Medium Power Arcjet Analysis and Experiments

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Abstract

This paper reports the investigations and test results of a 5-20 kW arcjet. The objective is to gain more insights into the operating conditions and to develop a flight oriented device with good efficiency and high specific impulse. A 5-20 kW radiation cooled arc jet thruster was developed and tested with hydrogen and a mixture of hydrogen and nitrogen, simulating hydrazine. The nozzle geometry and the electrode configuration are the same as in a previously investigated watercooled version. The characteristics of the two devices are compared. The influence of the ambient tank pressure on the operating characteristics were investigated for the radiation cooled device. A numerical temperature analysis has been performed with a finite element programming system. The simulation involves convective heat transfer of the flowing propellant and radiation interchange on the solid surface. The results are compared with temperature measurements, obtained with a pyrometer at the radiation cooled anode.

To gain more insight into arcjet operation a window was inserted in the nozzle throat of a modified watercooled 5-20 kW thruster. With a fast CCD-Camera images of the arc were taken and with image processing methods the fluctuation of the arc and the arc dimensions were determined for different working conditions. Preliminary temperature profiles of the arc in the constrictor are presented, based on intensity measurements of the Hα and the Hβ lines.

Introduction

In an arcjet the electric arc discharge increases the enthalpy of the propellant flow through a supersonic nozzle. The thruster consists of coaxial electrode systems which support an electric discharge within an axial gaseous propellant stream. The Joule heated gas or plasma is accelerated by thermal expansion. In the nozzle the thermal energy is converted into directed kinetic energy and thereby produces thrust. Thus it is possible to achieve specific impulses magnitudes which are higher by a factor of two compared to that of conventional thrusters. This holds even without the need to redesign propellant storage and feed systems.

In the early 1960’s development efforts were conducted on arcjet thrusters in the range of 1-200 kW using a variety of propellents, including nitrogen, hydrogen and ammonia. Many theoretical investigations and basic research on arcjet operation were started by Giannini Scientific Corp. [1] and AVCO Corporation [2]. Because space power sources were not available at that time to provide the required power, work on arcjet thrusters was terminated in the mid 1960’s.

Recently, the low power (1-2 kW) class has been reevaluated for application in the north/south station keeping for geosynchronous communication satellites. In the USA a flight type 1.4 kW system has been fabricated and life and performance tested [3]. In Germany a program to develop a 1-2 kW hydrazine arcjet was started in 1990 [4] and in Italy a comparable program is going on since 1988 [5]. In addition to the low power programs medium and high power arcjets are also being reconsidered for primary propulsion. A significant effort has been directed towards the development of a 26 kW ammonia arcjet that is scheduled for a near term flight test in the USA [6]. Most activities have focused on 10-30 kW devices with hydrogen as propellant for orbit transfer missions in which long term cryogenic hydrogen storage is not essential or with hydrazine as propellant. Such arcjet propulsion systems may offer considerable propellant weight savings over chemical systems for LEO to GEO orbital transfer missions. The weight savings may permit the reduction of launch vehicle requirements to the next smaller class of rockets.
At the Institut für Raumfahrtsysteme work on a 15 kW arcjet under subcontract from the ESA was started in 1986 leading to a water cooled laboratory device. The contract ended in 1990. Based on that experience, a 5-20 kW radiation cooled arcjet thruster was developed and tested with hydrogen and a mixture of hydrogen and nitrogen, simulating hydrazine as propellant [7].

The main heating of the propellant takes place in the constrictor. The more of the propellant is heated up to high temperature, the better an efficiency will be reached. This means that the arc should fill nearly the whole constrictor and that the temperature profile should be uniform across the constrictor. To investigate the arc dimension and the temperature profile in the constrictor under working conditions a model of the IRS watercooled thruster was modified to observe the arc in the constrictor by using a fast CCD camera. This investigation provides a better understanding of arcjet operation and gives support for arc jet thruster model calculations.

