Langmuir Probe Measurements of a Magnetoplasmadynamic Thruster

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Abstract:A 5 kw, gas-fed, applied-field magnetoplasmadynamic thruster(MPDT) has been designed, manufactured and preliminarily tested. Triple Langmuir probe is used for taking measurements into the plasma of the thruster. The thruster has been tested both in a complete working period of 250s and in quasi-steady conditions with 12 measuring points along the axial and radical direction to decide the MPDT plasma properties. In the first experiment, the influence of the thruster's working parameters such as the anode and cathode flow rate, the discharge current and the applied magnetic field on plasma's temperature(T_e) and density(n_e) are well elaborated. The electron temperature and number density are 12 eV and 4.6×10^{20} m^{-3} when the power of MPD is 4.2kw and the total flow rate equals to 60mg/s without the magnetic field. When the total flow rate decreases to 30 mg/s and the magnetic field equals to 0.009T, the temperature and density become 6.4 eV and 2.764×10^{19} m^{-3}. In the other experiment, the distribution of the plasma's T_e and n_e along the radial direction and axial direction is presented and the electron temperature and number density are 0.648 eV and 6×10^{19} m^{-3} 28cm downstream the thruster's outlet.

Nomenclature

A	=	area of probe
E	=	charge of electron
m_i	=	mass of ion
k	=	Boltzmann constant
n_e	=	electron density
T_e	=	electron temperature
V_{d2}	=	measured voltage difference between the positive probe and the floating probe
V_{d3}	=	fixed voltage between the positive and negative probes
V_n	=	voltage of probe n
β	=	constant indicating variation of ion current with probe potential
χ_{dn}	=	non-dimensional potential of V_n
η	=	non-dimensional form of β

I. Introduction

The Magnetoplasmadynamic (MPD) thruster is a form of electrically powered spacecraft propulsion system which uses the Lorentz force to generate thrust. According to the source of magnetic field, MPD thrusters can be divided into two categories, self-field MPD thruster and applied-field MPD thruster[1]. The lower current requirement

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and generally higher exhibited efficiency of applied-field devices provide an advantage over self-field thrusters for lower power missions[2].

The experimental investigation of gas-fed, applied field MPD thruster(AF-MPDT) is often limited by the availability of vacuum facilities capable of maintaining a back pressure under a certain limit value. So far, our tests carried out on AF-MPDT have been performed in vacuum chamber which can reach the limit of 5×10^{-4} Pa. The working pressure of the thruster is below 1Pa.

Langmuir probes were the first diagnostics developed to take measurements inside the plasma. For single Langmuir probe, a voltage vs. current curve is needed to properly determine the plasma properties from the probe measurements[3]. Triple Langmuir Probe theory was first introduced and implemented by Chen and Sekiguchi in 1965[4], which was a new and simple method to derive the electron temperature and density within the plasma over time at the specific locations. Then this method has been successfully used in MPD plume measurement by Dennis L.Tilley[5].

The anode and cathode flow rate, the discharge current and the applied magnetic field of 5 kw MPD were recorded by a computer data system. Triple Langmuir probe was used to simultaneously measure the electron temperatures and electron densities in the plume of the 5 kw MPD thruster.

II. Experimental Apparatus

A.Thruster description

The experimental system includes vacuum system, propellant system, electricity supply system, cooling system, data acquisition system, Langmuir probe system and the thruster itself. The schematic of the experimental system is shown in Fig. 1.

All the experiments were performed in the vacuum chamber, which is 1.8 m in diameter and 3.2 m in length. It is equipped with four rotary vane vacuum pumps, two roughing pumps, and two oil diffusion pumps. Each oil diffusion pump has a rated capacity of 26,000 liters/s at the pressure range of 1.3×10^{-3} Pa to 6.7×10^{2} Pa.

The schematic of the MPD thruster is shown in Fig. 2. It is 353 mm in length and consists of a tungsten cathode and a molybdenum anode, where propellant Ar can be extruded into the thruster and ionized by the electricity supply system. The thruster is fixed on the thruster stand in the vacuum chamber.

