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Estimation of Plasma Parameters for Microwave-Sustained Ar/He Plasma Jets at Atmospheric Pressure

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In this article, we have analyzed the measured probe characteristics of microwave-sustained Ar and He plasma jets at atmospheric pressure using the high-pressure probe theory developed by Talukder et al. in order to determine the generated plasma parameters (electron temperature, T_e, electron density, N_e, plasma potential, ϕ_p). The calculation shows some unusual temperature profiles (both axial and radial) as well as provides some over estimation of electron temperature measured from the distorted I-V characteristic due to a smaller electron to ion saturation current ratio coming from the limited electron saturation current. In order to overcome these limitations, the measured probe characteristics are also analyzed by using the asymmetric double probe theory developed by our group, which provides reasonable value of plasma parameters. The influence of microwave power and gas flow rate on the plasma parameters are also investigated.

1 Introduction

Atmospheric-pressure plasmas have attracted much interest recently in material processing technology, medical treatment, light sources, environmental applications and many more [1-3]. They may also have great potentiality for the very high heat-flux plasma beam intended for fundamental research on plasma-wall interactions (PWI) in next-generation fusion devices, such as ITER (International Thermonuclear Experimental Reactor) and DEMO (DEMOnstration Power Reactor) [4-6]. In this regard, the development of powerful, stable and efficient plasma generators is of high demand.

Recently, the production of microwave plasma jets at atmospheric pressure [7-9] using the recently developed TIAGO (Torche à Injection Axiale sur Guide d'Ondes, in French) nozzle [7] become very popular due to its simplicity, easy ignition, efficient microwave-to-plasma coupling, electrodeless operation, unnecessacity of vacuum chamber, availability of inexpensive sources at 2.45 GHz, and sustainment of the discharge at open air. However, to generate such stable and efficient plasmas using the TIAGO system, the discharge performance of the generated plasmas must be optimized by investigating the plasma parameters. Also for PWI study, high-temperature and high heat-flux plasmas are desirable, and sufficient knowledge of plasma parameters have to be known in this regard. The Langmuir probe is the most commonly used diagnostic tool to determine the plasma parameters under a variety of plasmas for both collisional and collisionless case. But the investigation of measured probe characteristic of collisional plasmas under atmospheric pressure is quite difficult due to the lack of high-pressure probe theories.

It has already been well-established that there are some difficulties to interpret the I-V characteristics of strongly ionized plasmas [10, 11] and detached recombining plasmas [12]. Because, in atmospheric pressure range, electrons and ions make numerous collision with the neutral particles before being collected by the probes,

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and therefore, the collisions between neutrals and electrons or ions in the sheath region near the probe surface can not be neglected because of shorter mean free path than the sheath thickness. In this case, diffusion process for charged particles become dominant than convective motion inside the sheath. An electrostatic probe characteristic using single probe in a dense, partially ionized plasma is studied by Su et al. [13] and Cohen [14], and some formulae are introduced by Talukder et al. [15], which can easily be applied to single probe diagnosis in order to obtain the plasma parameters by fitting the equation to measured probe data. Recently, an asymmetric double probe (ADP) theory is proposed by our group (Saito et al. [16, 17]) by extending the Cohen's theory to obtain the plasma parameters at atmospheric pressure. In this work, first, we have analyzed the measured probe characteristics of microwave plasma jets at atmospheric pressure using the high-pressure single probe (HSP) theory [15] in order to determine the generated plasma parameters (electron temperature, T_e and electron density, N_e), and then the measured probe characteristics are analyzed by using the recently developed ADP theory [16, 17] in order to compare the plasma parameters with those estimated by HSP theory [15].

