Development of a 1 kW class thermal arcjet thruster TALOS

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The thermal arcjet TALOS (Thermal Arcjet Thruster for Lunar Orbiting Satellite) as laboratory model has been developed, operated, and characterized at the Institute of Space Systems (IRS) of Stuttgart University. After first optimization investigations had been conducted with respect to the requirements of the lunar mission BW1, the laboratory model operates stably with a maximum thrust efficiency of 33 % at 800 W, reaching about 100 mN and 525 s specific impulse depending on the mass flow rate. Still further optimization and concepts have to be investigated to increase the current performance. For this purpose a new laboratory model based on the TALOS LM1 has been designed. The performance of TALOS LM1 and the new design of TALOS LM2 are presented in this paper.

I. Introduction

For more than three decades, arcjet thrusters within the power range from below 1 kW up to 100 kW input power have been developed and extensively investigated at IRS using hydrogen, simulated hydrazine, and recently also ammonia. Thereby specific impulse and efficiency of up to 2000 s[1] and thrust efficiency of 45 %[2] could be achieved (note that these data are referred to two different operation points and thrusters). Recently the development has focused on 1 kW class thrusters, since an arcjet with maximum 1 kW input power has been considered as primary propulsion for the lunar mission BW1 projected at the IRS.[3] Due to storage problem of hydrogen and the toxicity of hydrazine, ammonia will be used as propellant. Since ammonia is stored as a mixture of gaseous, liquid, and saturated steam, an advanced ammonia gas feed system with integrated vaporizer has been developed and built.[4] For the power condition the appropriated AMSAT-FM PPU, a heritage of the ATOS thruster, provides 4 kV start-up pulse and maximum 10 A thrust current in steady state operation. With the first laboratory model, TALOS LM1, some geometry optimization was conducted in reference 5. Thereby difficult starting procedures, causing a great amount of anode erosion, were encountered. But after successfully applying a soft staring approach, the anode erosion could be minimized. Now we are considering advanced concepts, which promise significantly improvements in thruster performance. Since the TALOS LM1 has a few drawbacks and restriction respect to the further investigation, a new laboratory model has been designed.

II. TALOS LM

A. Design

In figure 1 the cross section of TALOS LM1 is shown. It consists of a cathode with its bracket, a rear and front housing including gas inlet, nozzle, injector, ceramic insulators, and a compression spring. The ceramic insulator between the cathode bracket and rear housing is joint by electron beam. Due to the very high temperature of the nozzle, the front housing is made of TZM, a molybdenum alloy, and acts as thermal

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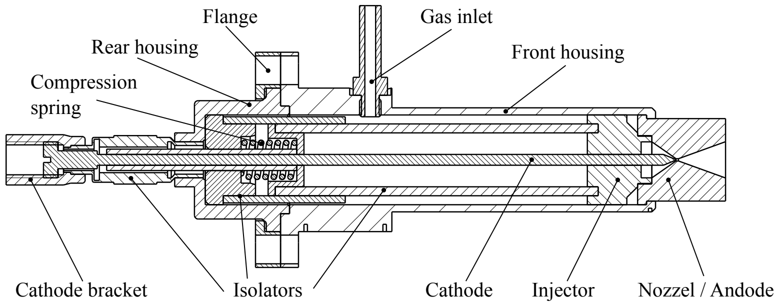


Figure 1. Cross section of TALOS LM1.

barrier between the nozzle and the pendulum thrust balance. The nozzle and injector are modular in design, so that these parts can be investigated independently from each other. Nozzles are made of tungsten alloys and have been investigated in terms of anode erosion.[6] Injectors are made of boron nitride, withstanding high temperature, are easily to manufacture, and act as insulator.

In order to assemble the thruster the nozzle, injector, and insulators have to be led through the front housing. At the junction of the housing and nozzle a graphite ring is inserted. By bringing front and rear housing together, the spring compresses the nozzle against the housing, squeezing the graphite ring and sealing the junction. Rear and front housing are braced by standard screws and nuts. The advantage of this technique is the simple design. The high temperature issue at the nozzle junction is solved smartly. But the assembly is complex, involving many risk to damage the thruster. The complexity also causes long preparation and assembling time. In order to change the nozzle or the injector the thruster has to be disassembled completely. For the geometry investigation of nozzle and injector, whereby the nozzle and the injector has to be changed frequently, this approach does not match the requirement. The fact that the nozzle has to be led through the housing also restricts the diameter of the nozzle to the inner diameter of the housing.

