Simulation of the Neutral Gas Flow Within an Electric Thruster by the Kinetic Fokker-Planck Method and Comparison with Force Balance Measurements

Jens Schmidt and Leo Basov

Abstract This study investigates the neutral gas flow in the DEEVA electric thruster, developed within DLR. The thruster uses electron-cyclotron-resonance (ECR) discharge and a magnetic nozzle to accelerate plasma, supporting noble and reactive gases as propellants. Simulations using the Fokker-Planck method in SPARTA were conducted for argon and xenon at different flow rates to understand asymmetries in the neutral gas plume. Results showed that the original injector design caused plume asymmetry due to pressure gradients, while a refined injector produced a symmetric plume. Experimental cold gas thrust measurements partially matched simulation results and analytical models, though deviations occurred for xenon at higher flow rates. Findings support injector optimization and provide initial conditions for plasma simulations, improving discharge modeling and thruster performance. Future work will focus on density measurements and studies with diatomic propellants.

Keywords Rarefied gas dynamics · Fokker-Planck-method · DSMC · Electric propulsion

1 Introduction

Within the German Aerospace Center's (DLR) *Decentralized Energy supplied Electric Propulsion* (DEEP) project, a microwave-heated electric thruster is developed [4]. The plasma is created using an electron-cyclotron-resonance (ECR) discharge and accelerated using a magnetic nozzle. This allows the usage of different propellants such as noble gases but will also allow the use of reactive gases like air. As a first step to calculate the plasma properties and understand the neutral gas distri-

J. Schmidt (✉) · L. Basov
German Aerospace Center, Institute of Aerodynamics and Flow Technology, Göttingen, Germany
e-mail: jens.schmidt@dlr.de

L. Basov
Applied and Computational Mathematics, RWTH Aachen, Aachen, Germany

M. Grabe et al. (eds.), *Rarefied Gas Dynamics*, Springer Aerospace Technology,
https://doi.org/10.1007/978-3-032-00094-1_55

bution within the discharge tube, a Fokker-Planck simulation of the the neutral gas flow is performed. This is motivated by an observed asymmetry of the plasma plume during operation which can not be explained by any effects on the charged particles. Since the power coupling efficiency of the ECR discharge and the confinement of the plasma depend highly on the local number density, the channel flow and the plume of the thruster should initially be simulated for neutral gas. Therefore a simulation was performed to understand the neutral gas distribution and how the injector design will influence it. In addition, simulations are performed with a different injector design. The simulations are performed for argon and xenon to understand the influence of the molecular weight on the neutral gas distribution. To validate the results of the simulation, the thrust is calculated from the flow and compared with experimental measurements of the cold gas thrust as well as estimates from an analytical model. The simulation is performed for argon and xenon at three different volume flow rates of $\dot{V} = 1, 10, 45$ sccm which are representative for the thruster operation and ignition.

2 Description of the DEEVA Thruster

The DEEVA (DLR Electrodeless ECR Via magnetic nozzle Acceleration) thruster, as shown schematically in Fig. 1 consists of 4 major components: the gas injector, the discharge tube, the slotted antenna and the magnet system. The neutral gas is injected into the discharge tube by the gas injector and then ionized due to the microwaves emitted by the two slits of the slotted antenna. Due do the magnetic field, the electrons perform circular motions around the magnetic field line. The electrons can be heated in resonance if they are excited at the same frequency at which they are gyrating around the magnetic field lines, which is dependent on the local magnetic field strength. The thruster is usually operated at a frequency of $f = 2.4 - 2.5$ GHz leading to a necessary magnetic field strength of $B = 0.875$ T.

