S3-1

Characteristics and Application of Atmospheric-Pressure High-Density Non-thermal Plasma Produced in Microgap

微小ギャップにより生成される高密度大気圧非平衡プラズマの特性と応用

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The basic characteristics of a high-pressure high-density non-thermal plasma produced in a microgap by microwave excitation are discussed on the basis of optical diagnostics and heat transport simulation. When considering an application to a VUV excimer light source, the gas temperature is one of the most important parameters. The simulation indicates that a strong non-gravitational convection is induced in the gas because of a very large temperature gradient between the plasma center and the wall. The convention appears to be an essential feature of small-sized high-pressure high-density plasmas.

1. Introduction

Recently atmospheric-pressure non-thermal plasmas attract considerable attention because of various potential applications arising from non-necessity of vacuum systems and from possible very high active species densities in the plasma. Microwave excitation is one of the effective methods of producing such plasmas. We are studying a high-pressure high-density non-thermal plasma produced by microwave excitation in the microgap between two knife-edge electrodes, aiming at a VUV light source application. In this presentation, we report basic diagnostic results of the discharge (electron density, electron temperature, and gas temperature) and the results of heat transport simulation. Clarifying the heat transport mechanism and the gas temperature characteristics should be essential for understanding the properties of high-pressure high-density plasmas.

2. Microgap plasma excited by microwave

Diffuse high-pressure high-density plasma can be produced continuously in a microgap between two knife-edge electrodes. Figure 1(a) shows the dimension of the electrodes (made of copper) we are currently using, which are attached at the end of the microwave strip-line structure [1]; the length (in the *z* direction indicated in the figure) of the electrodes is 10 mm. In 1-atm air discharge, dc and rf (13.56MHz) excitation lead to constricted discharge and microwave excitation was essential to obtain a plasma uniformly extending over the entire electrode width. We suppose that the difference is caused by the impedance effect; in the microwave frequency (2.45 GHz) the impedance of the constricted discharge path is large and should not be suitable for sustaining the discharge.

For the discharge in ambient air at a microwave power of 100 W, Thomson scattering measurements indicated that the electron density profile in the *x* direction has a FWHM of ~200 μm, with the peak electron density as high as 1.8×10^{15} cm^{-3} [2]. Note that a total power of 100W, if divided by the microgap volume of 100 μm × 100 μm × 10 mm, corresponds to a power deposition density of 1 MWcm^{-3}. The gas temperature in the microgap estimated from the optical emission spectrum of the N_2 $C^3\Pi_u$-$B^3\Pi_g$ band was ~2000K. For atmospheric pressure He discharge (containing 5% N_2) at a microwave power of 100W, the gas temperature was reduced to ~1200K. The dependence of the gas temperature on the microwave power as well as on the forced gas flow rate through the microgap was not well understood when only the diffusive heat conduction was considered as the heat transport mechanism [3].

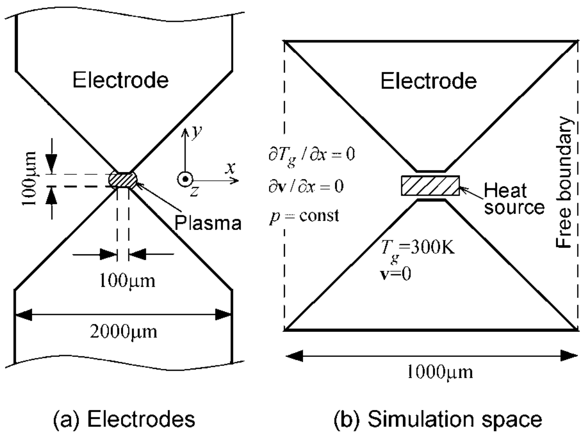

Fig. 1 Microgap discharge configuration and the simulation space for heat transport study.

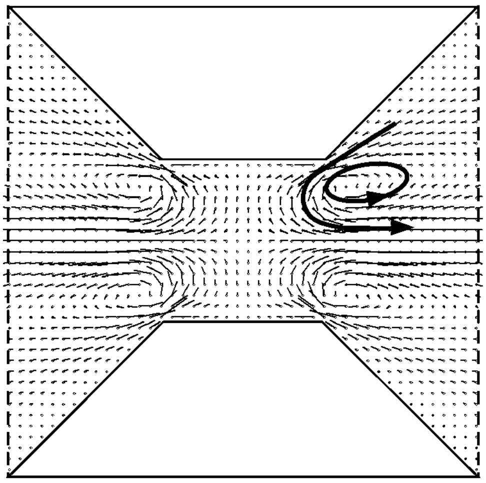

Fig. 2 Flow vector diagram in the central part of the simulation space for He without forced gas flow (Q_0 =0.5 MW/cm^3).

