A review on plasma diagnosis technology of pulsed plasma thruster

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Abstract. The plasma diagnosis technology is an essential tool to investigate the plasma characteristics in the pulsed plasma thruster, which can understand the fundamental mechanisms behind pulsed plasma thruster. This review introduces the application of plasma diagnostic technology in pulsed plasma thrusters, investigates the research status of plasma diagnostic technology applied to pulsed plasma thrusters, and discusses usual plasma diagnostics methods. In the contact diagnosis method, the application of Langmuir three probes in the plasma diagnosis of the pulsed plasma thruster is mainly introduced. In the non-contact diagnosis method, the application of optical emission spectroscopy in plasma diagnosis in pulsed plasma thruster is mainly introduced. The advantages and disadvantages of Langmuir three probes and optical emission spectroscopy in plasma diagnosis are analysed.

Keywords: Pulsed plasma thruster, Langmuir three probes, optical emission spectroscopy.

1. Introduction

With the development of the Micro-Electro-Mechanical System (MEMS), micro-nano satellites have good development prospects and have received extensive attention from various countries and related research. In order to complete the mission of satellite formation flight and satellite constellation formation, modern micro nanosatellites are generally required to have a propulsion system to realize the attitude control, orbit control, and orbit maneuver. The electric propulsion system has the advantages of high specific impulse, long service life, repeated starting, and high thrust control precision. Therefore, it can significantly increase the payload of spacecraft, prolong its service life and reduce its launch cost, and has been widely used in microsatellites. As one of the most widely used electric thrusters, Pulsed plasma thruster (PPT) [1] [2] [3] stands out because of its simple structure, low cost, high specific impulse at low power, small impulse and precise thrust control.

As shown in figure 1, the working process of the pulsed plasma thruster can be summarized as follows: the capacitor is charged to obtain energy, the spark plug is ignited under the control signal, and a small amount of initial charged particles are produced. These charged particles lead to the conduction between anode and cathode, so the energy storage capacitor begins to discharge, and a large current is generated between the anode and the cathode. When the propellant is ablated by the thermal effect of the electric current, it would be cracked, gasified, and ionized into plasma. Under the acceleration of the
electromagnetic force, the plasma ejects from the discharge channel and produces thrust. Because the plasma is accelerated by electromagnetic force, the plasma characteristics will affect the acceleration. Hence, to understand the fundamental mechanisms behind pulsed plasma thruster, we need to perform plasma diagnosis on PPT to study plasma parameters.

Figure 1. Schematic of PPT

2. Overview of plasma diagnosis for pulsed plasma thruster

With the adaptation of the plasma diagnosis technology, the plasma velocity, electron number density, electron temperature, plasma space potential, and other plasma characteristics of the thruster could be measured and obtain. Typically, Plasma diagnosis methods can be divided into contact diagnosis and non-contact diagnosis.

Contact diagnosis mainly includes the probe method, impedance measurement method and so on, while Non-contact diagnosis mainly includes the optical emission spectrometry, mass spectrometry and so on. The plasma produced by pulsed plasma thruster is transient rather than steady, and the time scale is in the order of microseconds. Therefore, the measurement method used for steady-state plasma might not be applicable with satisfactory accuracy, leading more requirements to the plasma diagnostic of the pulsed plasma thruster. The following two primary pulse plasma thruster plasma diagnostic methods, the probe method, and optical emission spectrometry, are introduced.

2.1. Probe method

Electrostatic probe, also known as Langmuir probe, is a tool for measuring plasma density, electron temperature, plasma potential, suspension potential and electron energy distribution function proposed by Langmuir and Smith in 1924. Electrostatic probes include the single probe, double probe, triple probe and quadruple probe.

Both the single-probe and double-probe methods need to scan the probe bias voltage at a specific measuring point, and record the current of the probe loop at the same time, and draw the two parameters of the bias voltage and loop current into a graph to form a typical I-V curve. The formation time of this I-V curve is about a few seconds. This response time is reliable for the measurement of the steady-state plasma parameters of the steady-state thruster. PPT is a transient thruster whose discharge time is on the order of µs. It is impossible to directly measure the time-resolved plasma parameters of PPT with single probe and double probe.

