Numerical Investigations of Applied-Field Magnetoplasmadynamic Thruster SX3

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Abstract: Currently achieved results for steady state applied MPD thrusters are under investigation and verification by making use of the IRS code SAMSA. Correspondingly code verification activities aiming at the adequate and representative numerical rebuilding of MHD plasma systems at IRS have been performed prior to the planned AF MPD thruster simulations. Among these are: The successful numerical rebuilding of magnetic influences toward a plasma boundary layer in terms of its deflection and hence in terms of the increase of the distance of the boundary layer edge. In addition, the plasma source with which the relevant experimental flows were produced has been rebuilt as well. This plasma source is a steady state self-field MPD device operated with Argon. The paper concludes with the summary of the current preparations for the simulation of steady state applied-field MPD thrusters.

Nomenclature

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient
Cx	=	force coefficient in the x direction
Cy	=	force coefficient in the y direction
c	=	chord
dt	=	time step
Fx	=	X component of the resultant pressure force acting on the vehicle
Fy	=	Y component of the resultant pressure force acting on the vehicle
f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) non-dimensional angular deflection rate

I. Introduction

THE successful implementation and understanding of MHD-effects within plasmas can be considered as enabling aspect for relevant space technology and energy applications. For the previous aspect space propulsion but also

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boundary layer influencing using magnetic fields are to mention while for the latter an improved understanding of test facilities e.g. for the purpose to test divertor materials for fusion reactors have to be mentioned.

For space propulsion pulsed and steady state continuous MPD propulsion systems have to be mentioned. The pulsed devices are often referred to as pulsed plasma thrusters (PPTs) given that the bank energies of the capacitors to be discharged is high enough[1]. The continuous devices are typically named self-field and applied-field MPD thrusters[2]. In a previous assessment IRS looked at approved and existing MHD plasma systems at IRS in order to qualify characterizing parameters such as the Stewart number as a measure to qualitatively and comparably judge on MHD plasma systems[3]. This, however, was continuously flanked by numerical modeling in the field[4].

For more than two decades IRS has been investigating steady state self-field MPD thrusters at powers of up to 1 MW[2, 5]. Some ten years ago this was extended to applied-field MPD thrusters as these devices can also cope with moderate to low powers while the former need a certain minimum power in order to produce the self-induced magnetic fields to an adequate extend[6,7,8,9]. Break through results for the AF MPD thruster SX3 referring to the achieved thrust efficiency can be verified against the achievements of DLR in the 1970ies. However, a maximum verification in terms of currently performed extended experimental campaigns but also numerical analyses needs to be applied in order to strengthen the level of verification. In addition, the used numerical IRS tool called SAMSA has been validated against the experimental investigations in reference 10 where the IRS plasma wind tunnel PWK1 equipped with the steady state MPD plasma generator RD5 was used to produce adequately ionized plasma flow conditions that were used for the investigation of MHD-based boundary layer influencing[11]. Besides the extensively used plasma diagnostic tools such as Langmuir probes, Pitot pressure probes and optical emission spectroscopy[12]. While the probe techniques delivered n_e, T_e, Ma number and Pitot pressure profiles, the OES showed a certain extend of charge separation in front of a plasma probe equipped with magnets. This observation was later confirmed by independent experiments at Baylor University, Waco, USA, where reference cells with the same magnetic configuration were used[13].

The paper reports on the numerical rebuilding of the RD5 plasma condition and on the preparation activities for the simulation of the AF MPD SX3.

II. Numerical Code SAMSA (Self and Applied Field MPD thruster algorithm)

SAMSA is described thoroughly in references 4 and 9. SAMSA makes use of a Navier-Stokes approach employing a hyperbolic character for the used transport equations. Both the Maxwell equations and the material equations, in particular Ohms law take into account the presence of magnetic fields. In addition, electrode models are implemented that have been validated against experimental data from self-field MPD thrusters[4].

III. Experimental set-up and test conditions

The IRS plasma wind tunnel PWK1 was used for the investigations. PWK1 is equipped with a vacuum tank that has 2 m in diameter and 6 m in length. It is connected to the IRS central vacuum system that has a suction capability of more than 250.000 m^3/h. The plasma source used was the self-field MPD plasma generator RD5. Both PWK1 and RD5 are depicted in Figure 1.