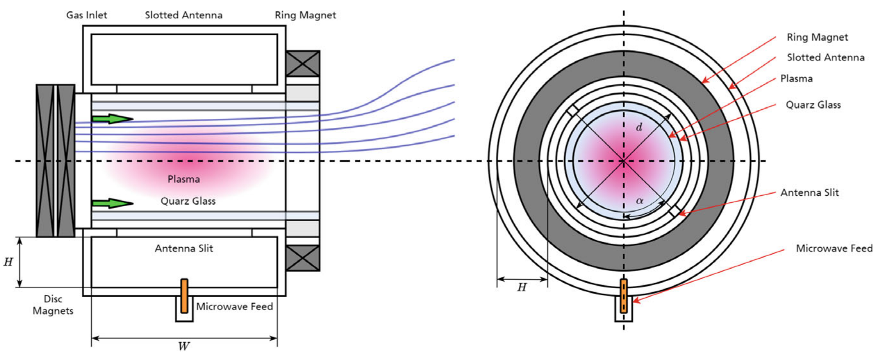
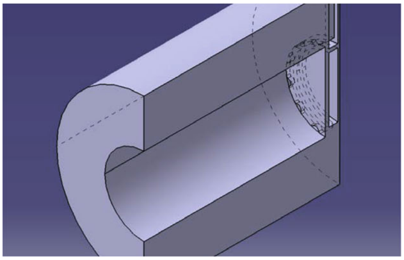
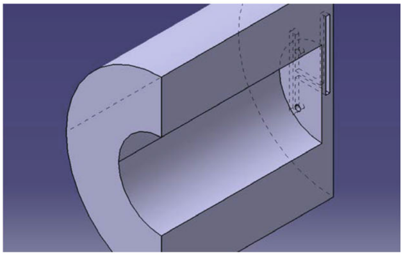


Fig. 1 Scheme of the DEEVA thruster as seen from the side (left) and front (right)



(a) Old gas injector geometry



(b) New gas injector geometry

Fig. 2 CAD model of the simulated geometries for the old (left) and new (right) gas injector design and discharge channel

Due to the magnetic field configuration, the plasma is then confined to reduce wall losses and expanded along the divergent magnetic field lines utilizing the field of the magnetic nozzle. Since the electric field strength of the microwave is stronger at the outer edge of the discharge tube closer to the slits, the number density of the neutral gas at the outer edge of the tube should be higher. In addition, the neutral gas distribution should be symmetric to not introduce any asymmetries into the plasma plume. This can be ensured by a proper design of the neutral gas injection which is studied numerically and experimentally. For this study, two injector geometries were compared numerically, both shown in Fig. 2, furthermore referred to as 'old' and 'new'. In the 'old' injector geometry, the gas is fed from the top and flows along the outer radius to the injector holes as seen in Fig. 2a. In the 'new' geometry, the gas first flows from the top to the center and then is spread radially in the four injector openings, resulting in a more equal pressure distribution.

3 Numerical Method

The simulations were performed using the kinetic cubic Fokker-Planck (FP) model [2]. The method is being continuously developed at DLR Göttigen as an extension to the open-source DSMC code SPARTA by Sandia National Labs [1, 3]. It is important to note that this is an extension of the code, not the DSMC method. Unlike Direct-Simulation Monte Carlo (DMSC), the FP method does not resolve the particle-particle interactions of the Boltzmann collision operator directly. Rather it uses a continuous stochastic process which leads to the computational cost being independent of the Knudsen number Kn. This allows the method to be computationally more efficient than DSMC in areas of low Kn numbers like in the inflow structure used in the thruster under investigation. The signal-to-noise ratio of both methods should be similar, as the noise scales with the inverse of the square root of the particle number. The FP method is necessary, as there is a strong pressure (and density) gradient within the discharge channel due to the gas injection at almost

Table 1 Boundary conditions and species properties from bird [1]

Boundary	Condition		
1–4	Outflow		
5–7	Inflow		
8	Wall (Diffuse Reflection with $T_w = 273.15$ K)		
Gas	m/kg	d_{ref}/m	ω
Argon	$6.63 \cdot 10^{-26}$	$3.657 \cdot 10^{-10}$	0.81
Xenon	$218.0 \cdot 10^{-27}$	$5.74 \cdot 10^{-10}$	0.85

atmospheric pressure and the expansion into high vacuum. The Knudsen number is $Kn \approx 10^{-5}$ in the discharge tube, and $Kn \approx 1$ in the plume, therefore there is a transition from a collisional into the collisionless regime, which makes a method necessary which is able to work in both regimes. The simulation was performed for Argon and Xenon as a neutral gas at different given volume flow rates $\dot{V}$ representing different operational points. The volume flow rates used were 1 sccm, 10 sccm and 45 sccm. The simulation was performed using only one half of the geometry to save computational time, since the geometry is symmetric along the middle axis. The downstream boundaries as well as the outside of the simulation domain were defined as outflow. The inflow in the injector was calculated using the given volume flow and calculating the number density in the inlet surface for a assumed temperature of $T = 300$ K. Variable hard sphere (VHS) parameters of the used species required for the simulation as well as the boundary conditions are given in Table 1. The resulting thrust force can be found by integrating over the local density $\rho(\vec{x})$ and velocity $\vec{v}(\vec{x})$ at the position $\vec{x}$ of the inlet and outlet of the control volume shown in Fig. 3 by

$$F = \oiint \rho(\vec{x})\vec{v}(\vec{x})\vec{v}(\vec{x})dS = \dot{m} \oiint \vec{v}(\vec{x})dS \tag{1}$$

to consider non-uniformities of the flow that might occur due to an asymmetry of the gas injection.

