, lies at lower current values at constant mass flow rates than the steady state onset point. Also, the current contour lines are measured and compared with a theoretical model.

II. Steady state MPD-thruster operation

II.1 Thruster Head Configurations

For the first tests the DT2-thruster configuration, shown in figure 1 is used.

The nozzle type thruster performance was improved by geometrical changes, especially a better symmetry of the cathode gas flow shifts the onset of oscillations and anode arc attachment spots to much higher values. Also the efficiencies increase one or two percent from sixteen to eighteen, but a better possibility to improve the thruster performance are shown by experiments with higher mass flows and thus higher electrical power input. They yield a better efficiency in operation of about 23 percent. Even if the power of over 500 kW is not available in space in the next decade, high power MPD thrusters should be investigated and developed for future application.

Simultaneously to the experiments, which determine the characteristic lines of the thruster itself, plasma probes are used to detect the conditions in the plasma plume and numerical codes are developed to model the physical conditions as good as possible.

II.2 Quasi-steady MPD-thruster operation

II.2.1 Thruster Head Configurations

For the first tests the DT2-thruster configuration, shown in figure 1 is used.

The test facilities at the IRS of the University of Stuttgart are well qualified for the investigations of steady state thrusters. For continuous mass flows of 0.8 g/s argon the vacuum system is able to realize tank pressures of about 0.5x10⁻³ mbar. The power system, which is current stabilised, supplies the installed devices with up to 6 Megawatt electrical power. So the most engines, which are a cylindrical one, three nozzle type ones (two for MPD-experiments partially described in this paper, one for simulation of reentry conditions) and two arcjets are operated in this mode. For the comparison of different characteristic values geometrically similar cylindrical and nozzle-type devices are investigated in a pulsed mode with pulse lengths of about two milliseconds.

A difference to former versions of the DT2
thruster type is the much better symmetry of the cathode gas injection, which is reached by assembling four gas connections around the cathode tube plus a distribution ring, made out of a porous brass filter, positioned between gas injection chamber and arc chamber. This improvement has a strong influence on the performance data of the DT2 thruster.

Also indicated in figure 1 are the geometrical variations of the nozzle. Removing the segment 4, with the cathode in its original distance from the exit plane of 85 mm, represents the version DT2A. Moving the cathode forward to a position with a distance of 78 mm from the front plate of the anode, yield the DT2B thruster configuration. When the three throat segments are replaced by segments with a smaller diameter (dashed lines), the thruster is termed DT3.

II.2 Experimental Results (DT2-Geometry)

Contrary to former results without the gas injection improvements, the voltage-current lines (fig. 2) now no longer depend on the fraction of the anode gas mass flow and the onset of oscillation lies at much higher values of the current. So the anode gas seems to stabilize the arc mainly relative to its symmetry axis. The influence of anode starvation as assumed in a theory of Hügel on the onset phenomena seems to be rather weak in the current range from 3.5 kA to 5.0 kA with 0.8 g/s Argon mass flow. In this range the onset is probably more a stability problem as described among others by Schrade at the IRS.

II.3 Variation of the Gas Species

II.3.1 Characteristic Performance Data

With argon (total mass flow of 0.8 g/s with anode gas fractions of 0, 5, 10 and 20%) stable conditions are detected up to 4500 A and the destructive anode spot onset does not appear up to 5000 A (fig. 3). With nitrogen (the same mass flow as with argon, which means a greater number of particles corresponding to the lower molecular weight) oscillations are detected at lower currents (about 4000 A). The comparison of the thrust for nitrogen and argon propellant with the same total mass flow (fig. 4) shows a better performance for nitrogen, also seen in the total efficiency plot (fig. 5).

The unstable behaviour of hydrogen has been reduced by the injection of argon at the anode, in this case 0.05 g/s. The results of hydrogen cannot be compared easily with those of Ar and N₂ because with the chosen mass flow of 0.15 g/s H₂ the number of particles is in this case a factor of about 20 (cold gas) larger than with argon. This mass flow is the highest reachable for the installed mass flow controllers. The curves (fig. 3-6) show that a better thruster performance can be reached with hydrogen in spite of the very high arc voltage of the discharge. The thrust for this low massflow and current is in the same range as for argon, and a higher specific impulse is reached with nearly the same efficiency.
The thrust efficiency is calculated as
\[ \eta = \frac{T^2}{2mUL} \]

Therefore the high efficiency of hydrogen at low specific impulse (fig. 5) is caused by the cold stream enthalpy which is not taken into consideration.

The arc chamber pressure, measured with a Hottinger-Baldwin pressure gauge, depends on the number of gas particles and temperature and is nearly linear over a wide current range (fig. 6).