Radiation Cooled 5-20 kW Arc Jet Thruster Experiments

The Thruster

A schematic of the radiation cooled thruster is shown in Fig. 1. The concept of the design is based on the ARTUS thruster presented in [4]. The electrode and nozzle configuration is similar to the basic configuration of the watercooled device TT1 described in [7]. The constrictor is 2.5 mm in diameter and has a length of 5 mm. The contour is conical with an expansion half angle of 17.5° and the expansion ratio is 1:100. The design concept allows for an easy exchange of the critical components and the investigation of other nozzle geometries by changing only one single part. The radiation cooled anode is machined from 2% thoriated tungsten and sits in a molybdenum housing. Between the cathode and the housing there is a boron nitrite insulator. The cathode is machined from 2% thoriated tungsten, has a 30° half angle and is 6 mm in diameter. It is press fitted into a stainless steel cathode feed tube. The propellant is fed in at the rear of the thruster through the cathode feed tube, cooling the backside of the cathode. This tube measures 6 mm in diameter with a 3 mm bore hole. The propellant is fed into a ring channel between the housing and the boron nitrite insulator, and to the injector ring, cooling the housing and the boron nitrite insulator. The propellant is finally injected tangentially into the plenum chamber through four holes with 0.5 mm in diameter.

Fig 1: Radiation Cooled 5-20 kW Arc Jet Thruster

The Test Facility

The thruster is mounted on the IRS thrust balance described elsewhere [7]. The thruster and the balance are integrated in a stainless steel tank with 1.25 m in diameter and a length of 4 m. The IRS vacuum system, the power supply, gas supply system and the starting procedure are described in [7] in more detail. It is possible to measure under computer control voltage, thrust, current, mass flow and pressure in the feed line of the propellant close to the thruster.

For temperature measurements on the hot anode a linear pyrometer, type LP2 from IKE Stuttgart, is used. The accuracy is 0.1%. The emissivity of the tungsten anode was chosen as 0.4 at a wavelength of 961.3 nm.

Experimental Results

Hydrogen as Propellant

Test runs were conducted with 50, 100, and 150 mg/s pure hydrogen as propellant. Figs. 2-4 show the results. The thruster was started at a power level of 10 kW and operated until thermal equilibrium was reached. Then a new current level was set and again kept constant until equilibrium. The depicted points are the points at thermal equilibrium.

For a constant mass flow rate the voltage decreases only slightly with increasing current. (Fig. 2). The voltage rise between the 50 mg/s mass flow rate and the 100 mg/s compared to the increase between the 100 mg/s and the 150 mg/s is much more pronounced although the increase of the line feed pressure is in both cases about 1.7 bar. The line feed
pressure is for the 50 mg/s in the range of 2.5 bar, for the 100 mg/s about 4.2 bar and increases for 150 mg/s to 5-6 bar.

In this definition of the thrust efficiency the contribution of the cold gas enthalpy to the thrust is not considered. At lower power and high mass flow settings that part is not negligible but difficult to incorporate.

The specific impulse with hydrogen was higher than 1000 s at a specific power of more than 150 MJ/kg. (Fig. 3). The thruster was operated from 6 kW to 11 kW for 50 mg/s, to 17 kW for 100 mg/s and 20 kW with 150 mg/s. Thus, for the lower mass flows more than 200 MJ/kg specific power were achieved without operational problems so that it will be possible to achieve higher specific impulse at higher specific power levels.

The efficiency ranges from about 35% for the higher power levels up to 45% for the lower power levels. The efficiency is calculated according to eqn 1.

\[ \eta = \frac{P^2}{2m \cdot P_{el}} \]  

cqn. 1

Fig. 2: Voltage versus Current with Hydrogen as Propellant

Fig. 3: Specific Impulse versus Specific Power for Hydrogen as Propellant

Fig. 4: Thrust Efficiency versus Specific Impulse for Hydrogen as Propellant

Hydrogen-Nitrogen Mixture as Propellant

A second possible propellant for space applications is hydrazine. As a first step in this direction a premixed gas with 33.3 vol % nitrogen and 66.6 vol % hydrogen was investigated. As shown by [4] it is not possible to draw direct conclusions from cold gas simulated hydrazine tests to actual hydrazine performance. Nevertheless, cold gas tests can be used to evaluate the basic performance of a thruster design.