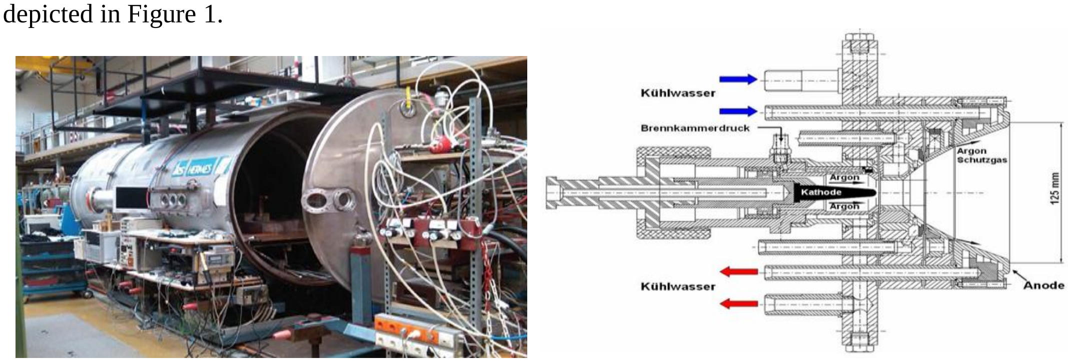

Fig. 1: PWK1 and RD5

The used test conditions are shown in table 1.

Table 1: Experimental Conditions

Gas Type	Argon
Mass flow /g s^{-1}	1.5 + 0.5
Amb. pressure / Pa	30
Arc current /A	1040

Distance of probe to RD5 outlet/ mm 130

The two mass flow rates outlined in the table are due to the fact that RD5 is also often run with air. In order to prevent a lack of charged particles at the anode these conditions can additionally be equipped with a tangential argon flow along the anode.

IV. Numerical Results

As outlined in the introduction the numerical results for the magnetic boundary layer deflection are already published in reference 14. For the sake of completeness, the plasma probe used is again shown in Figure 2[10]. Here, the so-called hemispherical magnetic plasma probe is shown. Its magnetic flux can be varied by the number of magnets (between 0 and 6). The right side of the figure shows a photographic representation of the probe without magnetic field and with magnetic field. Clearly the influence of the magnetic field in front of the probe can be seen by variation of the plasma radiation as detected by the system.

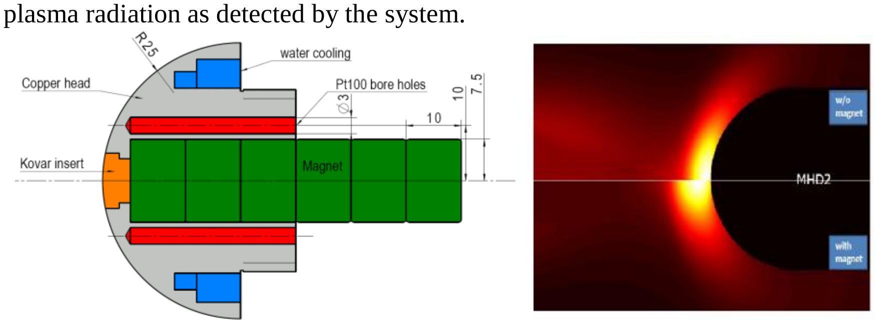

Fig. 2: Schematic of spherical plasma probe (left) and probe exposed to plasma with and without magnets (right)[10]

The core result is shown in Figure 3[14]. Both the value table showing the values as plotted in the diagram below and the diagram show the influence of the varied magnetic flux toward the boundary layer distance. In addition, the SAMSA corresponds very well with the experiments.

Magnet	FieldStrength	Knapp	SAMSA
0	0.000	5.3	5.3
1	0.200	8.0	7.1
2	0.225	8.9	7.4
3	0.243	9.6	8.1
4	0.254	9.7	8.3
6	0.265	9.9	8.4

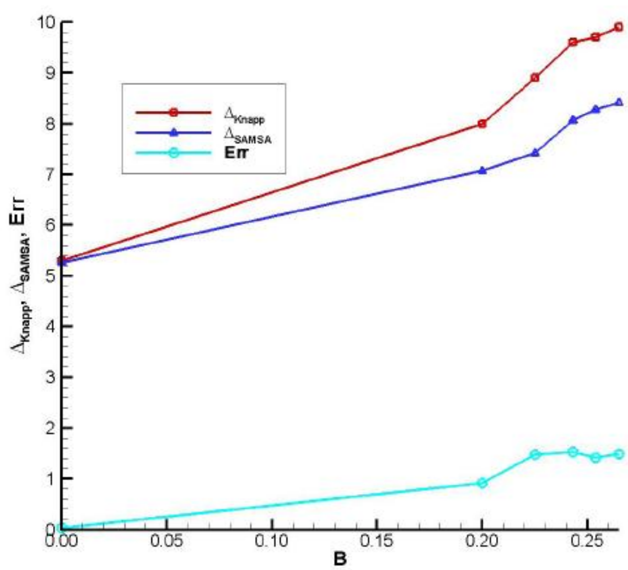

Fig. 3: Value table showing experimental results (Knapp[10]) and numerical results[14], below graphical representation