### II.3.2 Frequency Analysis

The oscillations as mentioned above are analyzed directly by a Nicolet storage oscilloscope with integrated Fast Fourier Transformation function. The frequency spectrum is calculated with a Hanning window function corresponding to the

\[ z(t) = \frac{1}{2} (1 - \cos \frac{2\pi t}{T}) \quad 0 < t < T \]
Two oscillation ranges are detected, for argon and for nitrogen, which include the main peaks: a) the low range between 200 and 600 kilohertz and b) the high frequency range from 1.5 to 2.1 Megahertz. This corresponds to results of other experiments11 which have been detected by Kuriki fairly in the same low and high frequency range with ms pulsed thrusters. A difference to various anode gas fractions was not determined, and the point of oscillation onset only slightly depends on the mass flow of the anode gas. With hydrogen the results are shown in figure 9. The frequencies here are marked in distinguished ranges: 0 - 4 MHz, 2.0-2.6 MHz, 11-12 MHz and 22-23 MHz. The table 1 gives an overview of the oscillation onsets.

<table>
<thead>
<tr>
<th>gas species</th>
<th>I [A]</th>
<th>m [g/s]</th>
<th>( \sqrt[3]{\lambda M A^2 s/kmol} )</th>
<th>( \sqrt[3]{{\lambda M A^2 s/kmol}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>4500</td>
<td>0.80</td>
<td>16.00 ( \times 10^{10} )</td>
<td></td>
</tr>
<tr>
<td>N(_2)</td>
<td>4200</td>
<td>0.80</td>
<td>8.25 ( \times 10^{10} )</td>
<td></td>
</tr>
<tr>
<td>H(_2)</td>
<td>1350</td>
<td>0.15</td>
<td>1.22 ( \times 10^{10} )</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Overview of oscillation phenomenon

M is the molecular weight and N\(_2\) and H\(_2\) are assumed as fully dissociated. The values \( (I^2/\lambda S) \times \sqrt{M} \) are contrary to the results of Hugel not a constant, but different for the various gases.

A theoretical model trying to explain these instabilities uses a linear dispersion relation2 and seems to have a good explanation for the instabilities in the range of the low frequencies.

II.4 Variation of the Thruster Geometry

After varying the kind of propellant, the second step was the changing of the geometry from DT2 over DT2A and DT2B to DT3 thruster head configuration. The results for argon are shown in figure 10 to 13. The voltage-current plot (fig. 10) shows great differences between the small throat DT3 thruster and the other geometries because the arc chamber pressure (fig. 13) is much higher and thus the thrust (fig. 11), especially the thermal part is increased. Since the thrust of the DT2A and DT2B geometries (short nozzle throat and different cathode positions) are fairly the same and the voltage difference grows for currents higher than 2000 A the DT2B thruster has the best efficiency. The DT2 thruster has a better thrust performance but also a higher voltage level, which push the efficiency down.

The operating range of the DT3-nozzle is limited by the steep increase of the arc chamber pressure, which causes an unstable behaviour of the arc above 1500 A. Although the thrust is much higher than of the DT2-types, the efficiency is quite low because of the higher arc voltages.

Figure 11 Thrust-current dependence for a mass flow of 0.8 g/s (10% anode gas fraction)

![Figure 11](image1)

Figure 12 Efficiency-I\(_{sp}\) dependence for a mass flow of 0.8 g/s (10% anode gas fraction)

![Figure 12](image2)

Although the DT2B geometry has the better performance data with a mass flow of 0.8 g/s, the 2.0 g/s tests show a worse behaviour of this MPD accelerator. Indeed
the voltage (fig. 14) is lower for the DT2B-geometry, because the length of the arc is shorter, but the arc chamber pressure (fig. 17) jumps to a relative high value after ignition and grows only slightly with increasing current. Thus the voltages (fig. 14) approach each other for lower currents. So the comparison with 2.0 g/s argon mass flow for the DT2 and the DT2B configuration seems to show advantages for the DT2 thruster, because the efficiency (fig. 16) is quite constant at 23% over a wide range of specific impulse and about two percent higher than those of the DT2B. In spite of these differences the efficiency of the 2.0 g/s DT2B thruster assembly is still three to five percent higher than for the 0.8 g/s DT2 operation.

Figure 15 Thrust-current dependence for a mass flow of 2.0 g/s (10% anode gas fraction)

Figure 16 Efficiency-I specific impulse dependence for a mass flow of 2.0 g/s (10% anode gas fraction)

In figure 18 to 21 the parameter is the relatively small mass flow of 0.3 g/s. The characteristics have fairly the same forms as for the higher mass flows and the variation from DT2 to DT3 thruster type. However, the steep rise of the voltage occurs at 2400 A for the DT2 geometry for 0.3 g/s according to the onset value of \( I^2/\rho \) of 1.92\( \times 10^{10} \) A²s/kg, for 0.8 g/s at 4500 A (2.53\( \times 10^{10} \) A²s/kg) and for 2.0 g/s at 7300 A (2.66\( \times 10^{10} \) A²s/kg). This implies that for this thruster type the critical \( I^2/\rho \) value is not a constant but a function of the mass flow. With higher mass flows the onset phenomenon seems to drift to higher current values thus improving the whole thruster performance.
II.5 Variation of the Mass Flow

For the DT2 thruster configuration a variation of the mass flow between 0.3 g/s and 2.0 g/s yields very different performances of the MPD devices. The high propellant flow with its necessary high power input up to 640 kW in these experiments causes on the one hand higher voltages. On the other hand the arc chamber pressure, and so the thermal thrust and the electromagnetic thrust are much higher than as compared with the low flow. Hence the efficiency increases in a very promising way for future high power experiments (fig.22-25).
According to OT2-geometry, the DT2 and DT3 thrusters have fairly the same patterns of the characteristic lines between two different massflows (fig.22-33). In all cases the lower mass flow yields the lower voltage trace which is nearly parallel to the higher mass flow trace until it reaches the onset region. Then it cuts the other line because of its steeper rise.

