

3D Thermal Simulation of a μ N-RIT

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Thermal behavior and electromagnetic losses of thrusters are of magnificent relevance for the high demands of space missions. Therefore, we built up a full 3D thermal and a 2D rotationally symmetrical electromagnetic model of a miniaturized radio frequency ion thruster μ NRIT-2.5 (Fig. 1) by using the commercial program COMSOL Multiphysics®. Using the electromagnetic simulation, power deposition in all components were determined. The thermal simulation includes the thermal conductivity between the components as well as the thermal radiation and irradiation of different surface texture. For the verification of the model we performed simulations and compared them with thermal measurements. The comparison was done for various thruster settings.

Nomenclature

E_c, E_1, E_2	= Young's modulus
$\vec{E}$	= electric field
h_c	= thermal conductance
j	= current density
k_c, k_1, k_2	= thermal conductivity
m	= effective root mean asperities slope
m_e	= electron mass
p	= pressure
T_{bottom}	= temperature of the bottom of the thruster housing
T_{bridge}	= temperature of the connecting bar inside the thruster
T_{chamber}	= temperature of the plasma chamber
T_{top}	= temperature of the top side of the thruster
T_{CS}	= temperature of the contact surface
σ_c	= root mean square of the surface roughness
ν_1, ν_2	= Poisson ratio

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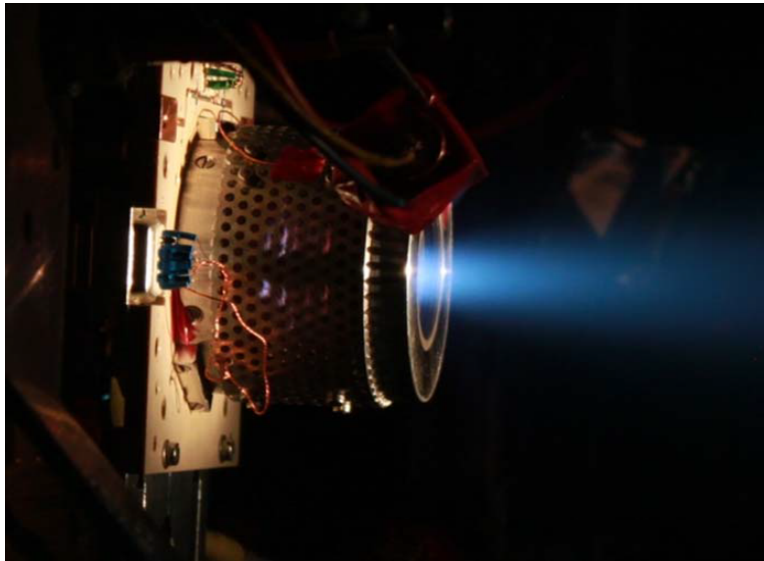


Figure 1. Miniaturized radio frequency ion thruster μ NRIT-2.5

I. Introduction

THE technology of radio-frequency ion thrusters (RIT) provides the possibility of very precise thrust control. This can be achieved by controlling the plasma's productivity through the variation of the rf-power and the adjustment of the extraction and acceleration voltage of the grid system. This ability of a thruster is necessary for many common space missions. Especially formation flying missions need an extreme fine positioning and a precise attitude control of the spacecraft. The new field of mini ion engines of RIT type are investigated at the University of Giessen in cooperation with EADS-GmbH since the year 2004^{1,2}.

Due to the small size of the spacecraft in such missions the available power is quite limited. Therefore the main focus lies in increasing the electric efficiency of the thrusters. For optimizing the power consumption a comprehensive modeling of the thrusters is necessary. A complete modeling of such type of thrusters is now under development at the University of Giessen. The thermal modeling is one of the main parts of this modeling procedure. It is important for three reasons:

The thermal model of the thruster is necessary to ensure the functionality of the thruster in the whole thrust range and in the different mission phases. In this case the thermally critical components should be distinguished and the thermal design should be adapted to avoid their overheating.

Generally thrusters are the hottest elements on a spacecraft. The thermal load of the thruster to the spacecraft should be designed according to the requirement catalog of the spacecraft designers.

The thermal modeling of the thruster can give information about the electric power dissipation in the thruster. So, one more power equation arises in the consideration of the thruster-plasma combined system.

This paper concentrates on the third aspect. A thermal model from a construction point of view is done by TAS-I and EADS-Astrium.^{3,4}

II. The Program COMSOL Multiphysics®

To analyze the thermal behavior of the μ NRIT-2.5 we use the program COMSOL Multiphysics®. COMSOL is a simulation program, which is based on the finite element method. It offers the option to describe multi-physical processes by coupling of different physical modules. For the simulation of the RIT-thruster, following modules are used:

For the thermal simulation we employ the heat transfer module and to determine the power deposition into all parts we are using the AC/DC-module.

