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Discharge Bifurcation of Microwave-sustained Helium Plasma Torch at Atmospheric Pressure

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Structural bifurcation of microwave-sustained helium jet discharge at atmospheric gas pressure has been found on the way to a generation of a stable helium plasma torch which may open the possibility of a new type of high flux test plasma beam for plasma-wall interactions in fusion devices and for volumetric radical species source in medical and industrial applications. The physical mechanism on such a bifurcation and a hysteresis characteristics is discussed in terms of distribution of microwave electric field around the jet nozzle, structure of the nozzle and gas enthalpy.

Keywords: structural bifurcation, microwave-sustained plasma, atmospheric-pressure discharge, helium plasma torch, enthalpy, discharge transition

1. Introduction

Atmospheric-pressure plasmas attract many interests recently for the application to material synthesis, medical treatment, environmental applications and so on. It may have also a great potential for the high-flux plasma beam intended to the plasma-wall interaction research in fusion devices. The conventional linear-plasma simulator for the fundamental studies on plasma-surface interaction has made several important roles [1]. However, the particle and heat fluxes in those machines are not sufficient for simulating those in the next generation fusion devices, like ITER (International Thermonuclear Experimental Reactor) and DEMO (DEMOnstration Power Reactor). Recently Pilot-PSI (Plasma Surface Interaction) seems to meet such a requirement by using cascaded DC arc discharge for the plasma production [2]. Unfortunately, an Ohmic heating current would be necessary to have a high heat flux on target plate which must be therefore, conducting materials. This scheme is very similar to so called "transfer arc" in the application to get heat source from arc discharges. The main heat carriers are electrons in the transfer arc. Such a situation is different from the plasma-wall interactions in the divertor plate on the reactor wall, since the ion bombardment is essential there. This deficiency comes from the electrostatic potential structure determined by DC arc configurations so that the control of the target potential turns to be difficult.

In order to overcome such difficulties, microwave-sustained plasma torch in atmospheric gas pressure is considered as a new plasma source with high particle and heat fluxes since it has no external fixing of electrostatic potential structure in the source, and the high power microwave helps to heat plasma electrons along the plasma beam by the dissipative surface wave propagation. The present work shows some fundamental discharge properties motivated by the above objectives. The helium gas is employed since the helium atoms and ions are important species in fusion devices as well as hydrogen isotopes.

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2. Plasma Device

Figure 1 shows the microwave circuit with a coupling launcher for plasma jet in which the isolator and E-H tuner ensures a stable transfer of 2.45 GHz microwave power of less than 1.0 kW through WRJ-2 waveguide to the launcher.

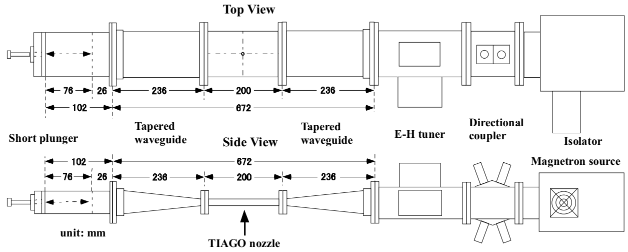

Fig.1 Microwave circuit for plasma torch at atmospheric pressure.

The tapered waveguide makes the electric field at the narrow gap section strong, and moreover the short plunger produces a standing wave so that the electric field may become maximum of standing wave at the launcher position on the straight waveguide with a small height between H-planes of waveguide. The distance between the short plunger and the launcher is set an odd multiple number of a quarter λ_g, where λ_g is the wavelength in the waveguide and 147.7mm. In the present case the odd number is 11.

We employed the TIAGO (Torche à Injection Axiale sur Guide d'Ondes, in French) nozzle for the launcher and gas injection developed by Moisan for the microwave-sustained plasma torch [2], as shown in Fig. 2. A conical structure of the nozzle enhances the microwave field around the top where the main discharge occurs.

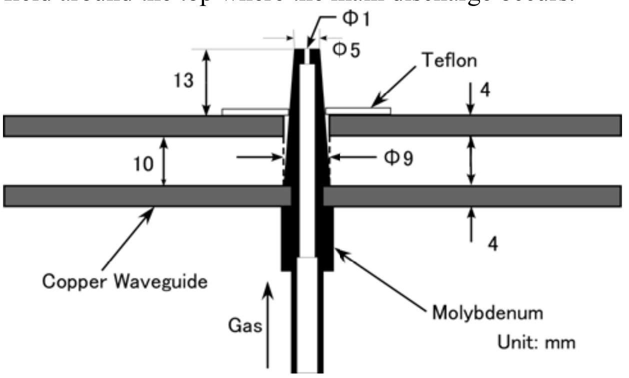

Fig.2 TIAGO nozzle set on the straight waveguide for microwave-sustained plasma torch.