2 Experiments

The experimental setup consists of a magnetron source (1.5 kW, 2.45 GHz), WRJ-2 rectangular waveguide (combination of both flat and tapered), an isolator, a directional coupler for measuring the incident and reflected power, an E-H tuner for impedance matching, a short plunger for producing the standing wave and a coupling launcher to produce the plasma jets by using the strong electric field of TE_{10} mode. The short plunger is adjusted so that the distance between the short plunger and the launcher become an odd multiple number (9 or 11 in the present case) of a quarter wavelength of waveguide, λ_g (about 147.7 mm in the present case) to ensure the maximum possible microwave field at the launcher position. The microwave-sustained Ar (0.5 L/min) and He (1.1 L/min) plasma jets are produced at atmospheric pressure with a microwave power of less than 400 W by applying the recently developed TIAGO (Torche à Injection Axiale sur Guide d'Ondes, in French) nozzle [7]. The flame-like spindle shape plasma torches corresponding to a so-called normal straight discharge, one of the bifurcated discharge modes [8], are observed as shown in Fig. 1(a). The single-probe (material: tungsten, L = 2.3 mm, ϕ = 0.8 mm) measurement has been performed at different height from the nozzle head by sweeping it using a computer-operated motion controllable single-axis motor with an angular speed of 20 degree/s to study both the axial and radial profile of plasma parameters.

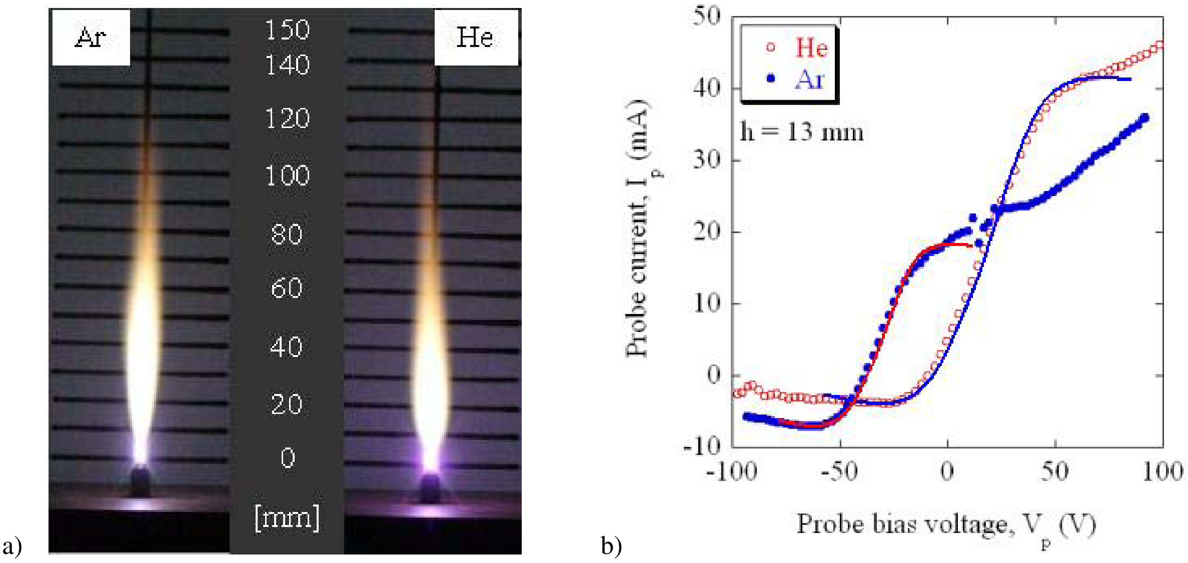

Fig. 1 (a) Typical still photo of Ar (0.5 lpm) and He (1.0 lpm) plasma jets with spindle shape at microwave input power of 320 W for both gases, and (b) I-V probe characteristics of Ar and He plasma jets (both raw data and their fittings) at a height of 13 mm from the nozzle head and at the center of the plasma jet (radial position, r = 0). (Color figure: www.cpp-journal.org).

3 Estimation of Plasma Parameters

The generated plasma parameters (electron temperature, T_e, electron density, N_e, plasma potential, ϕ_p) are calculated by analyzing the probe characteristics using the high-pressure single probe (HSP) theory [15]. The analysis is based on an iterative fitting process of measured probe data using non-linear least square method. A GUI (Graphical User Interface) computer program is developed for analyzing the data in order to obtain the plasma parameters from the Langmuir probe I-V characteristics. The typical I-V characteristics of Ar and He plasma jets measured at a height of 13 mm from the nozzle head with a microwave input power of 320 W are shown in Fig. 1(b). According to HSP theory [15], the best-fitted curves represented by solid lines will provide the plasma parameters.