In 1965, Chen and Sekiguchi invented the triple langmuir probe diagnostic method [4]. Compared with single langmuir probe and double langmuir probe, triple langmuir probe does not need to measure a complete current-voltage curve (I-V curve) to calculate the plasma electron temperature $T_e$ and electron density $N_e$ parameters, which has been widely used in the research of plume diagnosis of various electric thrusters. There are two kinds of triple langmuir probe: voltage mode and current mode [5]. For PPT, current mode triple langmuir probe is more suitable. Because the PPT discharge process will produce a strong electromagnetic signal, it will interfere with the voltage difference between the probes, which will affect the measurement results of the triple langmuir probe in the voltage mode.
The measurement principal diagram of the triple Langmuir probe in current mode is shown in figure 2. The voltage between probe 1 and probe 2, $\varphi_{12}$, and the voltage between probe 1 and probe 3, $\varphi_{13}$, are constant in the current-mode triple Langmuir probe which can effectively suppress the influence of potential probe fluctuations on the experimental results. By measuring the current values $I_1(t)$, $I_2(t)$, and $I_3(t)$ flowing through each probe, after a specific calculation, the electron density and temperature can be obtained [6].

In 1970, Vondra et al. conducted a plasma diagnostic experimental study on the Langmuir single probe corresponding to the PPT used in the LES-6 satellite. The results show that at 2.5cm on the surface of the propellant, the temperature of electrons generated by PPT discharge is between 20-25 eV [7].

In 1977, Palumbo and Begun et al. used the double Langmuir probe to measure the plume after 5 cm downstream from the propellant surface axis. It is found that the electron number density along the central axis of the PPT decreases monotonously with the increase of the downstream distance. Therefore, the electron density has a maximum value at 5 cm downstream from the propellant surface, the maximum electron temperature is 10 eV, and the maximum electron number density is $1.46 \times 10^{15}$ cm$^{-3}$. Using a time-of-flight probe to trace the position and shape of the plasma front peak, it is found that the plasma moving speed at the anode is faster than the moving speed at the cathode, and the speed at the cathode is about half that of the anode [8].

![Figure 2. Potential diagram of a triple Langmuir probe in current mode](image)

In 1996, Myers et al. used Langmuir probes and quartz plates to study the PPT plume used on the LES-8/9 satellite to evaluate the plume pollution. The measuring points are arranged at 0.24m, 0.39m, 0.55m and 1.2m from the thruster. The measurement results of the probe show that the peak ion density of the centerline is about $6 \times 10^{12}$ cm$^{-3}$, and the ion movement speed is 42000 m/s. The ion velocity measurement results are consistent with the measurement results of Vondra [7] et al [9].

In 1997, Antropov et al. used the Langmuir probe to study the physical phenomenon of the PPT discharge channel with a discharge energy of 80-100J. It is found that the plasma cluster consists of two parts with similar density but different velocities. The velocity of the faster part of the plasma cluster is $30 \sim 40$ km/s. And the plasma cluster containing the main mass move at a speed of $10 \sim 12$km/s, which is in good agreement with the interferometer measurement results. The electron temperature is actually independent of time, and the temperature is within the range of 1.8-2.6eV. The maximum electron density is $10^{16}$ cm$^{-3}$ at 15cm away from the propellant surface, and the divergence angle of plume is calculated to be $80^\circ$ according to 0.1 times of the maximum electron density [10].

In 1998, Bushman et al. used quadruple Langmuir probes to measure the plume of coaxial PPT. The electron temperature along the centerline of the PPT outside the nozzle is approximately constant below 1ev, and the electron density at 1cm of the exit section of the thruster is about $10^{16}$cm$^{-3}$. As time goes...
by, the electron density gradually decreases to below $10^{15}\text{cm}^{-3}$[11]. In 1999, Burton and Bushman used quadruple Langmuir probes to continue the plasma parameter measurement of the coaxial pulse plasma thruster PPT. The measurement result of the quadruple electrostatic probe shows that the maximum electron density of the symmetric plume is $2.0\pm1.0\times10^{14}\text{cm}^{-3}$, the initial electron temperature is $2.0\pm0.3\text{eV}$, and the electron temperature change on the center line is small. The ion Mach number is $3.0\pm0.5$. By measuring the arrival time of the electron density peak, the ion velocity is 34km/s. The measurement results of non-axis points show that the plume of the coaxial PPT has excellent symmetry. Compared with the centerline value, the plume has a lower density and a higher temperature [12].

In 2001, Eckman, Byrne and others used the triple Langmuir probe to continue to explore the LES8/9 PPT, and the measurement results were slightly different from before. Considering all discharge energy levels, the average maximum temperature is between 2 to 4 eV. The average maximum electron density of 5J, 20J and 40J discharge energies are $1.6\times10^{20}\text{m}^{-3}$, $1.6\times10^{21}\text{m}^{-3}$ and $1.8\times10^{21}\text{m}^{-3}$, respectively. The time average electron density of 5 J, 20 J, and 40 J discharge energies are between $10^{19}$–$2\times10^{20}\text{m}^{-3}$, $3\times10^{19}$–$10^{20}\text{m}^{-3}$, and $5\times10^{19}$–$1.4\times10^{20}\text{m}^{-3}$, respectively [13].