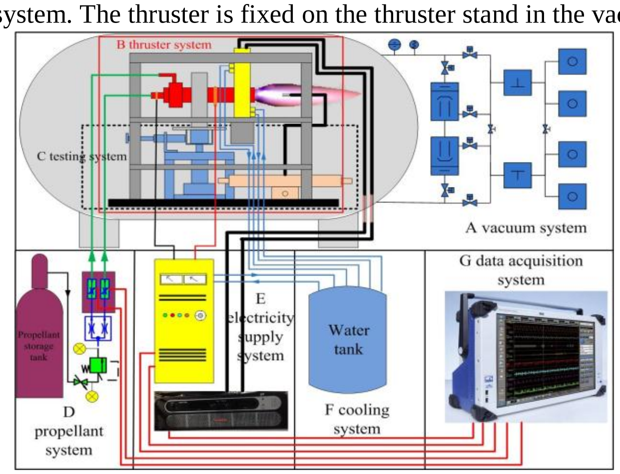


Figure 1. The schematic of the experimental system

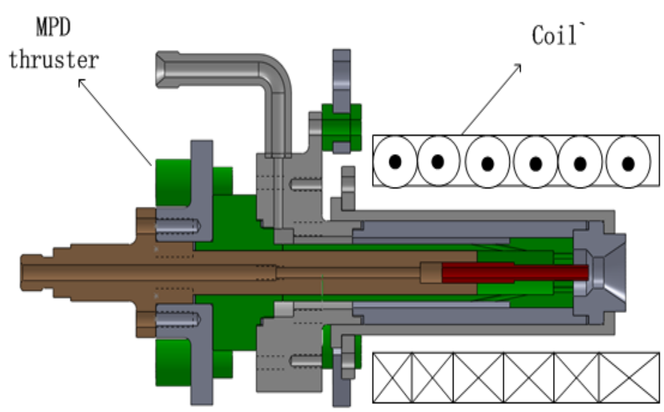


Figure2. The schematic of the thruster

B. Langmuir probe system

Experimental data measured through the tests include the discharge current and voltage, the anode and cathode flow rate, and the current of the coil. The triple Langmuir probe consists of three exposed wires as shown in Fig. 3. The schematic of the data acquisition system is shown in Fig. 4.The applied voltage V_{d3} is 30 V, the measured voltage V_{d2} and current I_3 are measured by Langmuir probe and recorded by the data collector as shown in Fig 4.

A step-motor-driven translation system was used to move the probe to a specific position. The translation system consists of a movement mechanism and a servo control system. The movement mechanism is set inside the vacuum chamber to move the Langmuir probe, and the control system is set outside the vacuum chamber, allowing for positioning or repositioning of the probe during testing. Movements of up to 150 mm are possible with the reposition precision less than 5 μm and the maximum velocity of 20 mm/s. It helps a lot to perform error analysis and examine the spatial and temporal variation of the plume properties. The probe and the thruster are placed in the chamber as shown in Fig. 5. After the experiment, the probe is badly burned as shown in Fig. 6.

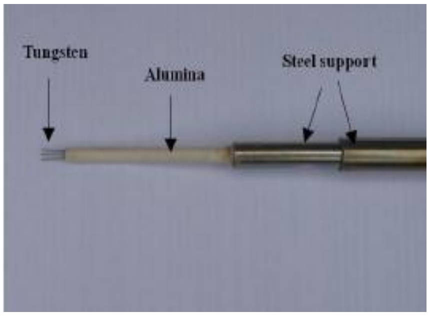


Figure 3. The assembly of the triple probe

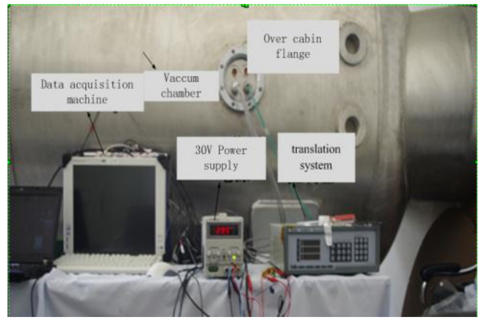


Figure 4. Data acquisition system

Figure 5.Using triple probe to diagnose MPDT

Figure 6. The probe after experiment

III. Data analysis and discussion

Based on the theory given by Robert Francis Eckman[6], the electron temperature T_e can be derived from V_{d2} using equation (1) and the electron density n_e can be derived from I_3 using equation (2).