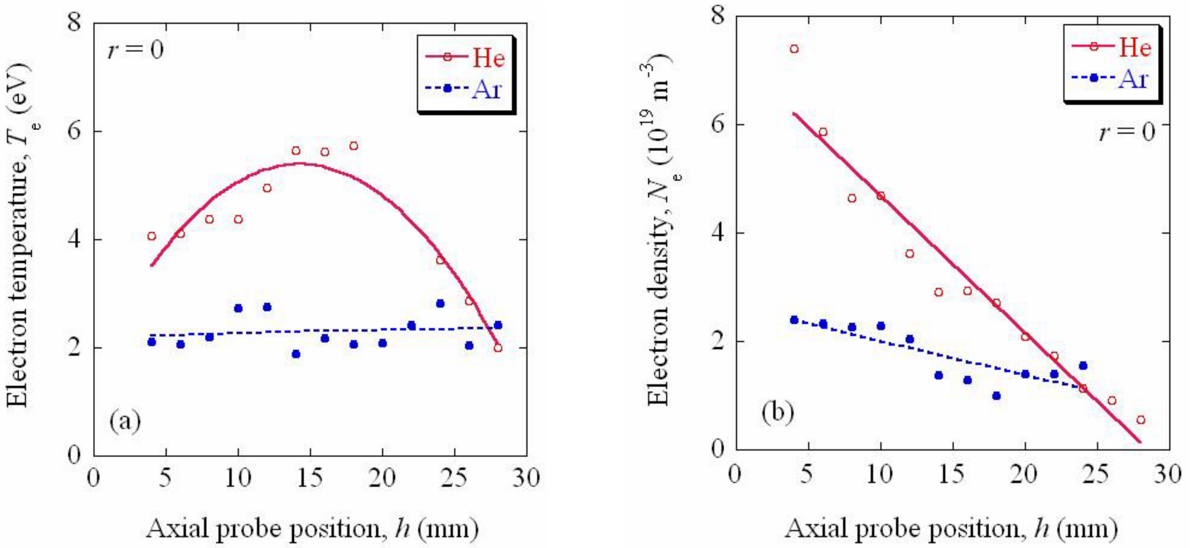

Fig. 2 Comparison between Ar and He plasma parameters estimated by high-pressure single probe theory [15]. Axial profile of (a) electron temperature, T_e and (b) electron density, N_e. (Color figure: www.cpp-journal.org).