Experiments were conducted with mass flow rates of 200 mg/s, 300 mg/s and 400 mg/s. The current was varied from 50 A up to 175 A. The voltage (Fig. 5) shows a similar behavior compared with pure hydrogen and at higher currents the slope becomes positive. For the 200 mg/s the voltage is lower and has a typical arcjet characteristic.

Because the power levels in these experiments were the same as those for pure hydrogen and the mass flow rates were higher, the specific power range was lower as can be seen in Fig. 6. The specific impulse is lower, too and ranges from 400 s up to nearly 600 s at higher power. The line feed pressure was about 3.5 bar for 200 mg/s, 6 bar for 300 mg/s and 7.5 bar for 400 mg/s and increased for all mass flow rates with about 100 mbar/kW.

The thrust efficiency is lower compared to pure hydrogen (Fig. 7). With 200 mg/s the efficiency is much lower, only about 30% in contrast to the other investigated mass flows, the specific impulses are the
same. This indicates that with this device and the mixture as propellant better operating conditions are achieved with mass flow rates larger than 200 mg/s.

Fig 5: Voltage versus Current for the N₂+2H₂ Mixture as Propellant

Fig 6: Specific Impulse versus Specific Power for the N₂+2H₂ Mixture as Propellant

In Fig. 8 the equilibrium temperature at the anode surface measured with the pyrometer is depicted. The pyrometer was focused on a point 3 mm from the nozzle end at the outer surface of the tungsten anode. With increasing power the anode temperature increases linearly and with higher mass flows the heat input to the anode is smaller. A maximum anode temperature of 1800°C was observed. Because the anode is made of thoriated tungsten, higher temperatures could be sustained so that with this device higher maximum power levels will be run in the future. The anode temperature is higher with the mixture than with pure hydrogen at the same power which confirms the better thermal efficiency measured with the watercooled thruster [7].

Influence of the Ambient Pressure on the Operating Conditions

An experiment was conducted to investigate the influence of the ambient pressure on the operation characteristics. The mixture with a mass flow rate of 300 mg/s was used. The thruster was ignited and the current was set at 100 A. This corresponds to a power level of 10.5 kW. The thruster was heated up until equilibrium was achieved at the lowest ambient pressure. That pressure was 0.047 mbar. Then the ambient pressure as increased in steps up to 6 mbar. The influence on the voltage and the thrust is depicted in Fig. 9. As can be seen a change of the ambient pressure has no significant influence on the voltage. On the thrust, however, an influence was detected. The decrease in thrust corresponds directly to the thrust calculated from the tank pressure multiplied with the exit plane area. In Fig. 9 the connected points are calculated by subtracting this pressure force from the thrust at the
lowest pressure. The result agree very well with the measured thrust.

Fig 9: Thrust and Voltage versus Ambient Tank Pressure for 300 mg/s \(N_2+2H_2\) Mixture at 100 A

Comparison of the Results with the Watercooled Thruster TT1

In Figs. 10-13 typical measurements of the watercooled TT1 thruster, presented in [7] and measurements of the geometrically similar radiation cooled thruster are depicted. The comparison of the current voltage characteristic is shown in Fig. 10. With hydrogen the characteristic shows the same shape but is about 60 V higher for the water cooled thruster. With the \(N_2+2H_2\) mixture the slope for the watercooled device is steeper and is approaching the values of the radiation cooled thruster at higher currents. These characteristics indicate that the anode fall for a cold anode is larger and that less energy is necessary in the hot radiation cooled device in order to sustain a plasma near the anode. This result does not agree with the measurements of the a 2 kW thruster presented in [8]. There, it was found that the voltage of a watercooled thruster was lower than that of a radiation cooled device. But those thruster were run at other operation points and had a different nozzle geometry and arc pressure.