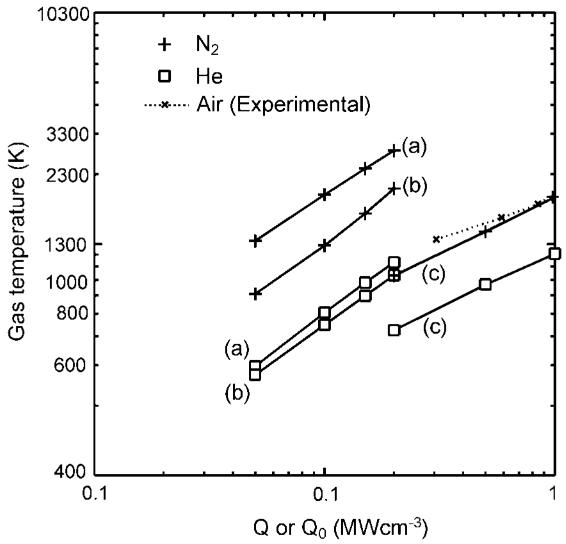

Fig. 3 Gas temperature at the center of the heating zone as a function of Q or Q_0 for He and N_2 gas in cases of (a) static gas, (b) flowing gas with Q=constant, and (c) flowing gas with $Q=Q_0 n_g/n_0$. Experimental results for air discharge in the microwave power range of ~30~100W are also shown, where the horizontal position of the plot is arbitrary chosen.

3. Heat transport simulation

To understand the gas temperature characteristics of the microgap discharge, a heat transport simulation based on a complete set of fluid dynamic equations consisting of mass, momentum, and energy balance equations was carried out. Figure 1(b) shows the simulations space, in which the central rectangular zone is the heat source simulating the plasma. It is assumed that in this zone the gas is given either constant heat Q (W/cm^3) or heat proportional to the local gas density, $Q=Q_0 n_g/n_0$ (n_g is the local gas density, n_0 the gas density in the standard condition [1atm, 273K], and Q_0 the constant). Temperature dependence of the heat conductivity and viscosity is taken into account.

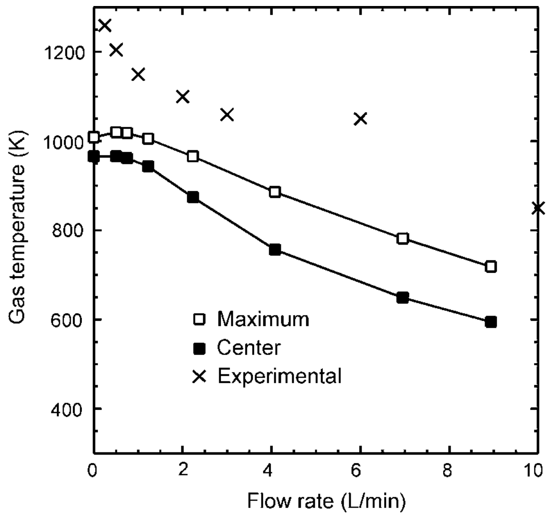

Fig. 4 Maximum and central gas temperatures as a function of the forced gas flow rate for He (=0.5 MW/cm^3), together with experimental values for He/N_2(5%) discharge at a microwave power of 100W.

Figure 2 shows the flow vector diagram in the steady state without forced gas flow, indicating the existence of strong natural convection; since we do not include gravitational force in the governing equations, the convection has a purely thermal origin.

Figure 3 shows the dependence of the gas temperature on the heat source intensity, together with the experimental gas temperature for air discharge as a function of the microwave power. The figure indicates that the natural convection affects the gas temperature significantly and the experimental results are better explained by the assumption $Q=Q_0 n_g/n_0$.

Figure 4 shows the dependence of the gas temperature on the gas flow rate. For flow rates above 1 L/min, the simulation reasonably well explains the experimental results. For low flow rates (<1 L/min) the simulated gas temperature is nearly constant because of the effect of natural convection; the discrepancy with the experimental results in this region is probably due to ambient air admixture in the discharge because of low flow rates.

Thus the simulation with the assumption $Q=Q_0 n_g/n_0$ reasonably well explains the experimental results, indicating a significant effect of gas dynamics on the heat transport. This appears to be an essential feature of small-sized high-pressure high-density plasmas. (Work supported by a Grant-in-Aid for Scientific Research on Priority Areas [15075205] from MEXT Japan)

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[3] A. Kono, J. Wang and M. Aramaki: submitted to Thin Solid Films (Proc. 7th APCPST, Fukuoka, 2004).