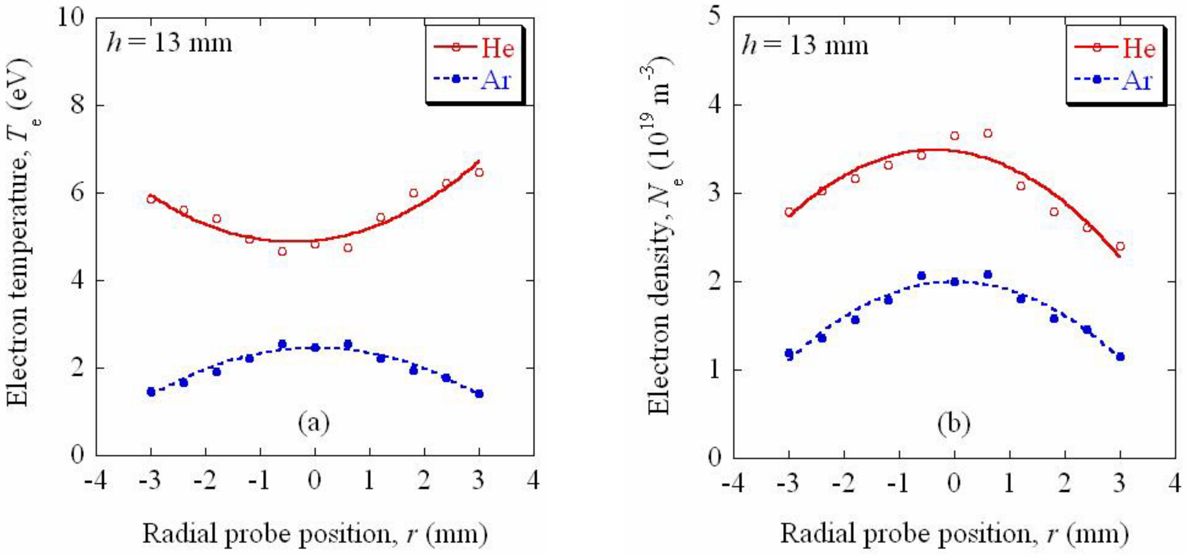

Fig. 3 Comparison between Ar and He plasma parameters estimated by high-pressure single probe theory [15]. Radial profile of (a) electron temperature, T_e and (b) electron density, N_e. (Color figure: www.cpp-journal.org).

The electron temperature, T_e of Ar plasmas estimated by HSP theory [15] is found to be almost constant of 2 eV over the range of height up to 30 mm from the nozzle head, and on the other hand, for the He plasmas, T_e increases from 4 eV to 6 eV over the range of height up to 20 mm from the nozzle head and then decreases from 6 eV to about 2 eV from 20 mm upward as shown in Fig. 2(a). The electron density, N_e is found to be decreasing from 2.5×10^{19} to 1.5×10^{19} m^{-3} for Ar Plasmas while from 7.5×10^{19} to $0.5\times10^{19}\mathrm{m}^{-3}$ for He plasmas over the range of height up to 30 mm from the nozzle head as shown in Fig. 2(b). Figure 3 shows the radial profile of T_e and N_e for Ar and He plasmas measured at a height of 13 mm from the nozzle head. It is observed that the HSP analysis [15] provides some unusual patterns of axial and radial profile of electron temperature: (1) electron temperature increases at higher plasma position as show in Fig. 2(a), and (2) electron temperature is lower at the center than that of plasma boundary as shown in Fig. 3(a). From Figs. 2 and 3, it is also observed that the HSP analysis [15] provides some over estimation of electron temperatures as high as 3 eV and 6 eV for Ar and He plasma, respectively, which are 2 to 3 times higher than the expected values for both the gas species. These discrepancies may occur due a smaller electron to ion saturation currents ratio in I-V characteristics than what is expected from the standard high-pressure probe theories. This feature may come from the limited electron saturation current caused by the insufficient contact of plasma with the reference electrode (TIAGO nozzle in the present case) having a small cross section [18-20].

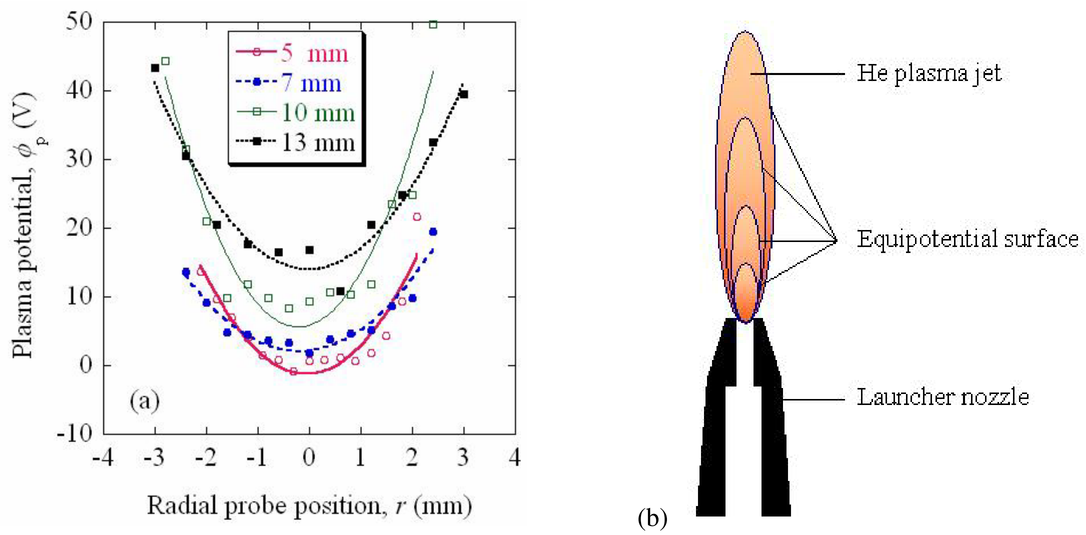

Fig. 4 (a) Radial profile of plasma potential, ϕ_p of He plasma jets measured at different height from the nozzle head and estimated by high-pressure single probe theory [15], and (b) Probable equipotential surface structure of He plasma jet. (Color figure: www.cpp-journal.org).