4 Experimental Setup

To confirm the numerical results, cold gas thrust measurements of the DEEVA thruster with argon and xenon were performed using DLRs DEPB thrust balance within the STG-MT vacuum chamber, which has previously been tested with other thrusters[5]. The thrust balance features quartz glass rods as load-bearing springs to minimizhe thermal drift, a Sartorius® WZA224-N load cell for precision, and an eddy current brake to dampen oscillations. The calibration is performed using fine

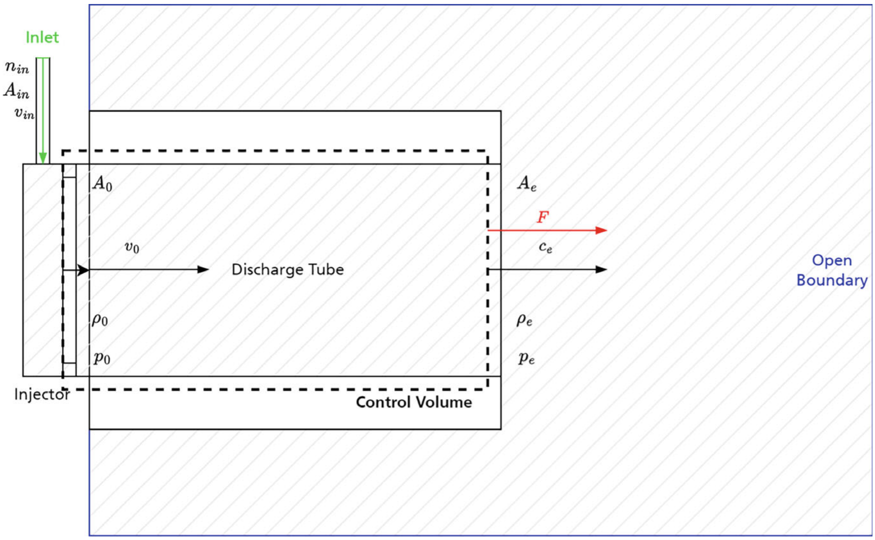


Fig. 3 Control volume used for the simulation and calculation of the thrust and boundaries. Boundary 4 is not shown. The area filled with hatches indicates the simulation domain

weights to ensure accurate and repeatable thrust measurements. This will lead to further understand the influence of the injector geometry and assist in optimization of the neutral flow injection into the discharge channel.

5 Analytical Model

The thrust is calculated with the analytical model under the assumption that the flow in the tube is subsonic. The exit velocity c_e can then be calculated from the isentropic relation

$$c_e = \sqrt{2c_p(T_e - T_0)} = \sqrt{\frac{\kappa}{\kappa - 1}(1 - (p_a/p_0)^{\frac{\kappa-1}{\kappa}}} \tag{2}$$

In which the isentropic coefficient was assumed to be a constant at $\kappa = 1.67$ for noble gases, the reservoir pressure was assumed to be $p_0 = 150000$ Pa and the ambient pressure was assumed to be $p_a = 0.001$ Pa, while the gas in the reservoir is assumed to be at room temperature of $T_0 = 300$ K. The thrust can then be calculated from