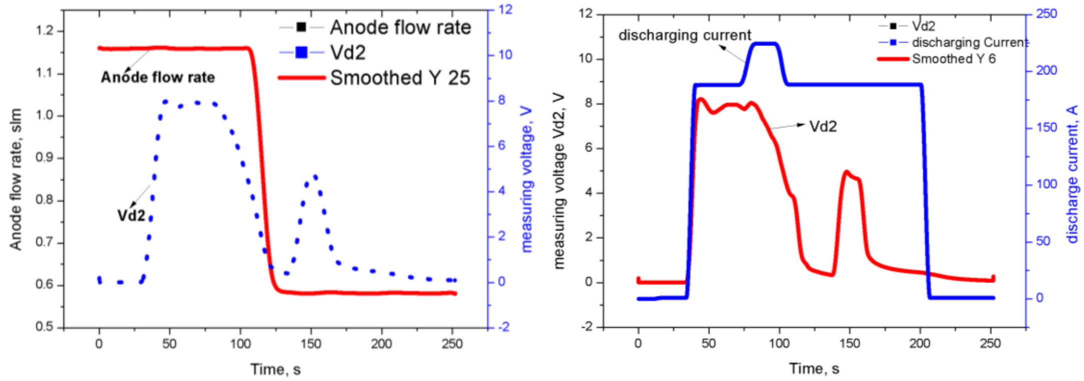
$$\frac{1}{2} = \frac{1-0.5\left(\left[1-\beta V_{d2}\right]^{0.5} + \left[1+\beta\left(V_{d3}-V_{d2}\right)^{0.5}\right]\right)\exp\left(-\chi_{d2}\right)}{1-exp\left(-\chi_{d3}\right)} \quad \textbf{(1)}$$

$$n_e = \frac{exp\left(0.5\right)\frac{I_3}{A_3}(1-\eta\left(\left(\chi_f-0.5\right)\right)^{0.5}}{e\left(\frac{kT_e}{M_i}\right)^{0.5}\left(\left[1+\eta\left(\chi_{d3}-\chi_{d2}\right)\right]^{0.5} - exp\left(-\left(\chi_{d3}-\chi_{d2}\right)\right)\right)} \quad \textbf{(2)}$$

$$\chi = \frac{e\left(V-V_p\right)}{kT_e} \quad \textbf{(3)}$$

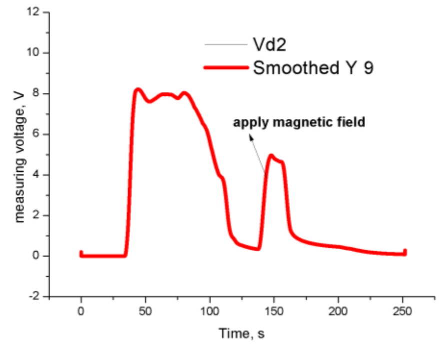
In the equations, V_{d2} and I_3 are the measured voltage and current. V_{d3} is the fixed voltage applied between the positive and negative probes. β is a constant indicating variation of ion current with probe potential. Since T_e and n_e are decided by V_{d2} and I_3 separately, the curve of V_{d2} and I_3 against time can reflect the properties of T_e and n_e.

In the first experiment, the influence of the thruster's working parameters on the electron temperature (T_e) and density(n_e) are analysed. These parameters include the discharge current, the anode flow rate, and the applied magnetic field. At the moment of starting the thruster, T_e and n_e increase sharply with the discharge current up to 188A as shown in Fig. 7(a). Then T_e decreases substantially when the anode and cathode flow rate decrease from 60 mg/s to 30 mg/s as shown in Fig. 7(b). After the applied magnetic field (0.09T) is given during this period, T_e increases to 6.4 eV as shown in Fig. 8 and n_e increases to 2.764×10^{19} m^{-3}. From Fig. 9 we can get some typical values of T_e and n_e during the working period of the thruster.



a) **b)**

Figure 7. Influence of the discharge current (a) and anode flow rate (b) to T_e



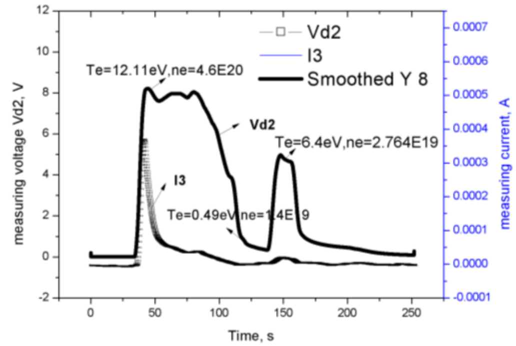
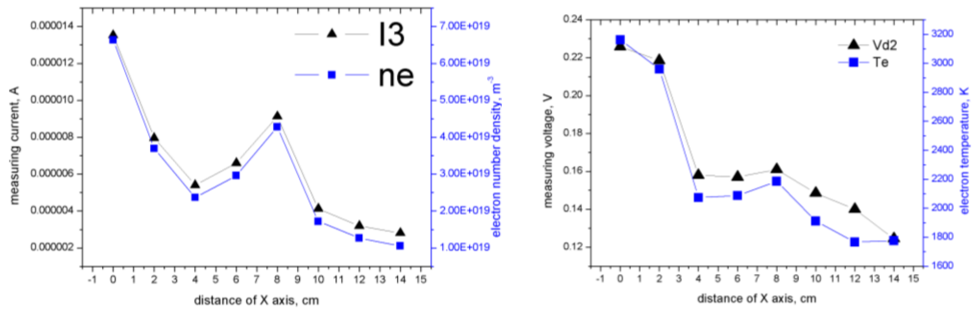