Figs. 11 and 12 show specific impulse versus the specific power for the two propellants. The water cooled thruster data follow the same trend as the radiation cooled thruster data, but the data are shifted by a nearly constant amount. The difference between the two thrusters is 320 s for 100 mg/s hydrogen at 100 MJ/kg and 140 s for the 300 mg/s \(N_2+2H_2\) mixture at 40 MJ/kg. For both propellants the low investigated mass flow rates have a smaller slope for both thrusters. The increase agrees with the results presented in [8]and [9], but the increase is larger than that of 196 s at 150 MJ/kg at 0.015 mg/s presented in [8] and the about 200 s presented in [9] with hydrogen as propellant. Thus with an increase in specific impulse a higher thrust efficiency is expected. In Fig. 13 the thrust efficiency as function of the specific impulse is depicted. It is shown that the water cooled thruster converts only 15-20 % of the input electric power into thrust power while its radiation cooled counterpart converts 35-42%. This means an increase of about 20 % in thrust efficiency. In the hot wall thruster some of the energy input into the anode regeneratively heats the incoming gas. None of the input power for the cold wall thruster is converted regeneratively since the incoming temperature is equal to the wall temperature.

Fig. 10: Comparison of the Current Voltage Characteristic

Fig. 11: Comparison of Spec. Impulse versus Spec.. Power Hydrogen as Propellant

The regeneratively heated incoming gas creates an increased inlet pressure. With the radiation cooled thruster it was not possible to measure the arc chamber pressure, but the line feed pressure near the thruster was measured (Fig. 14). This pressure is expected to be higher because of friction losses in
the feeding line. This increase pressure is necessary to sustain a constant mass flow in the hot thruster. Although the operating characteristics of watercooled and radiation cooled devices are quite different, data obtained from water cooled thrusters are very useful to determine general operating conditions, performance trends and theoretical insights into physics of the system.

Fig. 12: Comparison of Spec. Impulse versus Spec. Power for N$_2$+2H$_2$ Mixture as Propellant

Fig 13: Comparison of Thrust Efficiency versus Specific Impulse

Fig 14: Comparison of the Pressure

Numerical Analysis

It is of engineering interest to investigate for a given design the temperature distribution in the solid part of the arcjet and the propellant passing through the annular channel. In conjunction with measurements, the prediction of the temperature distribution, which exerts a strong influence on durability of critical components as well as on the effectiveness of the thruster, leads to an improvement of design and performance. The numerical analysis is performed with the finite element programming system SMART developed at the "Institut of Computeranwendungen", University of Stuttgart.

The analysis makes use of a simplified axisymmetric model, neglecting detailed design features, e. g. seals, and idealizing the geometry of the propellant supply. Furthermore, the propellant flow is not taken into consideration from the injector ring downstream through the nozzle.

The thermal analysis includes heat conduction in the solid structure, conduction and convection in the gas flow and radiation on the surface. The finite element grid is shown in Fig. 15.

Fig 15: Finite Element Grid of the Radiation Cooled Thruster

The hydrogen mass flow rate is set to 100 mg/s. Thus, the Reynolds number is Re=85, the Prandtl number is Pr=0.7. The gas flow is approximated by a prescribed parabolic velocity profile. Changes in physical properties of the fluid due to the temperature rise are not taken into account. Mean values for specific heat capacity and thermal conductivity are given at a specified temperature. The physical properties of the different materials used in the thruster are given as functions of temperature. The coefficients of emission are assumed to be constant.

The thermal load input along the diverging nozzle and cathode is determined from measurements of the heat flux distribution in the watercooled device TT1. The first calculation was performed with a total heat load on the anode of 1.65 kW and 50 W on the cathode tip. The calculated temperature distribution
is illustrated in Fig 17. In this case the physical properties of the fluid were taken at $T=20^\circ C$.

In Fig. 16 the result is compared with temperature measurements at the anode 3 mm upstream from the nozzle tip. It can be recognized, that the calculated temperature is lower than the measured one even from the beginning of the heating period. This was taken as an indication that the prescribed heat load had been too small. In a second calculation the heat load was set on the anode to 1.95 kW, at the cathode to 61 W. In addition the specific heat capacity and thermal conductivity of the propellant were taken at $T=427^\circ C$ in order to get more realistic conditions. Fig. 16 now shows a good agreement between computed and measured temperature during the heating period. As a consequence the heat load on a radiation cooled thruster appears to be about 20 % higher than with the watercooled version. This can be explained by higher heat conduction from the gas to the nozzle, because the gas is heated up by the hot thruster. In addition there is radiation inside the nozzle from the glowing walls.