Although it is possible to simulate inductive coupled plasmas with COMSOL, but in the case of our RIT we have to use another method to identify the power deposition into the plasma. For thin plasmas fluid equations are invalid, because the Knudson number is too large. The Knudson number is the ratio of the mean free path of particles to the characteristic size of the system.

III. Thermal Simulation

As far as the RIT technology needs for operating vacuum conditions convective effects do not occur the heat flux. To describe the thermal behavior of the thruster, it is therefore sufficient to consider only thermal conduction and heat radiation and define heat sources and heat sinks. The thermal conduction of the parts of the thruster and between them is described by Fourier's law. The radiation between the surfaces of the thruster and the walls of the test facility is given by Stefan-Boltzmann law.

Furthermore, it is very important to analyze each thermal contact resistivity between two touching parts. In COMSOL it is possible to use the plastic as well as the elastic model for the contact conductivity. We utilize the elastic model, which requires the following input parameters⁵

p : pressure between the surfaces in contact

k_c : effective contact conductivity

$$k_c = \frac{2k_1k_2}{k_1 + k_2} \quad (1)$$

where k_1 and k_2 are the thermal conductivity of both contact materials

σ_c : effective root mean square of the surface roughness

$$\sigma_c = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (2)$$

where σ_1 and σ_2 are the RMS of each surface

m_c : effective root mean asperities slope (see figure [2])

$$m_c = \sqrt{m_1^2 + m_2^2} \quad (3)$$

where m_1 and m_2 are the average slopes of the two material

E_c : effective Young's modulus for the contact interface,

$$\frac{1}{E_c} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad (4)$$

where E_1 and E_2 are the modulus of elasticity and ν_1 and ν_2 are the Poisson ratio of the two material.

With these parameters the thermal contact conductance h_c can be calculated using the following relation⁵:

$$h_c = 1.54k_c \frac{m_c}{\sigma_c} \left(\frac{\sqrt{2}p}{m_c E_c} \right)^{0.94} \quad (5)$$

The radiative conductance of the interfaces can be neglected, as long as the temperature of the surfaces is below 600°C^{5,6}.

In the above quantities the pressure between two contacting surfaces has a great influence on the conductance of the interface. The real contact pressure between all the parts of the thruster cannot be calculated exactly or measured directly. It has to be estimated by the forces, which are exerted by screws and bolts.

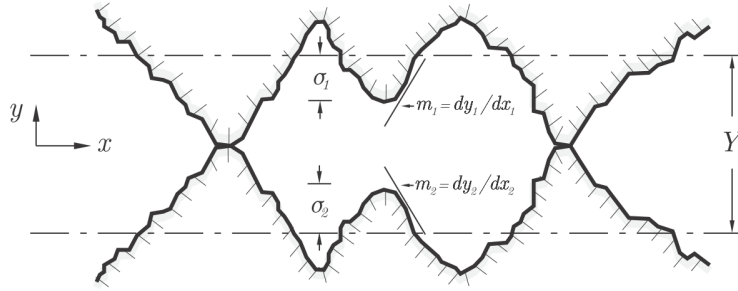


Figure 2. Graphical representation of absolute surface slope m and the RMS surface roughness σ_c : Picture from⁶

IV. Power Deposition

Before starting the thermal simulation we have to localize the heat sources inside the thruster. Except at the contact surfaces to the test facility, there is only one heating mechanism inside the thruster, called inductive heating. The time varying electric field $\vec{E}$ generated by the coil induces eddy currents inside the materials. Due to ohmic losses inside the materials, these parts heat up. The induced eddy current j is given by the Ohmic law:

$$\vec{j} = \sigma(T)_{el} \vec{E} \quad (6)$$

The power deposition inside the materials can be estimated by the Poynting theorem⁷:

$$P = \frac{1}{2} \int \text{Re} [\sigma(T)_{el}] |\vec{E}|^2 dV \quad (7)$$

where $\sigma(T)_{el}$ is the electrical conductivity of the materials which depends on temperature.

V. Simulation Model

Our full simulation model consists of two different parts: one electromagnetic simulation and one thermal simulation.

Using the electromagnetic simulation we investigate the heat sources inside the thruster. Due to the rotation-symmetrically construction we use a 2D model with one symmetry axis. The great advantage of using this symmetry is that the simulations take significantly less time. But to have a comparison we built up a full 3D electromagnetic simulation. Furthermore, the electromagnetic simulation includes the complete matching circuit. The circuit is necessary to get the correct power transfer from the radio-frequency generator to the coil.

The thermal simulation model is made up of all three dimensions. The simulation includes nearly all parts of the thruster and only a few were slightly changed. The model contains the radiation between all main surfaces. The radiation to the environment is defined as a radiation to a fictive surface with an ambient temperature and an emissivity equal to one. Furthermore, the thermal model considers the contact resistance between the main touching surfaces. Physical properties of all parts and surfaces, namely round about 90 parts with over 3000 surfaces, were allocated. Finally, the thermal model was adjusted in such a way, that the whole behavior can be controlled with a few physical parameters and boundary conditions.