3. Bifurcation Phenomena at Discharge Ignition

Some typical images of torch plasmas are shown in Fig.3. The discharge ignition is performed by the initial electrons of corona discharge produced with a Tesla coil. We found that the initial gas flow rate from the nozzle gives significant influence on the discharge ignition. Figure 3 (a) shows a straight helium discharge with a spindle structure of about 20 cm in length which seems macroscopically very stable. The flame length increases with incidental microwave power and has a maximum at an appropriate gas flow rate.

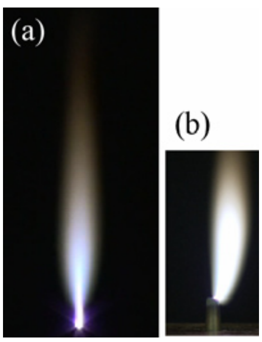

Fig.3 Typical still photos of microwave-sustained plasma torch (a) straight helium plasma jet with spindle shape, (b) curved discharge structure

On the other hand, a curved discharge (b) appears with a reduced preset gas flow, in which the foot of the discharge on the nozzle is not on the top center, but at circumferential edge of the nozzle head: this produces a curved discharge channel clearly as shown in the image. The foot turns from time to time around the circumferential edge, either clockwise or anti-clockwise.

Spectroscopy can clearly discriminate between these two discharge modes as shown in Fig.4 where (a) shows the ultraviolet and visible spectrum from the straight helium jet plasma close to the nozzle head indicating strong helium species although the molecular emissions from air components are visible, while (b) corresponds to that from the curved discharge plasma with few helium emissions. This fact indicates an air discharge with molybdenum contamination.

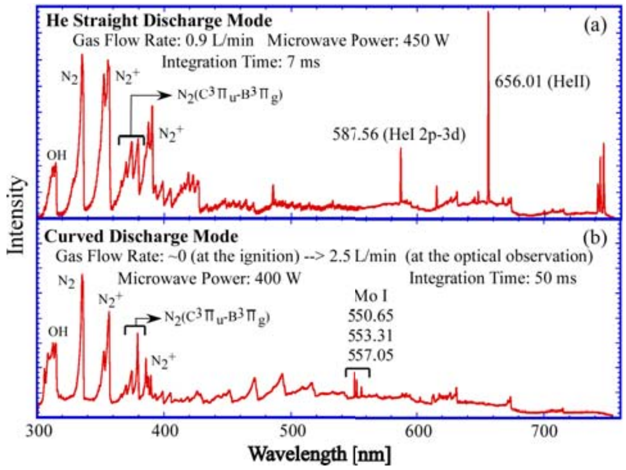

Fig.4 Spectra of optical emission from the foot of jet plasma close to the nozzle head. (a) was obtained from the straight helium plasma jet, while (b) corresponds to the curved discharge mode

Figure 5 shows the area corresponding to stable straight jet discharge ignition between two boundary lines in the parameter space of preset helium gas flow rate and incident microwave power. The figure shows the ignition conditions with Tesla coil. The stable ignition area expands with increase in incident power. The upper boundary shows a maximum initial gas flow rate above which the gas flow rate is too large to have an ignition. The lower boundary corresponds to a maximum initial gas flow rate below which we have a curved discharge ignition.

Once we obtain an unstable curved discharge with an appropriate preset gas flow rate corresponding to Figs.3(b) and 4(b), we still have a curved discharge even at an increased flow rate crossing the lower boundary after ignition. In fact the preset He gas flow rate for Fig.4(b) is close to zero at ignition and then increases to as much as 2.5 L/min. On the other hand we can reduce

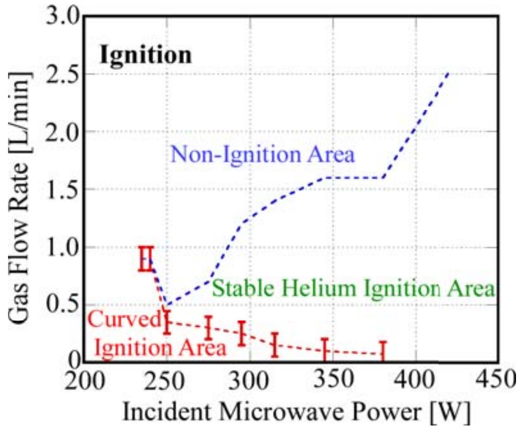

Fig.5 Ignition area for straight helium discharge in the parameter space of helium gas flow rate at atmospheric pressure and incident microwave power. The area between the two boundaries corresponds to straight helium discharge ignition. The upper line shows the boundary for straight discharge ignition above which we do not have any initial ignition, while the lower line does the boundary for curved discharge, below which we have rotating curved discharge ignition.