The results (Figs. 17,18) show that there is a large cooling effect at the backside of the thruster and the propellant is heated to $880^\circ C$ in case 2. This means that about 1.2 kW are transferred into the propellant by heat conduction so that only about 600 W are thermal loss. These it is 1 kW less than with the water cooled thruster, so that one can say that the thermal efficiency with a radiation cooled thruster is higher. These results agree with the measurements presented in [8]. There it was found that with hydrogen 6-12% of the input power was recovered regeneratively and converted into thrust while the radiation losses ranged between 4% and 20%.

The numerical investigation of the temperature distribution revealed the necessity of taking the convective heat transfer into consideration in order to get realistic results [10]. Pure heat conduction and radiation do not cover the significant cooling effect of the flowing propellant.
Observations of the Arc inside the Constrictor

The theoretical models for the description of arcjets [11] rely on certain assumptions for the characteristics of the electrical discharge. In order to obtain some direct data on the shape, size and stability of the arc channel inside the constrictor, a modified version of the watercooled TT1 thruster was built. Looking into the constrictor section with a high-speed digital video system, it became possible to study some of these features in near real time. In addition, preliminary studies were performed regarding the feasibility of temperature measurements using this two-dimensional imaging technique.

The Modified Thruster

The standard TT1 watercooled thruster is built as a stack of coaxial ring segments which define the contour of the injection chamber, the nozzle throat and the expansion section. All segments have separate water cooling loops to preserve the engine's modularity. Electric arcing between adjacent segments is suppressed through the use of ceramic spacers which create a gap of 0.5 mm. In the modified thruster, the two segments which form the constrictor section are replaced by a single segment. Two radial holes on opposite sides of this segment serve as viewpoints which permit the direct observation of the arc burning inside the throat. The holes have a diameter of 2 mm which should be compared to the dimensions of the constrictor (diameter: 2.5 mm, length: 5 mm). Thus, almost the complete channel is observable. The axial position of the viewports is 2.6 mm downstream of the cathode tip.

In the regular mode of observation, only one viewport is used for optical access through a quartz glass window. The other access port holds a pressure gauge to measure the pressure inside the constrictor, another quantity of interest. Nevertheless, this second hole is also required for the optical access since it helps to suppress reflections inside the channel. In an earlier single hole version, these reflections made quantitative optical measurements impossible. The overall configuration of the modified thruster is depicted in Fig. 19.

The Optical Acquisition System

In order to observe the discharge in the constrictor channel, a high-speed video camera is used in connection with a magnifying borescope (Fig. 19). The camera (DICAM-2, PCO Computer Optics) consists of a regular CCD video module (768x512 pixels) coupled to a microchannel plate intensifier (MCP). The MCP has two functions: it can amplify the received image and it works as a very fast optical shutter with exposure times down to 100 ns. These two features make it possible to look at the very bright discharge without any other filters for intensity control and to acquire short exposures at frame rates up to 6 frames/sec. A video digitizer (DT2855, Data Translation) is used to sample the images which are then available for on-line processing and storage on an IBM PS/2 P70 portable computer. The borescope (H100-12HM25, Olympus) has a working distance of around 54 mm and a magnification of 50, thus creating a sufficiently large image for the MCP camera. The complete camera/borescope assembly is mounted on a linear traverse driven by a stepper motor. Using this mechanism, the camera can be retracted from the viewport for filter changes and positioned with a high degree of repeatability. The motor as well as the camera can be remotely controlled to allow for gain, exposure and focus adjustments while the engine is running.
Experimental Procedures