$$F = \dot{m}c_e \tag{3}$$

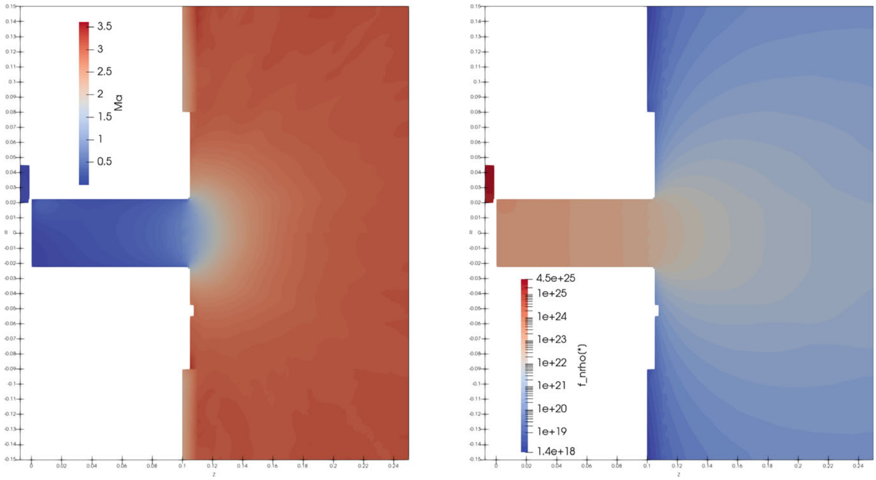
While this model is very simple, it can give a first-order estimate of the expected neutral gas thrust. The mass flow $\dot{m} = \rho\dot{V}$ was calculated from the volume flow $\dot{V}$ under the assumption of a ideal gas at a temperature of $T_0 = 300$ K to calculate the density.

6 Results

The simulation revealed details about the neutral gas flow within the discharge tube. As it can be seen for the results with the old geometry, in Fig. 4b, there is a pressure gradient in the gas injector as the gas flow is injected from the top and distributing within the radial channel. Since the pressure is higher at the top inlet ports, the flow velocity and density in the ports is also significantly higher. Due to the collisions downstream in the discharge channel, there is also a gradient in the exiting neutral gas plume, resulting in the observed asymmetry of the plume. With the new injector geometry and a central feeding of the gas into the discharge channel, the plume is symmetric (Fig. 5). In addition, it was observed for both the simulation results and the experimental measurements, that the cold gas thrust increases with the volume flow rate. The comparison of these results for argon and xenon with the analytical model are shown in Fig. 6, where the cold gas thrust F as calculated from the analytical model (circles), the measured experimental results (diamonds) and the calculated numerical results (squares) are shown. As it can be seen for argon in Fig. 6a, the agreement between the analytical model and the experimental and simulated results is quite good for argon and within the measurement uncertainty of the thrust measurements. For xenon, there are more differences observed. The analytical model increases linear with the volume flow rate, while for the experiment and simulation a logarithmic behaviour is observed. The results from the simulation and the experiment are within the measurement uncertainty for the lower flow rates but disagree for a very high flow rate. For the analytical model by the linear behaviour and the one-dimensional calculation not modelling all physics correctly. For the lower flow rates, this difference is significant enough. The disagreement between experiment and simulation for the higher flow rate can not be explained at the moment, except that Xenon at low temperatures due to the expansion might not be modelled correctly (Fig. 7).

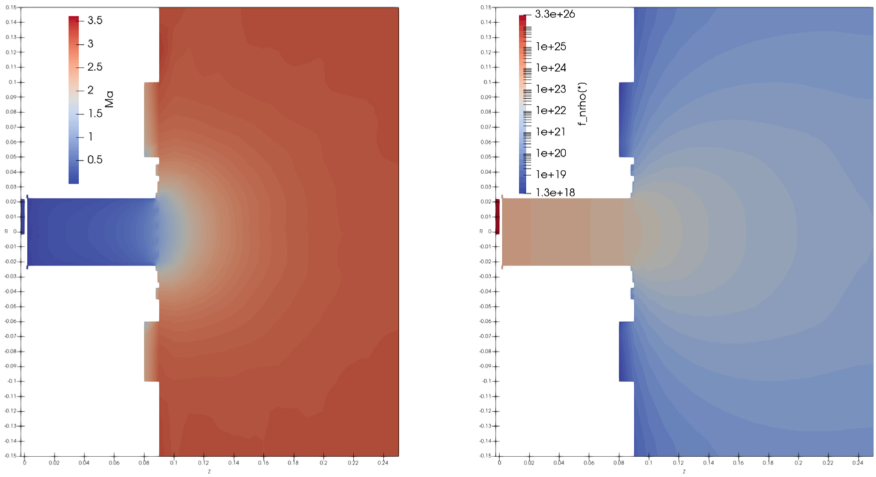
7 Conclusion

Within this work, the neutral gas flow within an electric thruster was simulated using the Fokker-Planck-method extension in SPARTA. Comparative measurements of the cold gas thrust were performed for argon and xenon. The results will allow to improve the design of the gas injector and the modelling of the plasma discharge itself, since the structure of the magnetic field and microwave radiation are known from independent measurements and simulations. Therefore, the knowledge of the local number density can directly assist in the improvement of the simple discharge models. Additionally, the results for the inflow from the injector can be used as an initial condition for particle-in-cell simulations. In addition, it was observed that the improved gas injector will produce a homogeneous distribution of the neutral gas in the plume. The comparison with the experimental results showed good agreement within the mea-