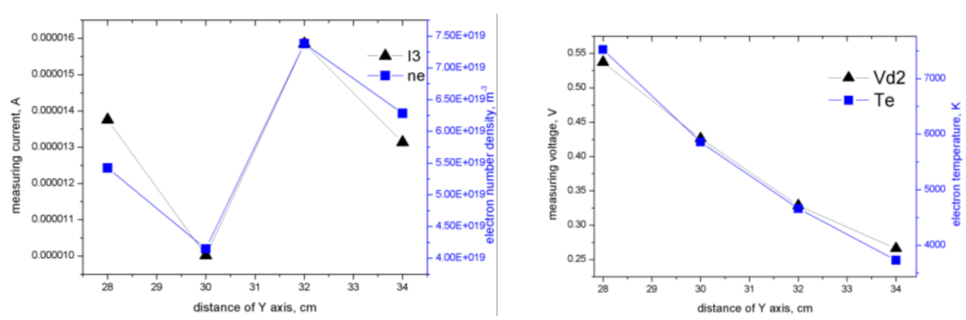
Figure 8. Influence of the magnetic field to $V_{d2}(T_e)$ **Figure 9. Curve of V_{d2} and I_3 against t**

In another experiment, the thruster worked in a quasi-steady condition with the power of 1.1 kw and the total flow rate of 78 mg/s. The magnetic field is 0 T. The distribution of temperature and density along the radical and axial direction are shown in Fig. 10 and Fig. 11.



a) **b)**

Figure 10. Distribution of I_3, n_e (a) and V_{d2}, T_e (b) with its radical length



a) **b)**

Figure 11. Distribution of I_3, n_e (a) and V_{d2}, T_e (b) with its axial length

The location of the measuring points are chosen to reveal the axial and radical distribution of the plume properties as shown in Fig. 12. In the vertical plane 34 cm downstream the thruster's outlet, the value of T_e and n_e reach a summit at the point of R=8 cm,and then decrease with the radical length as shown in Fig. 10. The gradient of the radical temperature is not equal everywhere, typically bigger near the centre and smaller near the edge.

T_e changes 1000 K between every two measuring points and n_e fluctuates near $6\times10^{19}\,m^{-3}$ in the axial direction. T_e reaches 0.648 eV at the point of 26 cm downstream the thruster's outlet and n_e reaches $7.38\times10^{19}\,m^{-3}$ at the point of 30 cm downstream the thruster's outlet as shown in Fig. 11.

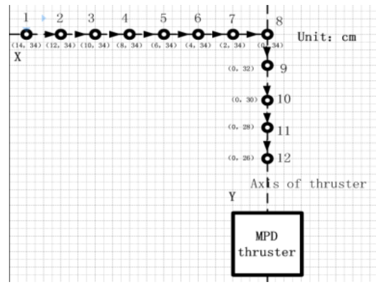


Figure 12. Measuring points

IV. Conclusions

The Triple Langmuir probe system has been established and used for the measurement of MPDT plume properties including the electron temperature and density T_e and n_e. Based on the measuring voltage and current V_{d2} and I_3, T_e and n_e can be calculated using C++6.0 programme[6].

In one experiment, the influence of anode flow rate, discharge current and the applied magnetic field on T_e and n_e are analysed. The electron temperature and number density are 12 eV and $4.6\times10^{20}\,m^{-3}$ when the power of MPD is 4.2 kw and the total flow rate equals to 60 mg/s without the magnetic field. When the total flow rate decreases to 30 mg/s and the magnetic field equals to 0.009 T, the temperature and density become 6.4 eV and $2.764\times10^{19}\,m^{-3}$.

In another experiment, the axial and radical distribution of the plume properties are given. The summit of T_e and n_e occurs at 8cm in radical direction. The gradient of the radical temperature is not equal everywhere, always bigger near the centre. However, the gradient of the axial temperature is almost 500 K/cm everywhere. The electron temperature and number density are 0.648 eV and $6\times10^{19}\,m^{-3}$ 28cm downstream the thruster..

Acknowledgement

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