During an experimental run, the arcjet is ignited with the camera in a retracted position for safety reasons. Once the arcjet has reached its operating point, the camera is moved into position. First, images are taken without any optical filters, giving a broadband view of the arc. Besides standard recording on video tape, two line profiles (256 pixels each) across the arc column are sampled and stored directly in the computer for later post-processing and analysis. Usually 200 exposures are recorded to obtain a large enough sample for statistical processing. Figs. 20-23 show video frames for two different runs with the line profile positions indicated by the vertical line markers. For the temperature analysis, this procedure is then repeated with two interference line filters in front of the borescope. In the first pass, a filter centered on the $H_a$ line in the hydrogen spectrum is used, the second filter run looks at the line emission of the $H_p$ line. The MCP gain is held constant for both filter runs to avoid ambiguities caused by potential nonlinearities in the camera's intensity response. All measurements are taken with a fixed exposure time of 100 ns.

Fig. 20: Arc in Constrictor with 100 mg/s Hydrogen at a Current of 50 Amps

Fig. 21: Arc in Constrictor with 200 mg/s Hydrogen at a Current of 50 Amps

Fig. 22: Arc in Constrictor with 300 mg/s $N_2 + 2H_2$ Mixture at a Current of 50 Amps

Fig. 23: Arc in Constrictor with 400 mg/s $N_2 + 2H_2$ Mixture at a Current of 50 Amps

Analysis of General Arc Behavior

The first conclusion which can be drawn from the results is that the arc does not fill the constrictor completely. There is a rather large cold gas layer surrounding the hot discharge core for both the pure hydrogen case as well as for the mixture. Similar experiments with argon as the propellant show a different behavior (Fig. 24). Here the discharge does fill the whole constrictor. The total emitted light intensity is generally smaller. After a few seconds, the hole starts to close up due to deposition of material, indicating a strong interaction between the hot plasma and the walls in the argon case. This observation is supported by the fact that the overall current voltage characteristic of the arcjet does not change in the hydrogen and mixture cases upon insertion of the observation holes, whereas it is altered for argon.

Fig. 25 shows the current voltage characteristic for different runs with the window assembly. There is almost no difference to the results presented in [7] for the standard TT1 thruster. The pressure readings are presented in Figs. 26 and 27. As should be expected, the pressures are smaller inside the constrictor than in the upstream injection section. The observed pressure ratios might be useful as input to some of the theoretical models of arcjet operation.
taking the 200 single exposures as the data ensemble. In order to compensate for the fluctuating behavior of the arc, the averaging was done following a shift of the individual profiles to eliminate their relative centerline displacements.

Arc Fluctuations

Using the short exposure times of the image acquisition system, significant fluctuations of both the position of the arc within the constrictor channel and of the discharge width were observed. An attempt was made to analyze these fluctuations more closely as they can provide a measure for the overall arc stability. Fig. 28 shows a single line profile along one of the scan lines crossing the discharge column. In order to eliminate the noise superimposed on the profile, a form signal averaging was applied, usually
results are consequently based on the shift-averaged line profiles.

![Graph showing intensity vs. arc radius for different propellants and currents.](image)

Fig. 29: Comparison of an Averaged and a Shifted and Averaged Intensity Profile

The magnitude of the arc position fluctuations is directly related to the standard deviation of the detected profile centerline estimates. Fig. 30 shows the standard deviation of those fluctuations, normalized with the average profile width (1/e edge intensities).

![Graph showing standard deviation vs. current for different propellants and currents.](image)

Fig. 30: Fluctuation of the Centerline

One notices that the magnitude of the fluctuations increases with increasing mass flow for both the pure hydrogen and mixture cases. Similarly, there appears to be a trend towards more stable arcs (smaller standard deviation) with increasing currents. It is interesting to note, however, that the fluctuations in the arc position are smaller than those in its width (see below). Since the analysis of both profile scans taken from the video frames show the same magnitude of the fluctuations, it appears that the arc motion within the constrictor is most of the time a simple lateral shift and not so much, say, a tilt.

The Arc Diameter

An analysis similar to the one for the arc position was also performed on the arc diameter. For this, the profile width was detected in the raw line scans using a thresholding criterion based on the maximum intensity. Fig. 31 shows the thresholds using 1/e maximum intensity fraction being used for the final results.