Figure 22 Voltage-current dependence for DT2 thruster head configuration

Figure 23 Thrust-current dependence for DT2 thruster head configuration

Figure 24 Efficiency-Isp dependence for DT2 thruster head configuration

Figure 25 Arc chamber pressure-current dependence for DT2 thruster head configuration

Figure 26 Voltage-current dependence for DT2B thruster head configuration
Only in the experiments with the DT3 nozzle the cutting point in the voltage-current lines was not reached, because the operational current range for the narrow throat DT3-type is limited. For a massflow of 0.8 g/s the arc became unstable at 1500 A (fig. 30), when the arc chamber pressure reaches a value of about 350 mbar (fig. 33). With 0.3 g/s the heat flux into the throat segment exceeds 7 kW/cm² (fig. 34), which is the limit for this construction. Although the thrust (fig. 31) is higher than with all other configurations, the efficiencies (fig. 32) are rather bad because of the high voltage (fig. 10, 11).

![Figure 27 Thrust-current dependence for DT2B thruster head configuration](image)

![Figure 28 Efficiency-Isp dependence for DT2B thruster head configuration](image)

![Figure 29 Arc chamber pressure-current dependence for DT2B thruster head configuration](image)

![Figure 30 Voltage-current dependence for DT3 thruster head configuration](image)

![Figure 31 Thrust-current dependence for DT3 thruster head configuration](image)
The Quasi-Steady MPD Thruster

The cylindrical pulsed MPD thruster is described in another paper\(^2\). The nozzle type quasi-steady operating thruster\(^3\) works at higher voltages (fig. 35) than the geometrical similar steady-state DT2-thruster. The thrust (fig. 36) is measured with a pendulum balance\(^4\). The measured values are scattering especially beyond the onset point, which is defined with the occurrence of strong voltage fluctuations\(^5\). The onset phenomena appears at \(1 \times 10^{10}\) \(\text{A}^2/\text{s/kg}\) (for the well-known I²/q correlation factor) for 0.8 g/s argon and drifts to \(1.5 \times 10^{10}\) \(\text{A}^2/\text{s/kg}\) for an anode gas fraction of 10%. It coincides with the "knee" in the double-logarithmically plotted voltage-current curve. The continuous devices do not show any spreading of the voltage-current lines depending on the anode gas fraction. However, a weak dependence of the oscillation onset is seen, which is here not identical with the break point and occurs at \(2.5 \times 10^{10}\) \(\text{A}^2/\text{s/kg}\).

The thrust of the quasi-steady thruster lies beneath that of the continuous one in a current-range lower than its onset current but gets higher for currents above onset. This may be caused by a higher mass flow due to ablation of thruster materials for the operation above onset conditions.

The great advantage of pulsed operation mode is the possibility to measure the plasma plume conditions with inductive probes\(^6\). Especially the current contour lines (fig. 37) can be calculated easily from the distribution of the magnetic B-field. The comparison with a theoretical model\(^7\) shows a fairly good agreement for the current of 2500 A. The assumptions made in this two-dimensional electron-adiabatic ion expansion and a boundary electron temperature of 10000 K.
Concluding Remarks

Regarding the results of the experiments with different gas species, hydrogen is the best propellant for missions, whose boundary conditions require a high specific impulse. With the quite good efficiency of about 15% a specific impulse of about 16 km/s can be realised. Also hydrogen is available on the most space vehicles and the technique of handling is well known. Only the problem of the unstable behaviour by the operation in an MPD device must be solved in the next years. For thrust applications, argon seems to be well qualified because for a wide current range the efficiency is nearly constant. Also it has a well-behaved operation characteristic and is easy adjustable. Nitrogen yields also a good thrust performance but its optimal working range is limited at an Isp of about 12 km/s where a distinct maximum of the efficiency exists.

The variation of the geometry with constant mass flows yields no definite statement for a certain geometry. It depends also on the mass flow but a higher mass flow leads in all experiments to better performance data, so that for future tests the optimal relation between the geometry and the mass flow should be investigated. Likewise for the different configurations the kind of propellant should be changed and the mass flows and thus the corresponding electrical power input should be increased.

For the quasi-steady MPD thruster the characteristic data are rather bad and the operation beyond onset in relation to anode spots, cathode erosion, insulator ablation and asymmetrical discharge is difficult for space applications. Nevertheless, experiments with this type of thruster should be continued to compare the working modes and to get results for the conditions in the plasma plume.

References