VI. Verification of the Simulation

To verify the thermal model, we have performed temperature measurements of the thruster without plasma for different input powers. For this task we utilize the four-wire sensing method and PT-100 sensors. The measurements and the simulation results for two different power settings are shown in table 1 and table 2. The given temperatures from the simulation are average values of the examined surfaces. The location of the temperature sensor is as follows (see Fig. 3): T_{chamber} is the temperature of the plasma chamber, T_{top} is the temperature of the top side of the thruster, T_{bottom} is the temperature of the bottom of the thruster

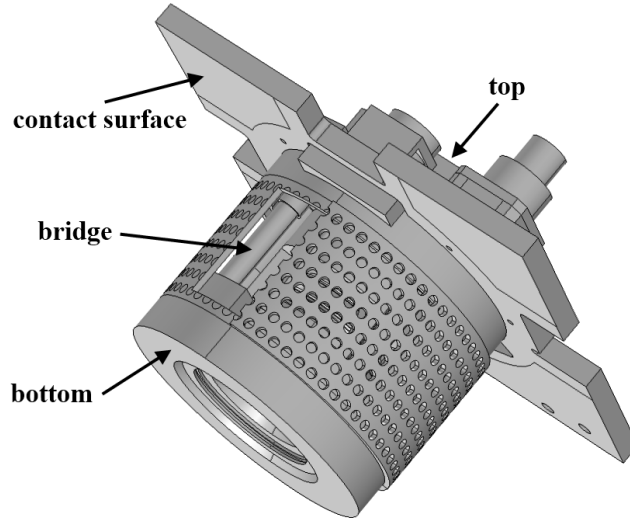


Figure 3. Location of temperature sensors on the thruster μ NRIT-2.5

housing. T_{bridge} is the temperature of a connecting bar inside the thruster and T_{CS} is the temperature of the contact surface to the test facility. The given power values P_{thruster} are corrected by the efficiency of the radio frequency generator (RFG).

P_{thruster} :	5.1 W		
	measured	simulated	relative deviation
T_{chamber} :	161.7°C	157.8°C	2.4%
T_{top} :	87.9°C	80.1°C	8.9%
T_{bottom} :	90.5°C	81.1°C	10.4%
T_{bridge} :	98.7°C	87.9°C	10.9%
T_{CS} :	17.1°C		

Table 1. Experimental and simulated results for coil power of 5.1 W without plasma

P_{thruster} :	6.8 W		
	measured	simulated	relative deviation
T_{chamber} :	189°C	187.2°C	1%
T_{top} :	101.4°C	92.8°C	8.5%
T_{bottom} :	104.4°C	94°C	10%
T_{bridge} :	115.8°C	103.6°C	10.5%
T_{CS} :	17.4°C		

Table 2. Experimental and simulated results for coil power of 6.8 W without plasma

With a deviation of less than 11% the simulated values show a relatively good agreement with the experimental values.

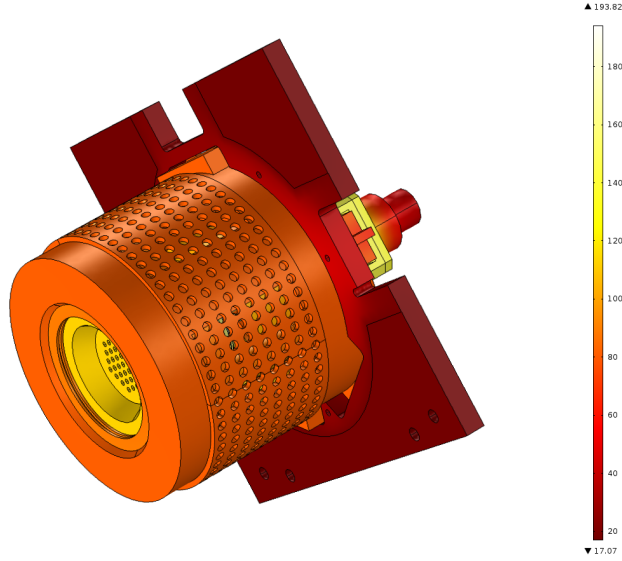


Figure 4. Example of a thermal simulation of a μ NRIT-2.5 (unit $^{\circ}\text{C}$)

VII. Conclusion

For further investigations, we need studies with much more detailed information about the thruster. These studies will include more temperature sensors inside the thruster and a better specification of the power transfer into the thruster parts. At the moment we build up a diagnostic system, which will deliver the plasma parameters for a given thruster setting. These additional information enable the calculation of the plasma conductivity. Knowing the plasma conductivity the electromagnetic coupling to the plasma and the heat transfer from the plasma to the wall can be calculate.

Acknowledgments

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