![Graph showing intensity vs. arc radius for different propellants and currents.](image)

Fig. 31: Illustration of Arc Width Criteria

This detection criterion yields course arbitrary width estimates but the dependencies on current and mass flow should be detectable in a consistent manner.

In Fig. 32 the results are depicted for both propellants. One sees that the arc diameter increases with increasing current but that it decreases with increasing mass flow. Regarding this latter trend, it should be kept in mind that an increase in mass flow is accompanied by a large increase in pressure (Figs. 27, 28). There also appears to be a trend for the second profile to be slightly broader than the first one for hydrogen as propellant. Since the second profile was 0.3 mm further downstream of the cathode tip - which is 2.13 mm upstream of profile 1 - , this means that the arc is expanding slightly. The same analysis was done for the profiles in the case of the hydrogen/nitrogen mixture. Fig. 32 also presents these results. Again, an increase in arc diameter with increasing current can be observed as well as the decrease with mass flow. No systematic difference between the upstream and downstream profiles could be detected. For the N₂⁺₂H₂ Mixture and the 200 mg/s pure Hydrogen the arc diameters are nearly identical. The variation in arc diameter as a function of mass flow rate is smaller for the mixture than for pure hydrogen.
sample of 200 scans for each wavelength. These profiles were further smoothed through application of a spline fit and processed by an inverse Abel transformation [12] in order to convert the line-of-sight integrated intensities into true radial profiles. A word of caution appears necessary regarding the data reduction procedure described above. First, the temperature equation (2) implies the existence of two isolated spectral lines. This is not precisely true for the arc emission since there exists also broadband background radiation which will contribute to the emission intensities passed by the interference filters. It is assumed that this background is sufficiently small and that the intensity ratio will not be affected too much. Nevertheless, a clear isolation of the effect will require a separate measurement of the continuum emissions. A second problem arises from the assumption of optical transparency of the plasma, which has to be satisfied for the applicability of the Abel inversion. It could be possible that the discharge column is optically "thick" (absorptive) which would mean that one does not obtain line-of-sight integrations but only a view of the hot outer layers of the plasma column. While model computations using the known plasma parameters might clarify this question independently, it was felt that the validity of the Abel transform can also be deduced from the self-consistency of the final inversion results. This approach gains some credibility from the fact that the inverse Abel transform at a fixed radial position depends only on the integral of the input profile from that same position on outward. Thus, the outer regions of the discharge column can always be restored since they are colder and, most likely, optically thin. Problems might only arise for smaller radii and require the introduction of a lower cutoff radius below which the Abel inversion will not be valid any more. The results of the Abel inversion of the intensity profiles for the Hα and Hβ lines at different discharge currents are shown in Fig. 33, a run with 100 mg/s pure hydrogen. One recognizes that for large radii (>40 in the units of the figure) the radial intensities increase with increasing current and that the arc radius is consequently growing as well. For smaller radii, on the other hand, this trend is reversed and the intensities are in some cases actually smaller than in the outside region. This could be due to a growing number of ionized hydrogen atoms at high temperatures which would radiate broadband and not at the frequencies of the electron's bound-bound line transitions. Another explanation for this effect could however also come

Temperature Analysis

In addition to the direct arc profile analysis, an attempt was made to determine the temperature profiles inside the discharge channel. As was mentioned above, the arc emissions were measured not only in the broadband mode but also through two narrowband interference filters centered around the two strongest hydrogen lines Hα (656 nm) and Hβ (486 nm). The filter width of 10 nm is sufficient to include the frequency shifts due to the Doppler effect and Stark broadening [12]. Under the assumption of local thermal equilibrium (which should be valid in the channel due to the high pressures involved) the gas temperature can be derived from the emission measurements for two spectral lines,

$$T_{ex} = \frac{1}{k} \ln \left[ \frac{E_2 - E_1}{\gamma \left( \frac{l_1}{l_2} \right)^{\lambda_1} \left( \frac{l_2}{l_1} \right)^{\lambda_2}} \right]$$