In 2002, Jurg C. Zwahlen used NASA Lewis Research Center’s LES8/9 PPT to use the current mode quadruple Langmuir probe for the first time. At discharge energy levels of 5, 20, and 40 J, the measurement points are selected within a 40-degree deflection angle from the central axis at a distance of 10 cm, 15 cm and 20 cm from the propellant surface. The measurement results show that the electron temperature has two peaks during the entire pulse operation, and the greater the discharge energy, the more obvious the phenomenon. The electron temperature after the initial high temperature peak is less than 2 eV. Near the exit plane of the thruster, the electron density is highest. For PPT with different discharge energies of 5J, 20J, and 40J, the maximum electron density values 10cm from the propellant surface are $1.04\times10^{20}$±$2.8\times10^{9}\text{m}^{-3}$, $9.8\times10^{20}$±$2.3\times10^{9}\text{m}^{-3}$, $1.38\times10^{21}$±$4.05\times10^{20}\text{m}^{-3}$. The electron temperature and density decrease as the angle from the centerline increases and the distance from the propellant surface increases. The plume is more symmetric in the parallel plane than in the vertical plane. The plume shows asymmetry in the vertical plane, and the plume faces the anode of the thruster. The ion velocity ratio near the exit of the thruster is the lowest, and it increases with the increase of the downstream distance [14].

In 2002, in order to improve the sustainable thrust power level of PPT design, Kamhawi and others of Ohio State University evaluated different propellant and electrode geometries. By changing the length and spacing of the plates, three propellants of standard PTFE, high-density PS and PTFE with a carbon content of 2% were selected for experiments, and the triple Langmuir probes were used to measure the electron temperature and electron density, and it was found that all three propellants were effective the electron temperature in the plasma plume is between 0.7 and 4eV. The electron density of standard and 2% carbon content PTFE is similar, and both are twice that of high-density PS. For standard and 2% carbon content PTFE, the front of the plasma mass moves at an average speed of 37km/s. For high-density PS, the plasma bulk moves at an average speed of 53km/s [15].

2.2. Optical emission spectroscopy method
Optical emission spectroscopy is an important means to diagnose the complex physical and chemical processes that occur in plasma and to measure plasma parameters, as shown in figure 3. Since the spectroscopic diagnosis is non-contact, there is no interference to the plasma. For thrusters that operate transiently like PPT, Optical emission spectroscopy (OES) is also one of the commonly used plasma diagnostic methods for PPT.
The plasma spectrum is related to the radiative transition process of particles in the plasma. After atoms or ions are subjected to thermal or electrical action, the outer electrons gain a certain amount of energy. The electron will transition from a lower energy level to a higher energy level, and the atom or ion in this state is said to be in an excited state. A particle in an excited state is unstable. It will transition from a high energy level excited state to a ground state, or a relatively stable low energy level, and at the same time release excess energy, which is released in the form of light to form an emission spectrum. The wavelength of the spectral line radiated by different particles transitioning between different energy levels is unique, and the characteristics of the plasma can be obtained by analyzing the wavelength information of the spectral line radiated by the plasma.

In 1972, for the plume area of the LES-6 PPT, Thomassen, Vondra and others of the Massachusetts Institute of Technology used optical emission spectroscopy and Faraday cups to measure plasma parameters. It is found that the plume contains C, C +, C ++, C +++ +, F, F +, F + +, F + + +, iron ions produced by stainless steel plate sputtering and spark plug erosion. 90 percents of the plume is neutral particles. At the beginning of the discharge, the particles are ionized into high-valence ions. At the end of the discharge, the energy is not enough to ionize the particles, and the particles are released in the form of neutral particles. The trivalent carbon ion has the fastest average speed, in the range of 30km/s-40km/s [17].

In 1997, Markusic and others of the Electric Propulsion Laboratory of Edward Air Force Base in the United States conducted emission spectroscopy diagnosis of plasma generated by XPPT-1 and detected five particle components F, F+, C+, C++ and C2. It is found that as the discharge energy increases, no new plasma components are formed. The intensity of the emission spectrum is closely related to the PPT current and depends on the discharge energy. Under the assumption of local thermodynamic equilibrium, the electron temperature is calculated to be 1.4±0.2 eV. After the first half cycle of the discharge, the final velocity of the ionized matter in the plasma is between 14~16 km/s [18].

In 2007, Koizumi and others of the University of Tokyo used emission spectroscopy, high-speed photography and magnetic probes to perform plasma diagnosis on the discharge channel of APPT. The resulting spectrum shows that ions exist from the electrode discharge channel to the outside of the thruster outlet plume, while neutral particles are confined near the surface of the propellant. The emission spectrum measurement results are consistent with the previous Thomassen, Vondra et al. [17], Markusic et al. [18]. Based on the spectrogram, we selected representative neutral particles with a wavelength of 514.5 nm and ions with a wavelength of 426.8 nm for high-speed photography. The
results showed that the high-density, ablated neutral gas stayed near the surface of the propellant, only a small part of it. Neutral particles are transformed into plasma and accelerated by electromagnetic force [19].

