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Development of a self-consistent plasma generation model for inductively coupled plasma

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Abstract
As a significant stem of thermal plasma that performs high gas temperature and high energy density, atmospheric-pressure inductively coupled plasma (AP-ICP) plays an essential role in surface processing, such as etching and filming. To further improve the surface processing performance, it is necessary to conduct a diagnosis of the plasma state characteristics, such as gas temperature and reactive radical concentration. However, current sensing equipment, including thermal cameras and resistance temperature detectors (RTDs) for temperature, and optical emission spectrum (OES) for radical intensity, primarily lacks sufficient spatial resolution ability for plasma diagnosis. In this study, we developed a self-consistent argon AP-ICP state diagnosis model, which has been validated by experiment and both observed a fast internal plasma fluctuation. As a result, the mechanism of inducing plasma fluctuation inside AP-ICP was uncovered, providing an in-depth sight of AP-ICP interior characteristics.

Numerical simulation, atmospheric-pressure inductively coupled plasma (AP-ICP), plasma fluctuation

1. Introduction

In recent years, there has been a strong tendency to avoid costly vacuum chambers for plasma generation and processing, leading to the quick development of atmospheric pressure plasma techniques [1]. Due to its superior properties, such as very high gas temperature and great power density, atmospheric-pressure inductively coupled plasma (AP-ICP) has become one of the most crucial thermal plasmas for various applications that require high reactivity and high thermal energy [2,3]. However, as per the distribution of time-variant magnetic fields around the coils, the induced electric ring field that activates and sustains AP-ICP will cause a relatively low uniformity at the plasma bulk region. To achieve better plasma processing performance, the diagnosis of AP-ICP in reactive radicals and the gas temperature becomes increasingly indispensable. However, current sensing methods, such as contact-free optical emission spectroscopy (OES) for plasma spectrums and contact resistance temperature detectors (RTDs) for gas temperature, face several challenges in distinguishing localized data (rather than integrated measurements along the optical path) and preventing electromagnetic interference.

To overcome the difficulties in AP-ICP's condition and behaviour analysis with sensors, numerical modelling methods have become increasingly attractive and serve as an essential tool for plasma diagnosis. Numerical modeling is based on solving highly coupled sets of physical field equations that describe plasma properties, in terms of electromagnetics, chemical reactions, fluid dynamics, heat transfer, and more. However, the accuracy of numerical models should be accordingly validated by experiment, before conducting the plasma diagnosis. As a result, specific information about plasma properties can be obtained at any position, and the plasma itself does not experience electromagnetic interference while the data is measured. AP-ICP is a typical thermal plasma with a very close gas temperature and electron temperature (classified as local thermodynamic equilibrium [LTE] state), making it popular in magnetohydrodynamics (MHD) modelling. However, MHD modelling does not consider plasma chemistry and has witnessed a significant deviation at the plasma edge [4]. It cannot provide any radical information inside the plasma and has limited diagnostic accuracy.

In this study, different from the conventional MHD modelling, a self-consistent plasma generation model that considers plasma chemistry was developed for AP-ICP diagnosis, together with the high-speed motion camera observation, and witnessed the plasma fluctuation phenomenon in AP-ICP. Subsequently, the formation mechanism of this fluctuation was discussed and analyzed.

2. Simulation modelling and experiment setup

Figure 1 (a) shows the schematic image of our AP-ICP generator, which involves coaxial quartz tubes for inputting process gas and cooling gas, and induction coil are driven by radio-frequency (RF) power at 27.12 MHz. The simulation model was assumed to be 2D axisymmetric for computation cost reduction, as presented in Fig. 1 (b). There were two velocity inlet boundaries for process inlet and cooling inlet, respectively. The outlet boundary was assumed to be a pressure outlet condition for better convergence ability. The reduced electric field of our atmospheric

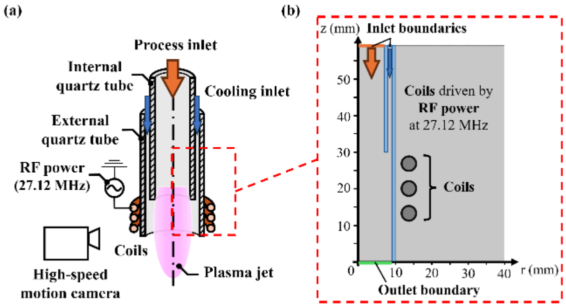

Figure 1. Schematic image of AP-ICP generator. (a) experimental setup, (b) simulation model.

argon plasma bulk is roughly 3 Td, within the range of the database [5] for modelling elastic collisions and inelastic collisions in argon plasma, where the electron impact reactions among electrons, argon neutral atoms, metastable argon atoms (4s), and argon ions were considered in this model. To precisely capture the electron transport and energy dissipation in atmospheric plasma, the electron mobility used in this model was referred to *ref* [6].

In the experimental setup, high-purity argon gas was supplied to the process inlet (Ar: 1.5 slm) and the cooling inlet (Ar: 10.8 slm), respectively. The RF power (*f*= 27.12 MHz, P= 700 W) was used to drive the copper coil set, enabling the activation and sustainment of AP-ICP. A high-speed motion camera was placed next to the generator and focused on the plasma bulk near the modelling region. To capture a clear and continuous plasma fluctuation phenomenon, its capture frequency was set as 5 kHz and with a short exposure time (*t*= 7 μs). The whole recording time is 200 milliseconds.