B. Anode erosion

Since the starting procedures of arcjets is significant in terms of anode erosion, many publications are related to this issue.[7–11] In the past anode erosion limited the life cycle of TALOS LM1. Usually after ignition the arc attaches in the subsonic region, where the pressure is still high causing spotty arc attachment resulting in high local heat load and damages on the anode. Pushing by the gas dynamic force of the propellant flow, the arc attachment moves through the constrictor into the supersonic region, where it attaches diffusely. This transition process takes a certain time depending on the gas dynamic force directly related with the

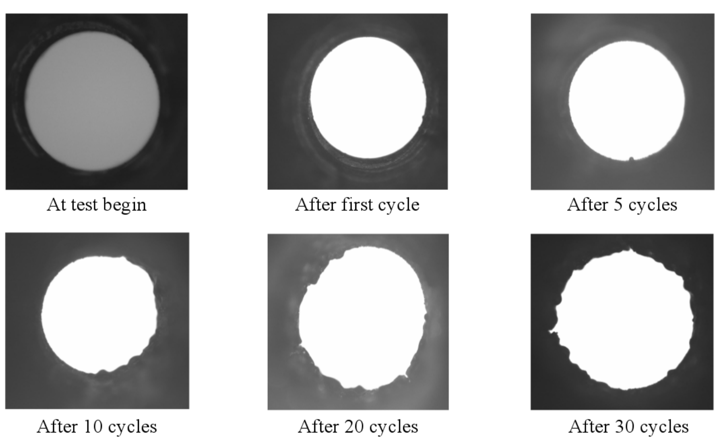
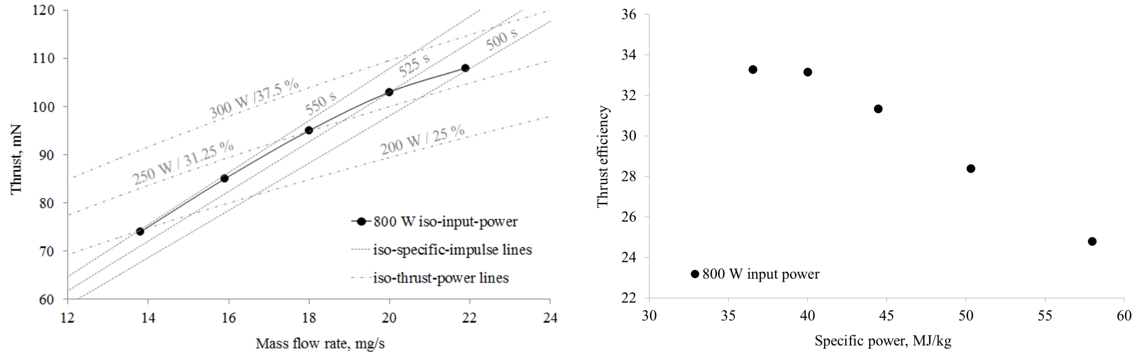


Figure 2. Anode erosion using tungsten lanthanum oxide alloy (WL10)[6] as anode material.



(a) Thrust to mass flow rate diagram with iso lines (b) Thrust efficiency with constant 800 W input power

Figure 3. Performance of TALOS LM1 using ammonia.

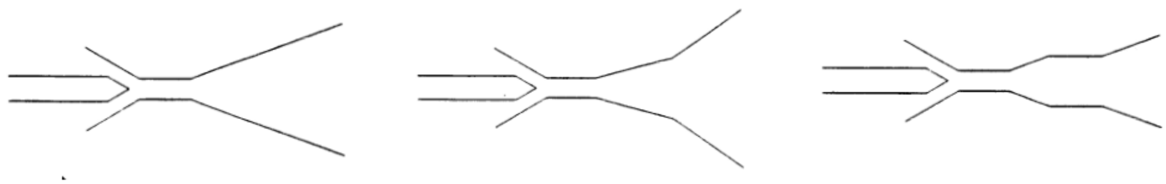
mass flow rate. Investigation about anode erosion of TALOS LM1 with respect to the anode material was performed in reference 6. The test was conducted with 30 cycles of one hour operation followed by one hour cool down. Optical control after 1, 5, 10, 20, and 30 cycles has been done and shown in Fig. 2. One can see that both the shape and size of the constrictor has been changed only after 10 cycles. The results for tungsten thorium oxide alloy and tungsten-rhenium alloy are similar or even worst. It is reported that in the first few minutes after ignition the thruster operates unstable and anode material coming out of the nozzle has been observed. It can be assumed that the nozzles sustained most erosion in these starting procedures.