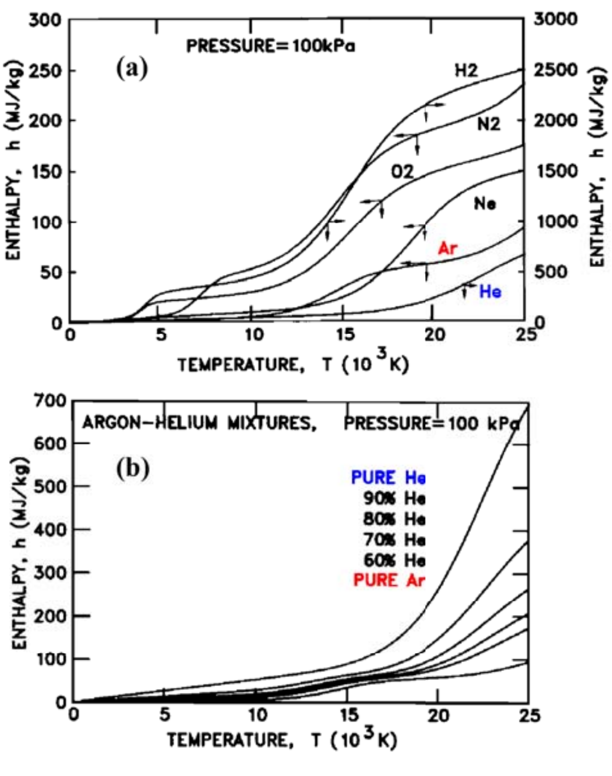

Fig. 6 Enthalpy for various gases. (a) Specific enthalpy of various gases at atmospheric pressure versus temperature. (b) Specific enthalpy of various Ar-He mixtures (vol %) at atmospheric pressure versus temperature. The upper most line corresponds to pure helium From Figs. 6.16 and 6.19 of ref [5].

the flow rate while sustaining a stable straight discharge mode slightly below the lower boundary after obtaining a stable ignition with an appropriate preset gas flow rate corresponding to Fig.3(a) and 4(a).

4. Discussions on the Physical Mechanism

We now try to explain the physical mechanism of this bifurcation [4] of discharge structure at the ignition. Based on the spectroscopic analysis and image observations, the curved discharge mode is considered to form a round about discharge channel bypassing the straight helium gas flow. There is little helium emission species from the curved discharge plasma, which is considered to be composed of air components.

Usually people recognize that the helium is one of the most easily discharged gases, probably due to the presence of some metastable states although the ionization potential is the highest. Comparing the molecular gas species like N_2 and O_2, the monoatomic molecule like He has a lower enthalpy than molecular gas does as shown in Fig.6. Nevertheless, we have a roundabout air (N_2, O_2) discharge even in the presence of helium gas flow at the nozzle center.

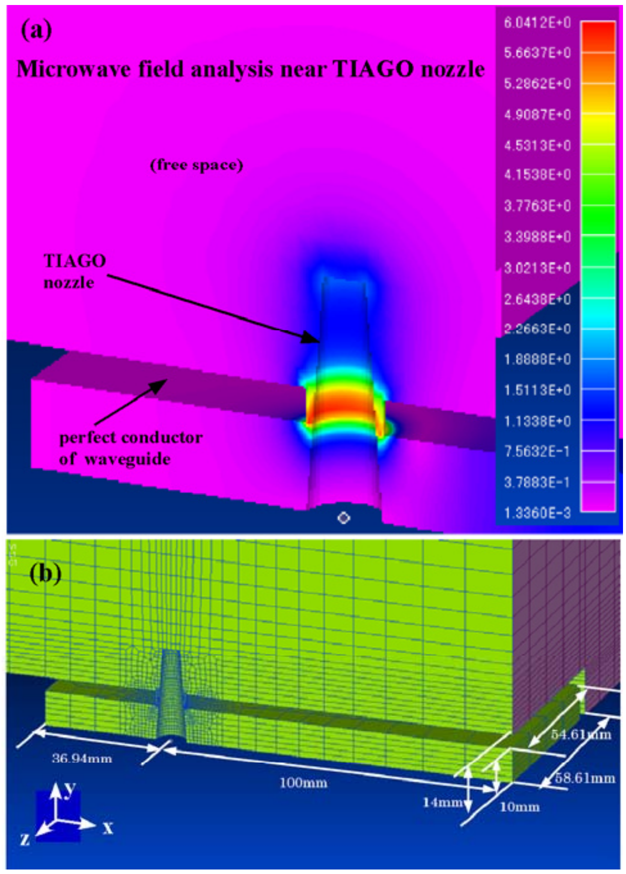

Fig.7 Numerical analysis on the spatial distribution of microwave electric field around the TIAGO nozzle by using PHOTO-Wavejω(Photon Co. Ltd.). (a) The distribution of microwave electric field, and (b) mesh structure for numerical analysis.