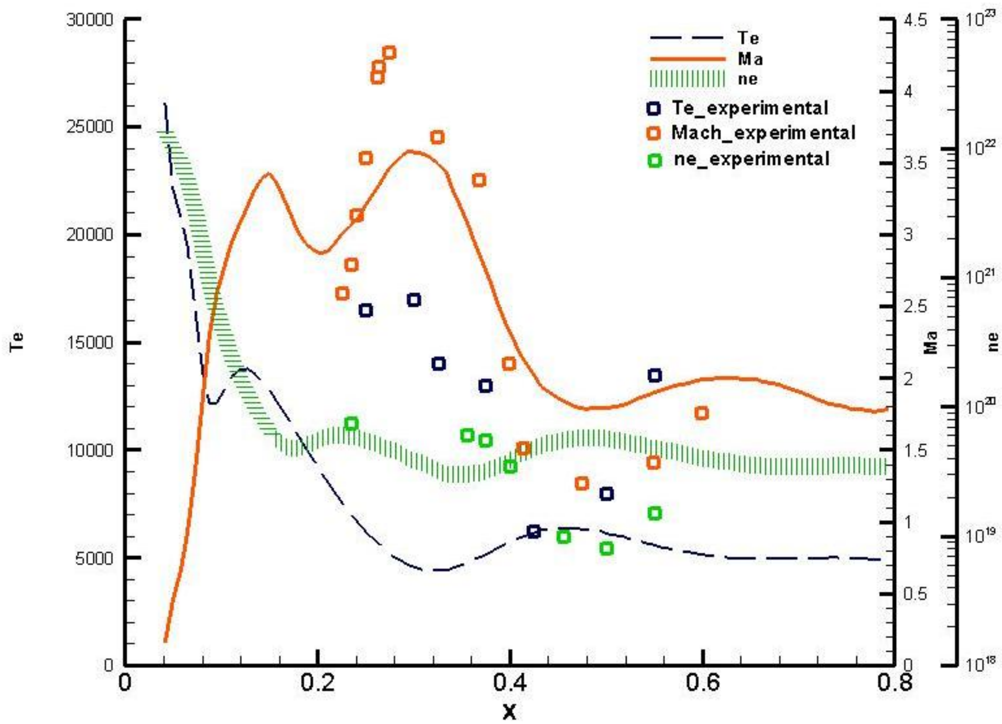

Fig. 4: Comparison of numerically simulated profiles for n_e, T_e and Ma with experiment, p_{amb}=30 Pa (n_e in $1/m^3$, T_e in Kelvin)

Figure 4 shows parameter profiles along the centerline of the plasma axis of RD5 from SAMSA simulations and, in addition, the respectively obtained n_e-, T_e- and Ma number profiles from the experiments. The correspondence for the electron densities is acceptable given that one takes into account the error bars of the n_e-measurements that can be up to ±50 %. For the electron temperature there seems to be a trend that the experimental values are higher. However, this may be due to the boundary conditions, in particular due to a uncertainty of the static pressure assumed with 30 Pa, see also the analyses below. The Mach number seems to correspond well given that the coarse assumptions applied to their experimental determination is taken into account: Here, the one dimensional Rayleigh-Pitot equation has been taken conveying significant uncertainties.

Figure 5 shows profiles along the centerline of the plasma axis of RD5 from SAMSA simulations and, in addition, the respectively obtained Pitot pressure profiles from the experiments. The correspondence is quite acceptable. Here, one has to note that the Pitot pressure probe used was a 50 mm diameter blunt body equipped with a bore diameter that significantly integrated the pressure over the diameter.

