1 kW Ammonia Arcjet System Development for a Science Mission to the Moon

IEPC-2005-075

Presented at the 29th International Electric Propulsion Conference, Princeton University
October 31 – November 4, 2005

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Abstract: This paper presents first steps for the development of a thermal arcjet system for a science mission to the moon. A first approach for a propulsion feed system as well as results accomplished during tests with a laboratory model of the thermal arcjet ARTUR-2 are introduced. The tests were done at different power levels from 0.9 up to 1.5 kW at mass flows between 10 and 15 mg/s hydrogen. The cathode gap was kept constant at 0.8 mm during all tests. The constrictor diameter is 0.6 mm. The highest effective exceeded exhaust velocity was 8 km/s at a thrust efficiency of 32%.

Nomenclature

$\eta_T$ (%) thrust efficiency
$\eta_{T,th}$ (%) theoretical thrust efficiency
$F$ (N) thrust
$P_{el}$ (W) electric power
$F_{cold}$ (N) cold gas thrust
$I_{sp}$ (s) specific impulse
$\dot{m}$ (mg/s) mass flow

I. Introduction

The Institute of Space Systems (Irs), University Stuttgart, launched the "Small Satellite Program" in 2002. In this context four satellite missions are planned: An earth-sensing satellite (Flying Laptop), a satellite for technology demonstration of electric propulsion systems (PERSEUS), a reentry demonstration satellite (CERMIT), and an all electrical satellite mission to the moon (Bw1). In this context all electrical satellite system refers to the propulsion system of the Bw1 satellite, which will consist of two different parts: a cluster of instationary pulsed magnetoplasmadynamic thrusters (I-MPDS) and a thermal arcjet thruster in the 1 kW class with ammonia as propellant. Both thruster systems are developed and qualified at Irs.

The use of arcjets for North-South station keeping of geostationary satellites has been state-of-the-art for more than one decade. The new approach is the use of a combination of a cluster of instationary pulsed magnetoplasmadynamic thrusters – SIMP-LEX (Stuttgart Instationary Magnetoplasmadynamic Thruster for Lunar Exploration) – and a thermal arcjet as propulsion unit for a university satellite to the moon.

The flight to the moon is divided into four distinct phases: Phase one starts from GTO and lasts until the spacecraft perigee is raised above the outer van-Allen-belt. Phase two stretches from there to the sphere
of the Moon; phase three extends to the stable elliptical lunar capture orbit at an altitude of about 1400 km above the lunar surface and the final phase inserts the satellite into a circular polar mission orbit at an altitude of 100 km around the Moon.

To minimize the time satellite spends inside the van-Allen-belt and therefore also to reduce possible radiation damage to the solar panels and electronics on board the satellite, the thermal arcjet thruster, as the "high thrust" propulsion unit (approx. 100 mN), will be used during phase one. As during phase three the forces by the earth, the moon and the sun nearly cancel out the influence of perturbations on the satellite orbit increase resulting in a higher demand of thrust during this mission phase. Therefore, the thermal arcjet thruster will be used during this mission phase. During the other mission phases solely the I-MPDS will be used for propulsion.

The thermal arcjet system development includes numerical simulations of the plasma flow, thermal simulations of the thruster, experiments under space environment conditions and the development and space qualification of an appropriate propellant feed system.

II. Propellant Feed System

For the development of an appropriate propellant feed system first studies were accomplished at IRS. The main task of the propellant feed system is to supply gaseous ammonia for injection into the thermal arcjet. Special interest during the first studies was placed on possible difficulties in providing gaseous ammonia inside the complete pipeline system behind the gas generator. This is due to the fact that the propellant will cool down after vaporization and possibly become a mixture of gaseous ammonia and saturated steam. This resulted in the requirement that the ammonia must be gaseous behind the gas generator to guarantee proper functioning of the thruster.

The propellant feed system is designed for a mass flow of 20 - 25 mg/s ammonia. The experience from the development of a 750 W thermal arcjet with ammonia as propellant for the satellite mission AMSAT-P3D5 points at a mass flow between this range. The exact required mass flow for the lunar mission Bw1 will be defined during the optimization phase of the thermal arcjet thruster. The feeding will be conducted by the pressure difference between the tank and the point of injection into the thruster. The pipelines are made of stainless steel.