Figure 4(a) shows the radial profile of plasma potential, ϕ_p for He plasma jets at atmospheric pressure measured at different height from the nozzle head and estimated by HSP theory [15]. It is seen that the plasma potential decreases at the center of the plasma while increases at the edges. The plasma potential also increases with increasing height of probe position from the nozzle head. From the two-dimensional profile of plasma potential, He plasma jet can be considered as axisymmetric, which has an equipotential and isothermal surface just like an onion structure as shown in Fig. 4(b).

Figure 5 shows the microwave power and gas flow dependence of plasma parameters estimated by high-pressure single probe analysis [15]. From Fig. 5(a) it is observed that both the microwave power and gas flow rate has no such significant effect on electron temperature for He plasmas, while electron temperature slightly increases for Ar plasma jets with increasing either the gas flow rate or the input power. From Fig. 5(b) it is observed that the gas flow rate has no significant effect on electron density for He plasmas, while electron density exponentially increases with increasing the input power. For Ar plasmas, on the other hand, the electron density increases with increasing either the gas flow rate or input power.

Finally, in order to overcome the limitations of HSP theory [15], we analyze the measured probe characteristics using the recently developed asymmetric double probe (ADP) theory [16, 17], and compare the plasma parameters with those estimated by single probe theory [15]. The axial profile of electron temperature, T_e of Ar and He plasmas estimated by HSP [15] and ADP theory [16, 17] are compared in Fig. 6(a) and 6(b), respectively. From these figures it is observed that the temperature estimated by ADP theory [16, 17] decreases with increasing the probe position from the nozzle head for both the gas species as expected, which is the opposite pattern getting from the HSP theory [15] ensuring the reliable plasma parameters estimated by ADP theory [16, 17]. The electron temperature estimated by the ADP theory [16, 17] is found to be in the range of $1.2\sim1.5$ eV in the case of Ar plasmas while $0.9\sim3$ eV in the case of He plasmas indicating that ADP theory provides more reasonable values of plasma parameters.