In order to solve this paradox, the electromagnetic field of microwave has been analyzed with the numerical code WAVEjω of PHOTON Co. Figure 7 shows its numerical result (a) and a modeling mesh structure (b) for the finite element method. The result indicates some enhancement of microwave electric field around the circumference edge of TIAGO nozzle. The edge electric field is 1.4 times as large as that at the middle of the part of the conical nozzle above the upper H-plane. The enhanced field provides a sufficient microwave energy for ionization to the air gas surrounding helium gas stream. These observations and analysis suggest that the annihilation of edge effect by cutting the sharp angle as shown in Fig.8 may introduce a dramatic change in the bifurcation phenomena. In fact, it is demonstrated in Fig.9 that the transition from curved discharge to straight spindle-type discharge occurs by increasing the helium gas flow rate. Figure 9 shows several sequences of transition by changing the helium gas flow rate, increasing or decreasing. By the way, in the case of argon as a working gas such transitions have been observed even for the original TIAGO nozzle without any edge smoothing. It means that the argon jet with TIAGO nozzle does not have a bifurcation like that for helium jet. This suggests that the enthalpy of Ar would be smaller than helium gas in the temperature range concerned according to the reference of [5] as shown in Fig.6(b).

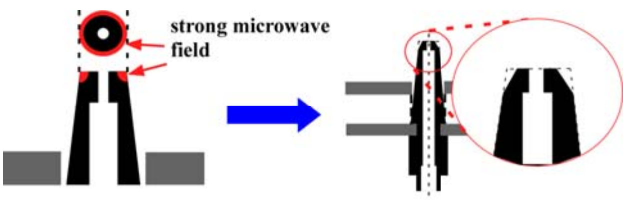

Fig.8 Moderation of localized electric field by cutting the sharp edge of TIAGO nozzle head.

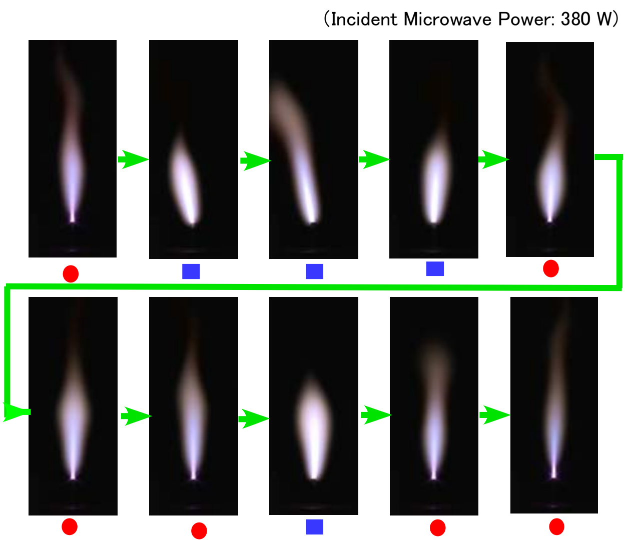

Fig.9 Smooth transitions from one to the other by changing the helium gas flow rate in the case of modified TIAGO nozzle shown in Fig.8. The circle corresponds to normal straight discharge, while the square curved one.

5. Conclusions

We identified a stable helium jet ignition area in the parameter space of preset helium gas flow rate and incident microwave power for straight jet discharge at atmospheric pressure. Two different discharge modes, macroscopically stable straight helium discharge with a spindle shape and curved air discharge, have been observed. Even at the same gas flow rate and incident power, a different mode appears depending on the preset gas flow condition, such a structural bifurcation of discharge may be explained by the enhancement of microwave electric field at the circumference of TIAGO nozzle head, which was confirmed by the observation that the bifurcation changes to transition by cutting the sharp edge of the nozzle head. Some difference between argon and helium gases is discussed in terms of gas enthalpy which has a lower value for argon that for helium in the temperature range of this type of thermal plasmas.

A possibility of a new type of high-flux test plasma beam for plasma-wall interactions in fusion devices and for medical or industrial applications was suggested.

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