As the propellant feed system will be developed and qualified at the IRS, the structure is being kept as simple as possible. A first concept of the propulsion feed system is shown in Fig. 1.

![Figure 1. Sketch of propellant feed system](image)

A check valve directly behind the tank, where the ammonia is stored as a mixture of gaseous, liquid and saturated steam, opens and closes the propellant flow. The ammonia mixture will be completely vaporized by the gas generator. Two control valves behind the gas generator compensate pressure variations by generating a pressure buffer zone within the volume between them (plenum). Doing so keeps the pressure just in front of the flow aperture within a given range to guarantee the desired mass flow, which is adjusted by a defined...
To guarantee the requirement that only gaseous ammonia is allowed behind the gas generator the temperature and pressure of the ammonia in the pipelines will be measured by pressure transducers and thermocouples so that the pipelines can be heated if necessary. Based on this concept the requirements for the different elements of the propellant feed system were defined and a laboratory model is currently being built to perform first system tests.

### III. Experiments

The approach to develop a thermal arcjet system for the lunar mission Bw1 is to perform an optimization of an existing laboratory thermal arcjet model with regard to the requirements of the lunar mission. The step after the optimization will be the development of an engineering model under consideration of the optimization results according to the design of the engineering model ARTUS (Fig. 9).

The thruster used for all experiments described here is a modified laboratory model called ARTUR-2 (Arcjet Thruster University Stuttgart Regeneratively Cooled) with a radiation cooled nozzle. Figure 2 shows the structural design of the thermal arcjet ARTUR-2. The gap between cathode and anode (cathode gap) can easily be adjusted by a screw. The whole thruster can be disassembled so that different nozzle configurations can be tested. To characterize the thruster and its sensitivities the first tests, which are described here, were carried out with hydrogen as propellant. After the characterization and identification of the sensitivities of the thermal arcjet, ammonia will be used as propellant.

The aim of the experiments was to identify the operation parameters of the thruster as a function of mass flow and current. For this reason the mass flow was varied between 10 and 15 mg/s and the current between 10 and 15 A. Figure 3 shows the thruster during operation. The cathode gap (0.8 mm) and constrictor diameter (0.6 mm) were kept constant during the tests.

#### A. Experimental Setup

At IRS there are two test facilities especially dedicated to developing and qualifying thermal arcjets in the power range between 0.5 and 2 kW. For the development and qualification of the thermal arcjet system for the Bw1 mission one of the facilities is used for the test of the propulsion feed system and life-cycle tests later in the project.

The test facility as shown in Fig. 4 consists of a cylindrical vacuum chamber made of stainless steel 1.2 m in diameter and 2 m in length. Its own 3-stage roots pumping system with a pumping speed of approx. 13000 m³/h provides a background pressure of $10^{-3}$ hPa prior to the tests and less than 0.2 hPa at thermal arcjet operation with mass flows up to 15 mg/s hydrogen.
Figure 5 shows the scheme of the thermal arcjet test facility at IRS. The propellant is fed from a bundle of hydrogen gas bottles or one ammonia gas bottle through pipelines made of stainless steel. The measurement and adjustment of the mass flow is carried out by different mass flow controllers for the different gases (Tylan MFC Typ 280 for hydrogen and Tylan MFC Typ 280S for ammonia). They were calibrated by direct weight measurement with a so-called "sartorius-balance".

The current supply of the thermal arcjet is accomplished by special flight-oriented PCU equipment. It provides a decent current of 0 A up to 25 A and a switch voltage of about 1500 V. The thrust measurement is realized with a pendulum-type thrust stand by measuring the deflection of the pendulum on which the thruster is mounted with a non-contact displacement sensor (NCDT). A set of known weights is used to calibrate the thrust stand previous to every experiment. Optical access to the thruster during the tests is possible through windows inside the tank walls. Control and data acquisition is accomplished by a PC.