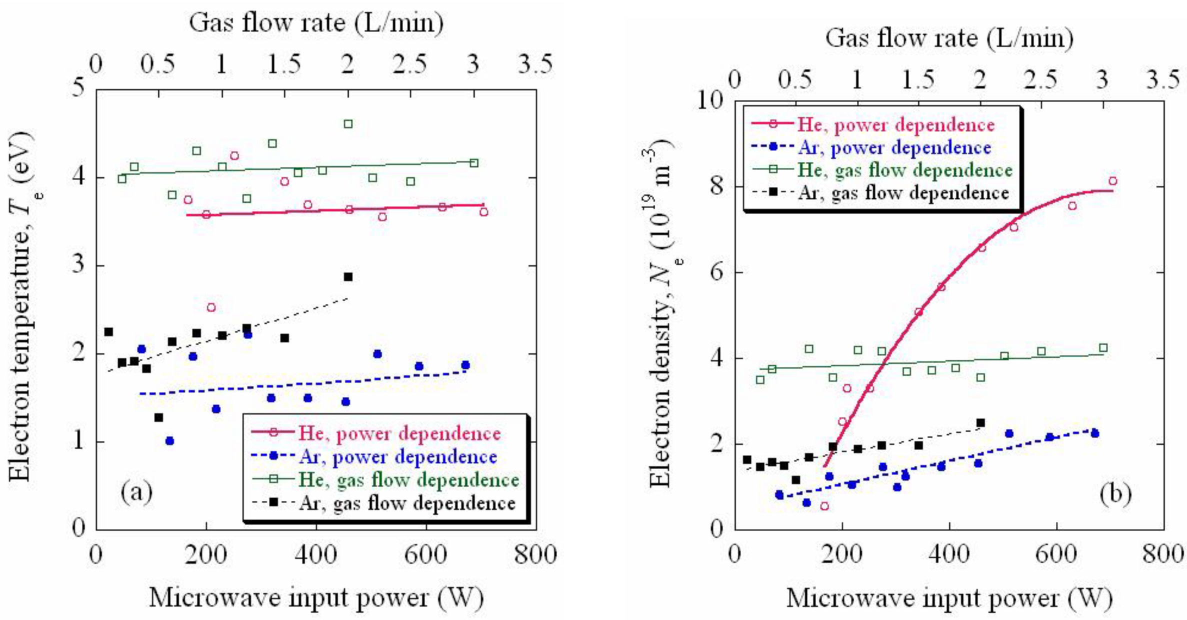

Fig. 5 Microwave power and gas flow dependence of plasma parameters estimated by high-pressure single probe [15]. (a) Electron temperature, T_e. (b) Electron density, N_e. (Color figure: www.cpp-journal.org).

Figure 7 shows the comparison of electron density, N_e of He plasma jet estimated by HSP theory [15] and ADP theory [16, 17] under the quasi-neutrality condition $N_e = N_i$, where N_i is the ion density. The radial profile shows that the plasma density (measured at a height of 13 mm from the nozzle head) has a higher value at the center of the plasma while lower at the edges near the boundary of the plasma and surrounding atmosphere for both cases as shown in Fig. 7(a). On the other hand, from the axial profile shown in Fig. 7(b) it is observed that the plasma density decreases at higher position of the plasma as expected. It is noticed that the electron density measured by ADP theory [16, 17] is found to be a half order higher than those measured by HSP theory [15]. From Figs. 6 and 7, it is observed that the characteristic lengths of spatial gradients of electron temperatures are found to be about 20 mm and 10 mm for Ar and He plasmas, respectively, which are much larger than the probe dimensions (L= 2.3 mm, ϕ = 0.8 mm). Similarly, the characteristic lengths of spatial gradients of electron density are found to be about 10 mm and 7 mm for Ar and He plasmas, respectively, which are also larger than the probe dimensions. These features of having high spatial resolution ensure the reliability of the probe measurements under the present experimental conditions.

4 Summary

The high-pressure single-probe analysis provides some over estimation of electron temperature as high as 3 eV for Ar plasmas and 6 eV for He plasmas. It also provides some unusual pattern of axial and radial profile of electron temperature: (1) electron temperature increases at higher plasma position, and (2) electron temperature is lower at the center than that of plasma boundary. These features probably come from the limited electron saturation current and consequently a smaller electron to ion saturation currents ratio in I-V characteristics than