3. Results and discussion

Figure 2 presents the plasma fluctuation phenomenon in AP-ICP observed by both experiment and numerical simulation. In Fig. 2(a), the plasma bulk intensity was continuously recorded by the high-speed motion camera and a measured spot was selected for further analysis. The plasma intensity changes over time have been presented in a grayscale graph and processed by the Savitzky-Golay (SG) filter for random noise reduction [7], as shown in Fig.2(b). In Fig. 2(c), to locate the main frequency of the plasma fluctuation in AP-ICP, the Fast Fourier Transform (FFT) has been applied to the fitting result, and the main period of current plasma fluctuation is approximately 9.94 milliseconds. A fitted period wave with this period has been illustrated in a red, while the gas temperature result by numerical modelling is in a green and with roughly 6.66 milliseconds in the period. The predicted fluctuation period by simulation is about 33.0% shorter than the experimental result, and this might be caused by simplified plasma chemistry reaction sets, constant electron mobility used in this model. This self-consistent plasma model is available for a qualitative analysis of the formation in the plasma fluctuation of AP-ICP. However, further improvements regarding the reaction set optimization and real-time electron mobility computation, are still needed for a higher modelling precision.

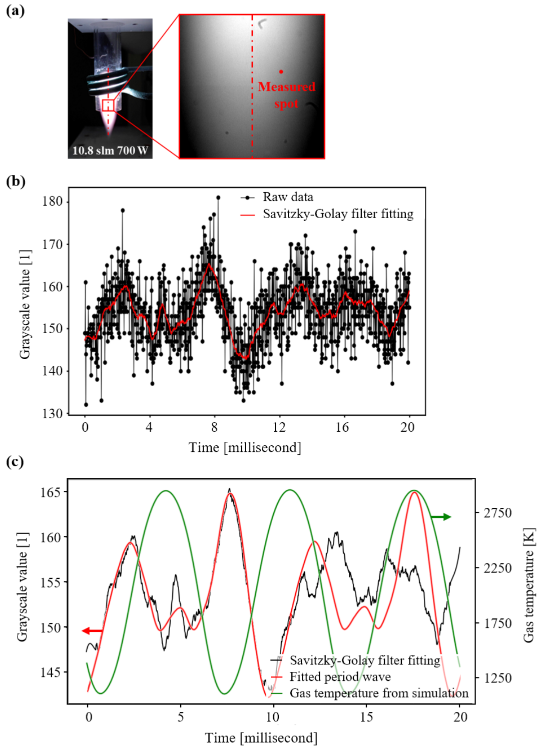

Figure 2. Plasma fluctuation of this AP-ICP with (a) measurement region, (b) plasma intensity changes along the time, (c) fluctuation period fitting and related modelling result.

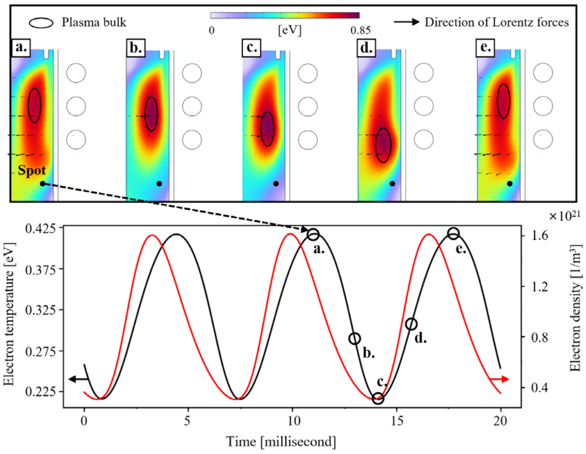

Figure 3. Time-variant plasma fluctuation characteristics including electron temperature and electron density that predicted by our model.

To investigate the mechanism of causing plasma fluctuation characteristics of AP-ICP, electron temperature and electron density were predicted by numerical simulations, as shown in Fig. 3. In the same measuring spot, both electron density and electron temperature were observed to share the same period of about 6.66 milliseconds, whereas there was a time lag (roughly 1.2 milliseconds) before the increase in electron temperature against the electron density. It might be due to after AP-ICP is fully developed; in each period, electrons with relatively high energy will be quickly consumed by new non-excited processing gas and produce more electrons through inelastic collisions, before the maximum electron density is achieved. As a result, the accumulation of the total electron energy has been postponed. Furthermore, graphs named Labels a. to e., present the electron temperature distribution changes within one period. The graphs show that the plasma bulk moves downstream by the Lorentz forces and once it moves far away from the coils, a new plasma bulk will be quickly ignited. This movement plays an essential role in affecting the plasma bulk's maximum electron density and motivates the above periodic behaviour in electrons from happening.

4. Conclusions

In this study, the period plasma fluctuation of AP-ICP has been observed in both experiments and simulations. The mechanism to induce the periodic fluctuation is primarily caused by the Lorentz forces inside the plasma bulk. This also leads to a change lag between the electron temperature and electron density. Further optimization and validation of this plasma model will be conducted, particularly in broader working conditions.

5. Acknowledgements

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