A soft-starting approach utilizing a pressure pulse immediately after the ignition was developed by LeRC.[7] The pressure pulse increases the gas dynamic force, thereby reducing the transition time and anode damages. Recently a similar technique is applied for TALOS LM1. Shortly before sending a high voltage pulse to start the thruster, the mass flow rate is doubled. The timing is set, that the pressure pulse should arrive the nozzle immediately after the arc just broke down, pushing the arc attachment through the constrictor into the supersonic area. A preliminary experiment of 100 ignitions in series has shown that the anode erosion could be reduced significantly using this approach. Also no material coming out of the nozzles has been observed. The transition time for reaching steady-states operation could also be reduced to lower then 10 s.

C. Thruster performance

In this section the performance of TALOS LM1 is discussed . It is shown in a thrust over mass flow rate diagram in Fig. 3(a). This diagram provides a set of important information. Since the specific impulse is the quotient of thrust and mass flow rate, the iso-specific-impulse lines are straight lines through the origin. The iso-thrust-power lines are square root functions. These lines can be shown additively to the diagram revealing the specific impulse range of the thruster. In case the performance of the thruster is presented as iso-input-power lines, the thrust efficiency can also be read from the diagram. Assuming that future spacecraft will operate with power limited continuous burn propulsion the thrust over mass flow ratio diagram consists lots of information for the mission analysis. There are many operational points leading to the fact that the system has an envelope which also highlights the throttle ability. This information will be fed as restricted condition for mission analyse tools, which will determine the optimal operation point of the thruster for the given mission.

In figure 3 the performance of TALOS LM1 is presented with a 800 W iso-input-power line. Unfortunately due to a breakage of the ceramic insulator between the cathode bracket and rear housing just one iso-input-power line can be presented. Still this line shows the typical tendency of arcjets. With decreasing the mass flow rate, meaning increasing the mass specific power by keeping the input power constant, the iso-input-power line moves downwards to lower iso-thrust-power line, being equivalent to decreasing thrust efficiency. The decrease of the thrust efficiency can be clearly seen in Fig. 3(b).



(a) Conventional nozzle concept (b) Dual cone angle nozzle (c) Nozzle with energy recovery chamber

Figure 4. Schematic drawings of different nozzle design.[12]

III. Considering advanced concepts

The frozen flow and thermal losses amount to the greatest fractions of the overall losses within arcjet operation. Reducing these losses would take the greatest effect on the thrust efficiency. Thermal losses could be reduced e.g. by regenerative cooling. But just only propellants with high thermal capacity, such as hydrogen or helium, have a significant impact. Correspondingly, structural adaptations in particular in the nozzle zone come into focus for the assessment of this purpose. The Electric Propulsion Laboratory, Inc. (EPL) summarized that using dual cone angle nozzle (also called bi-exit nozzle) or energy recovery chamber the frozen flow losses could significantly reduced. The schematic drawings of these nozzles and conventional nozzle are shown in Fig. 4. All nozzles of TALOS LM1 belong to the conventional concept.

In comparison to conventional nozzle both dual cone angle nozzle and nozzle with energy recovery chamber provide an intermediate pressure zone directly after the constrictor. Also the dwell time in this regime is higher due to the smaller expansion compared to conventional nozzle concept. This facts leads to significant conversion of chemical energy back into kinetic energy of the gas flow. The intermediate zone also results in a higher arc voltage, up to 50 % for a given configuration compared to conventional nozzles.[12,13]