(eqn. 2)

Here, $E_{l,2}$ are the excitation energies of the lines, $g_{l,2}$ the statistical weights $f_{l,2}$ the absorption oscillator strengths and $\lambda_{l,2}$ the wavelengths. The emission intensities $I_{l,2}$ are used to compute a ratio which has to be rescaled in order to compensate for the unequal transmission coefficients of the filters and imaging optics. The correction factor $\gamma$ was determined in a separate experiment using a calibrated black body radiation source ($T=1875K$) and the unmodified optical measurement setup filter/borescope/camera. The intensity profiles were extracted from the line scan profiles as described above, using the shift-and-average technique on a
from the presence of an optically thick plasma at least in the inner part of the arc column, as was discussed above. Such an interpretation is augmented by the observation that the intensity profiles before the Abel inversion (Fig. 28) show a marked flat top characteristic for small radii. This feature is particularly strong for the Hα lines and tends to become more pronounced for larger currents. The Hβ line shows the same behavior somewhat later, that is for higher currents. It can be shown that such flat top profiles will lead to an oscillation in the Abel inversion similar to the observed overshoots. In order to obtain a conservative estimate, the temperatures computed with eqn. 2 from the Abel inverted intensities should be considered valid only in a reduced radial range, say, beyond r > 0.32 mm (Fig. 34).

The same data reduction was performed for an experimental run with the hydrogen/nitrogen mixture at 300 mg/s. Fig. 35 shows the Abel inverted profiles for Hα and Hβ at the two scan line positions (profile 2 is downstream) at a current of 50A. The inversion results for a run with 70A (not shown) are again affected by the intensity drop phenomenon described for the pure hydrogen case. Since no such drop is visible for the 50A case, one might expect a valid temperature computation across the whole radial range. The two temperature profiles are presented in Fig. 36. They are similar, with the downstream distribution showing higher values across the whole profile. Although this might be caused by the continuing heat input into the gas by Joule heating in the arc, the size of the temperature increase is within the tolerance limits of the measurement and cannot be cleanly attributed to such an effect. The drop in the temperature for small radii is present in both the upstream and downstream profiles. As was explained, it is in this case less likely due to the optical thickness effect. Instead, it could be due to the depletion of the hydrogen line emitters, or, since we are dealing with a mixture, due to a growing amount of ionization in the nitrogen which would reduce the energy deposition into the hydrogen component.

Based on this evidence, the temperature calculations in the discharge column seem to provide at least some rough estimate for the magnitudes involved. The computation of complete profiles - which might be even more important for modelling purposes - seems to require more supporting evidence from additional measurements since certain assumptions in the numerical procedure cannot be verified unambiguously.
Conclusions

This paper reported on different experiments performed to enhance the understanding of basic arcjet functionality and operation. The design and comparative use of actively and passively cooled versions of the same arcjet geometry provided insights into the basic heat transfer and energy balance mechanisms. A numerical model for the thermal behavior of the system augmented and confirmed these results. A conclusion is that, in order to achieve maximum performance the thruster should be run at the highest temperatures the materials will allow.

Finally, a direct observation and analysis of the discharge column in the constrictor section provided spatially resolved data in this crucial part of the arcjet assembly. It was shown that the arc doesn’t fill the constrictor and that there is a cold gas layer surrounding the hot arc column as assumed in calculation models like the Dual Channel Model. The arc investigation indicates, that the optical thickness of the $H_\alpha$ and $H_\beta$ lines for normal operating conditions of the thruster is neither "thick" nor "thin" but in the transition regime. Therefore radiation transfer calculations should to be included in computation schemes which could create problems due to the theoretical difficulties in solving the radiation transport equations.

It is hoped that the evidence provided by this paper will help in the creation of a refined global model for the behavior of arcjets and that future enhancements, especially in spectroscopic temperature measurements, will eventually lead to a successful interpretation even on the microscopic level.

References


Fig. 36: Temperature Profile for 300 mg/s Hydrogen/Nitrogen Mixture, Current 50 A