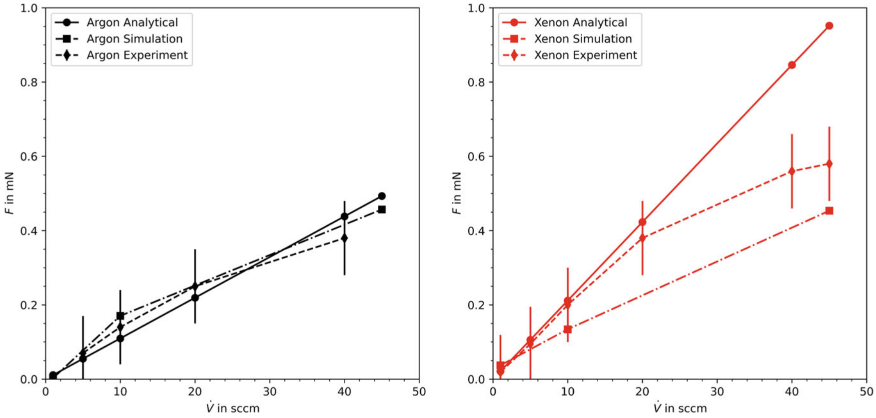
(a) Mach number Ma (b) Number Density n

Fig. 4 Mach number and number density in the old geometry for argon at a flowrate of $\dot{V} = 1$ sccm



(a) Mach Number Ma (b) Number density n

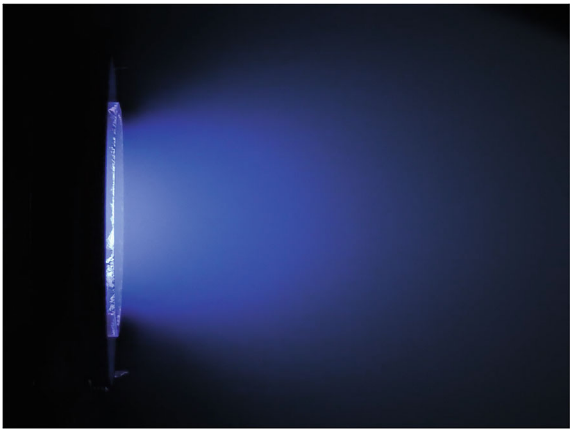
Fig. 5 Mach number and number density in the new geometry for argon at a flowrate of $\dot{V} = 1$ sccm



(a) Results for Argon (b) Results for Xenon

Fig. 6 Comparison of the cold gas thrust measurements (diamonds) with the analytical model (circles) and the numerical results (squares)

Fig. 7 Thruster plume during operation with argon at a volume flow rate of 2 sccm and a microwave power of $P_{MW} = 60$ W



surement uncertainty of the thrust balance for for argon, but disagreement for xenon. In future, the number density in the plume should be measured using a Patterson probe to understand the neutral gas distribution and compare it with the simulation results. In addition, more operation points shall be studied at a lower measurement uncertainty and for diatomic or multispecies propellants.

References

1. Bird GA (1994) Molecular gas dynamics and the direct simulation of gas flows. Oxford University Press
2. Gorji MH, Torrilhon M, Jenny P (2011) Fokker-Planck model for computational studies of monatomic rarefied gas flows. J Fluid Mech 680:574–601
3. Plimpton SJ, Moore SG, Borner A, Stagg AK, Koehler TP, Torczynski JR, Gallis MA (2019) Direct simulation Monte Carlo on petaflop supercomputers and beyond. Phys Fluids 31(8):086101
4. Schmidt J, Simon J, Grabe M (2022) The DEEP thruster concept. In: IEPC (ed) 37th international electric propulsion conference, Boston, pp 1–9. https://elib.dlr.de/148314/
5. Schmidt J, Simon J, Neumann A (2023) Thrust measurements of the RIT-10 thruster with a new type of thrust balance. Int J Energetic Mater Chem Propulsion 22(4) (Begel House Inc)