Rocket Research Company developed a hydrogen thruster with regenerative cooled dual cone angle nozzle (they called it bi-exit nozzle).[14,15] The thrusters operated at 10 kW input power reaching 1150 s specific impulse with 39 % thrust efficiency using ammonia. The EPL also developed a thruster with dual cone angle nozzle operating with hydrogen reaching a specific impulse of 1,295 s at an efficiency of 43.6 % and an input power of 5.16 kW.[12] Compared to this hydrogen thrusters (MARC) developed at IRS reached 1282 s at an efficiency of 36.3 % and an input power of 9.8 kW. The development of dual cone nozzle thrusters at the EPL led to a design with a regenerative cooling nozzle with energy recovery chamber and a corresponding patent.[16] Still the development of these concepts is at the very beginning. Optimizing this concept seems promising great improvement in performance. Hence a geometry study with TALOS nozzles applying these concept is planned.

A concept using an applied magnetic field, established by an electromagnetic coil, at and round the constrictor areal will considered. The coil is arranged so that the magnetic eld in the subsonic and constrictor area is axial and homogeneous. The axial magnetic field gives the arc a drift, preventing a spotty arc attachment in the subsonic area causing grave erosion. Furthermore, it is expected that the starting process rapidly reaches steady state operation. Thrustes operating with subsonic arc attachment use this approach to drift the arc attachment preventing local damage of the anode.[17,18] A subsonic arc attachment is not considered for TALOS but the influence of a magnetic field on the thruster's performance, thermal behaviour, and life time issue will be investigated.

IV. Design of the new model

Due to its drawbacks discussed above the TALOS LM1 has been modified to the second laboratory model, the TALOS LM2. Its cross section is shown in Fig. 5. The cathode bracket and the rear housing remain unchanged. Just the gas inlet has been moved from the front housing to the rear housing. This gives less restriction to the front housing for further modification. For the front housing graphite has been selected as material, due to its thermal resistivity, easily machining, and low cost compared to TZM. The insulators just have been adapted to the new design. Instead of using the compression force, generated by the spring,

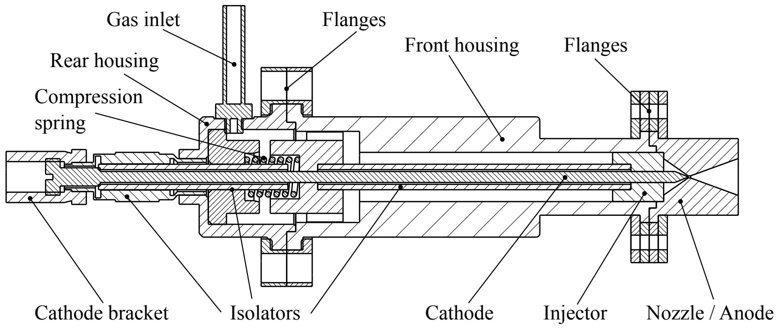


Figure 5. Cross section of TALOS LM2.

flanges will be applied to joint and seal the junction of the nozzle and housing. Now the spring just have to compensate manufacture tolerances, resulting in reduced compression forces to the ceramic component. A thermal analysis conducted in reference 6, whereby the nozzle surface temperature has been measured below 1000 °C at the input power of 800 W and a mass flow rate of 25 mg/s. It can be assumed that the temperature of the housing and the flanges will also be below 1000 °C. Concerning this high temperature resistive screws and nuts have to be applied here.

With the new design restriction of TALOS LM1 can be avoided. The flange joint type gives quick accesses changing the injector and the nozzle, such that it can be rapidly changed saving assembly and disassembly time and costs, being an important factor for the geometry parameter study of advanced concepts. Furthermore, since the nozzle do not have to be led through the housing, its dimension is no more restricted to the inner diameter of the housing. In terms of thruster performance, excluding the thermal aspect, there are no significant discrepancies expected with respect to TALOS LM1, since the nozzle geometry, cathode, and the configuration remain the same.

V. Conclusion

In this paper the design of TALOS LM1 and its performance was presented. Operational conditions shown are reference for BW1 and starting point of further optimisation. For this purpose TALOS LM2 has been developed and designed. High flexibility is given enabling a quick plug and play feature. This allows an easy and fast experimental assessment of design change impacts e.g. with respect to the operational behaviour of TALOS. In the near future the dual cone angle nozzle and the energy recovery chamber will be experimentally investigated with an geometry study promising higher performance.

Acknowledge

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