In 2013, Schönherr of the University of Tokyo and others used emission spectroscopy to analyze the changes in the plasma characteristics of the discharge channel of PPT over time, space and discharge energy. It is found that the plasma composition in the cross section of the discharge channel is not uniform and asymmetric, and the temperature near the cathode decreases with time, while the temperature on the center line increases. Under the assumption of local thermodynamic equilibrium (LTE), the electron temperature of the discharge channel is calculated to be between 1.7-3.1 eV, and the electron temperature measurement results are consistent with Markus et al. Using the stark broadening method to calculate the electron density, it is found that the electron density near the electrode is higher. Relative to the electron temperature distribution, the diffusion process on the plasma cross section is likely to be slower than the plasma movement time. The electron density distribution of the entire acceleration channel remains constant, the electron density is about $10^{17} \text{m}^{-3}$, indicating that the plasma diffusion on the cross section is slower than the plasma movement speed. The plasma velocity measured by emission spectroscopy is about 45km/s, and the three ion velocities of C+, C++ and F+ are close, indicating that the amount of ion charge has no significant effect on the velocity [20].

In 2013, Wang of Hebei University of Technology, Liu Feng of Fudan University and others conducted emission spectroscopy studies on PPT. The electron temperature in the space of the PPT plate was calculated by emission spectroscopy, which proved that some local thermodynamic equilibrium rules can accurately and effectively determine the electron temperature. Found that there are two distinguishable plasmons [21].

In 2017, Liu, Wu and others of Beijing Institute of Technology used emission spectroscopy to measure the plasma parameters of the discharge channel of a double pulse discharge PPT. Under the assumption of local thermodynamic equilibrium (LTE), the electron temperature was calculated to be about 1.5 eV, the electron density is between $13.0 \times 10^{16}$-$14.6 \times 10^{16} \text{cm}^{-3}$. As the discharge energy of the second discharge channel increases, the electron density increases and the electron temperature increases [22].

In 2019, William of Beijing Institute of Technology and others used emission spectroscopy to explore how asymmetric PPT with different anode plate lengths affects and changes the emission spectra of plasma components. For all asymmetric PPTs with different anode plate lengths, the electron temperature is calculated to be in the range of 1 eV under the assumption of local thermodynamic equilibrium (LTE). The electron density of the discharge channel is measured by the stark broadening method. The maximum electron density value of the symmetrical plate (the length ratio of the cathode and anode plate is 1:1) and the 15 mm anode (the length ratio of the cathode and anode plate is 1:0.75) is about $10^{23}$-$10^{24} \text{m}^{-3}$. The maximum electron density of the plate space with the anode length less than 10mm increased by 3 orders of magnitude, reaching $10^{27} \text{m}^{-3}$, and the best anode plate length is inferred to be between 5-10mm [23].

In conclusion, the emission spectrum has been used in the study of PPT discharge channel acceleration mechanism. The emission spectrum line diagram is used to determine the plasma composition, the electron temperature is calculated based on the local thermodynamic equilibrium (LTE) assumption, and the electron number density is calculated by the Stark broadening method. The physical process from plasma formation to acceleration in PPT discharge channel is more deeply understood. Compared with the triple Langmuir probe, the emission spectrum, as a non-contact diagnosis method, will not be interfered by the strong electromagnetic signal of the discharge channel, and the non-contact emission spectrum diagnosis will not interfere with the working process of the PPT. However, emission spectroscopy, as a non-contact diagnostic method, cannot achieve point-to-point measurement. The collected optical signal is an integrated signal in the depth direction, and the depth information is lost. The use of optical emission spectroscopy combined with high-speed photography technology plays an important role in understanding the acceleration process and mechanism of PPT.
3. Conclusion

Probe method and optical emission spectroscopy method have been widely used in plasma parameter measurement of PPT. Due to the strong electromagnetic signal generated by the discharge channel of the PPT, it interferes with the signal collection of the probe. The probe method is mainly used to measure the plasma plume outside the discharge channel, because the plasma luminescence intensity of the discharge channel is relatively large, and the emission spectroscopy method is more applied to the plasma diagnosis of the PPT discharge channel. In comparison, the spectral diagnosis research in PPT is not as extensive as probe diagnosis, and there is still room for further exploration. In the future, it can be considered to combine the triple Langmuir probe with optical emission spectroscopy to realize the integration of time and space plasma parameter measurement from the PPT discharge channel to the plume area.

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