**B. Results**

The results presented in this section were achieved during different tests. The graphs and numbers shown here are representative for all the conducted tests. Figure 6 shows the voltage as a function of the current exemplary for the results attained.

The voltage varies between 90 V at a mass flow of 10 mg/s and a current of 12.36 A and 103 V at a mass flow of 15 mg/s and a current of 9.33 A. Here, the characteristic typical for thermal arcjets – decreasing voltage with increasing current – can clearly be seen. Figure 7 shows a representative result of the thrust vs. input power during different operating conditions.

With the mass flow \( \dot{m} \), the measured thrust \( F \) and the electrical power \( P_{el} \) of the thermal arcjet, the thrust efficiency \( \eta_T \) can be calculated. Equation 1 gives the equation usually applied for calculating the thrust efficiency. For thermal arcjets of low power, the cold gas thrust has to be considered for the calculation of the thrust efficiency, according to equation 2.

\[
\eta_T = \frac{F^2}{2\dot{m}P_{el}} \tag{1}
\]

\[
\eta_{T,\text{th}} = \frac{F^2}{2\dot{m}P_{el} + F_{cold}^2} \tag{2}
\]

The calculation of the received thrust efficiency for a mass flow of \( \dot{m} = 12 \text{ mg/s} \) and \( \dot{m} = 10 \text{ mg/s} \) according to equation 2 and the specific impulse \( (I_{sp}) \) according to equation 3 leads to the results presented in Table 1.
Figure 6. Voltage vs. current characteristic for hydrogen

Figure 7. Thrust vs. input power characteristic for hydrogen

\[ I_{sp} = \frac{F}{\dot{m} g_0} \]  

One can see that the characteristic typical for thermal arcjets of decreasing thrust efficiency with increasing specific impulse is present.\(^6\)
Table 1. Measured \( (F, I, \dot{m}) \) and calculated \( (\eta, I_{sp}) \) performance values

<table>
<thead>
<tr>
<th>( \dot{m} ) (mg/s)</th>
<th>( I ) (A)</th>
<th>( \eta_T ) (%)</th>
<th>( \eta_{Th} ) (%)</th>
<th>( F ) (mN)</th>
<th>( I_{sp} ) (s)</th>
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<tr>
<td>10</td>
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</table>

IV. Summary and Outlook

Experiments with hydrogen as propellant at different mass flows between 10 mg/s and 15 mg/s and power ranges between 980 W and 1.6 kW were conducted. The cathode gap was 0.8 mm and the constrictor diameter 0.6 mm. The maximum exit velocity was 8 km/s at a thrust efficiency of 32%. The results indicate that the thruster ARTUR-2 shows the typical characteristic of thermal arcjets. Furthermore, a stable ignition behavior was retained during the conducted tests.

For further tests the cathode gap will be varied and different nozzle geometries will be examined. In this context optical temperature measurement of the nozzle temperature by means of a pyrometer and an infrared camera will be integrated in the tests. As a next step tests will be conducted with ammonia as propellant to define an optimal working point for the thermal arcjet under consideration of the requirements for the lunar mission Bw1.

The development of an engineering model under consideration of the results of the optimization will be following the optimization process of the thermal arcjet ARTUR-2 laboratory model. The design of the engineering model will be based on that of the engineering model of the thermal arcjet ARTUS (Fig. 8 and 9).

Figure 8. Structural design of engineering model

Figure 9. Picture of engineering model ARTUS

For the flow simulation of the thermal arcjet a numerical program called SINA developed at IRS will be used. This program allows the modeling of flows which are of high enthalpy, viscous and turbulent. At present only calculations for hydrogen, argon and nitrogen are possible.\(^8\) For the calculations of ammonia the chemical processes inside the plasma plume during thermal arcjet operation have to be developed and implemented. The numerical simulations have the temperature distribution on the thermal arcjet elements as output data. This will be the input for the thermal modeling. Thermal modeling of the arcjet will be conducted by use of the commercial finite-element-program called ANSYS.

For the thermal modeling first a geometry model inside ANSYS will be built up. The geometry will be modeled as rotation-symmetrically constructed for reasons of simplicity.

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