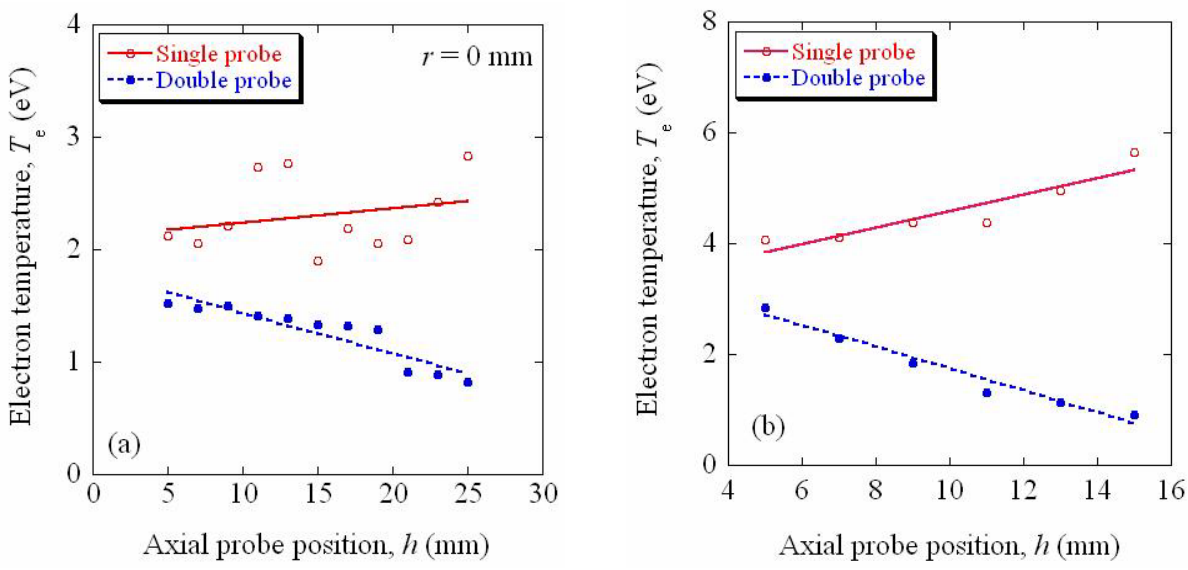

Fig. 6 Comparison of electron temperature, T_e estimated by high-pressure single probe [15] and asymmetric double probe [16, 17] theory. (a) Ar plasma and (b) He plasma. (Color figure: www.cpp-journal.org).

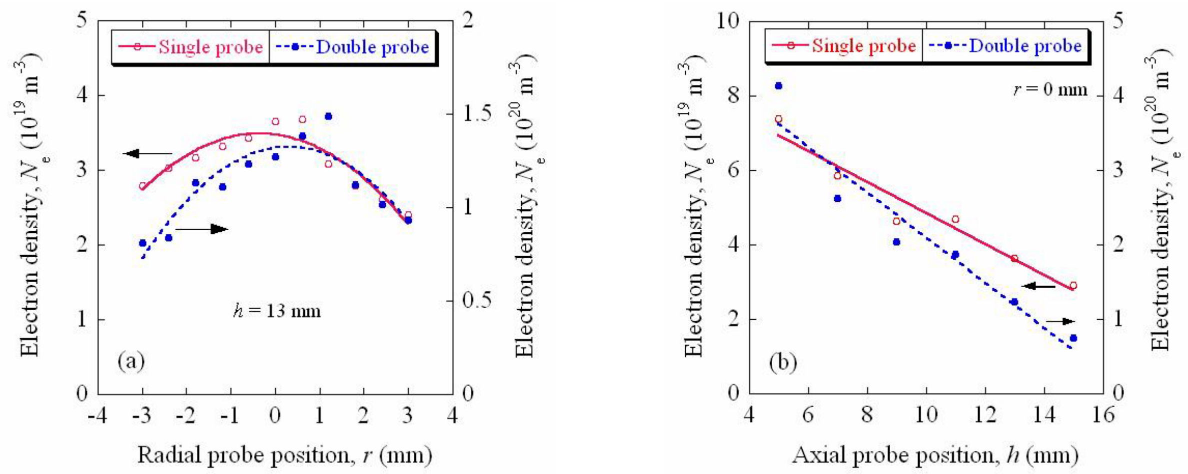

Fig. 7 Comparison of electron density, N_e of He plasma jets estimated by high-pressure single probe [15] and asymmetric double probe [16, 17] theory. (a) Radial profile measured at a height of 1 0mm from the nozzle head and (b) Axial profile measured at r = 0. (Color figure: www.cpp-journal.org).

what is expected from the standard high-pressure probe theory. To overcome these limitations, the measured probe characteristics are analyzed by recently developed asymmetric double probe (ADP) theory, which provides a revised value of electron temperature in the range of 1∼3 eV. It gives electron density in the order of 10^{20}m^{-3}, which is about one order higher than that measured by HSP analysis. These measurements indicate that the asymmetric double probe analysis provides the reasonable plasma parameters of microwave-sustained Ar and He plasma jets at atmospheric pressure.

5 Future Work

In this work, the measured single probe characteristics are analyzed by asymmetric double probe theory in order to obtain the reasonable plasma parameters. Our future work will include the analysis of double probe data using the asymmetric double probe theory along with the estimation of secondary electron emission current.

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