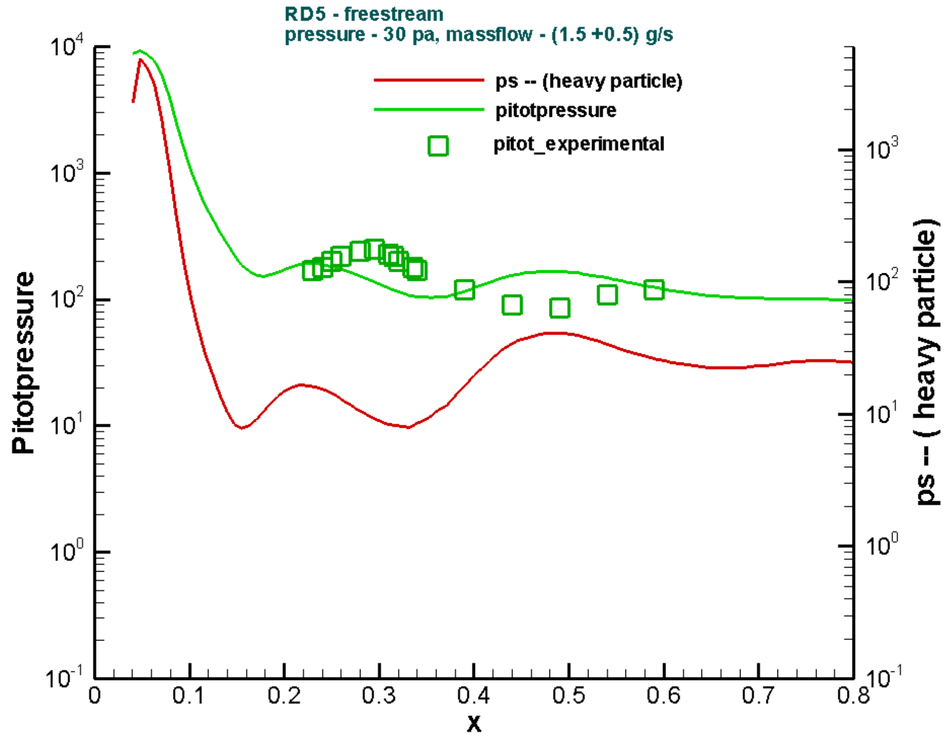

Fig. 5: Comparison of numerically simulated profile for p_{Pitot} with experiment, p_{amb}=30 Pa

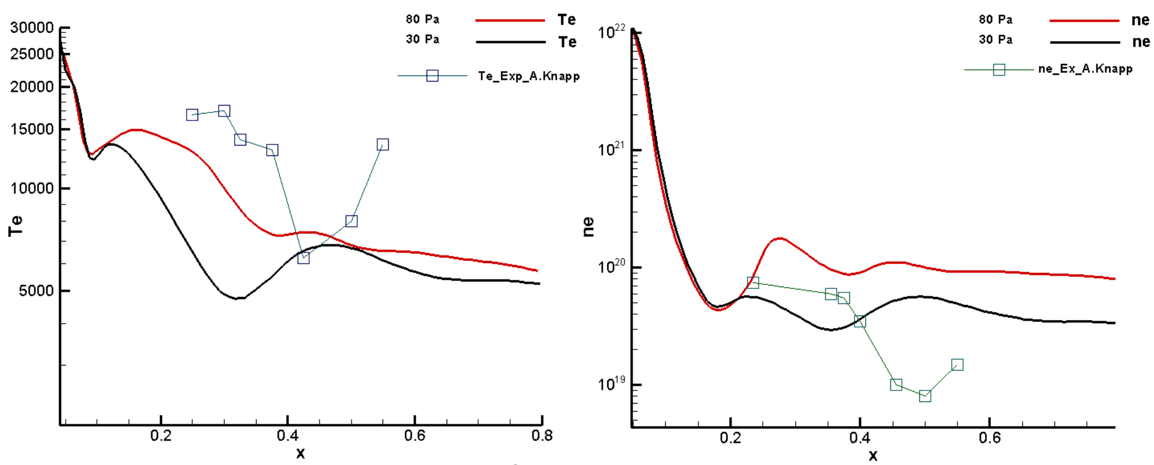

Fig. 6: T_e and n_e comparison with varied p_{amb} (n_e in $1/m^3$, T_e in Kelvin)

Figure 6 shows a preliminary sensitivity analysis with respect to boundary conditions (here the ambient pressure, as this value is accompanied by a certain inaccuracy). As expected the slight increase of the ambient pressure helps for an improved correspondence of the T_e-values while for n_e it is vice versa. However, for ne this is not that critical due to the limited sensitivity and, in addition, due to the inaccuracy of the Langmuir probe measurements.

V. Conclusion

SAMSA could be verified due to the successful simulation of the self-field MPD device RD5. Moreover an applied field case i.e. the magnetic probe in an Argon plasma could be successfully rebuilt. The next step will be the implementation of the AF MPD SX3 which is already ongoing.

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