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Influences of gas flowing on the features of a helium radio-frequency atmospheric-pressure glow discharge

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HIGHLIGHTS

- A zoning model is used to study the features of the RF APGD plasmas.
- The gas flowing effects on the key parameters in the plasmas are simulated.
- The modeling results are qualitatively validated by the experiments.

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ABSTRACT

In this paper, a zoning model is employed to investigate the influences of gas flowing on the characteristics of the high-purity helium radio-frequency atmospheric-pressure glow discharge (RF APGD) plasma. The modeling results show that the influences of the gas flowing on the plasma features in the discharge region and the jet region are different. In the discharge region, the heavy-particle temperature decreases with the increase of helium flow rate, while the variations of the electron energy and the species concentrations are less than 0.5%. In the plasma jet region, the variation of the heavy-particle temperature shows a non-monotonous form with the gas flow rate, while the species concentrations become higher within a certain distance (e.g., smaller than 2 mm away from the plasma generator exit) at a higher helium flow rate. The modeling results are also qualitatively validated by comparing with the measured gas temperatures in both the discharge region and the plasma jet region.

1. Introduction

Radio frequency atmospheric pressure glow discharge (RF APGD) plasma sources produced using a pair of water-cooled bare-metallic electrodes have attracted much attention of the researchers due to their unique features, such as low breakdown/discharge voltages, low gas temperatures, high concentrations of chemically reactive species and convenient operations in open air, especially for the application in the biomedical fields [1–3]. Although some numerical simulation results on the features in the discharge region of the RF APGD plasmas have been published, most of the authors focused on the chemical reaction processes, while the energy exchange process between the electrons and heavy particles in the plasmas were seldom considered (e.g., Refs. [4–10]). However, for the typical RF APGDs, the RF power input usually ranges from tens to hundreds of Watts [11,12]; and thus, the gas temperature may be significantly higher than the room temperature resulted from the frequent collisions between the electrons and heavy particles in the plasma system. Therefore, the levels of the gas temperature and the chemically reactive species concentrations are the two key factors that should be considered carefully for the plasma treatment of the heat-sensitive materials, e.g., the living bio-materials or the precision instruments [1–3].

On the other hand, different from the low pressure glow discharge plasmas, the gas flowing always exists in the RF APGD plasmas for forming a stable plasma jet at the downstream of the plasma generator, which may, to some extent, influence the spatial distributions of the gas temperatures and the concentrations of the chemically reactive species. Recently, Hemke and his co-workers studied the characteristics of the helium oxygen RF APGD plasmas both in the discharge region and jet region operating in a pure helium atmosphere numerically using a two-dimensional transient computer code *nonPDPSIM* [13]. In Ref. [13], a triangular

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unstructured mesh with approximately 10,000 nodes was employed to obtain a complete picture of the dynamics of the RF APGD plasmas including the discharge region and the downstream effluent region. Due to the very small gap spacing between the electrodes and the large volume of the plasma jet region comparing with that of the discharge region in space, as well as the very high driving frequency of the power supply compared with the characteristic time of the gas flowing, it is a very time-consuming job to simulate both the discharge region and the jet region simultaneously based on a serial computer code.

Therefore, the purpose of this paper is to study the influences of the gas flowing on the levels of the gas temperatures and the chemically reactive species concentrations both in the discharge region and the jet region in a high-purity helium RF APGD plasma system based on a zoning model; that is to say, the spatiotemporal evolutions of the plasma parameters, including the electron and heavy-species temperatures (T_e and T_h), the electrical potential (ϕ), and the species concentrations (n_i), in the discharge region are simulated using a one-dimensional (1-D) transient fluid model, while the quasi-steady spatial distributions of T_e, T_h, n_i and the flow fields of the plasma jet region are predicted using a two-dimensional (2-D) steady fluid model based on the calculated time-averaged parameter values in the discharge region as the inlet boundary conditions. The calculated results are also compared with the measured gas temperatures in these two regions.

2. Model descriptions

In this paper, the features of the high-purity helium RF APGD plasmas produced by a planar-type plasma generator, as shown in Fig. 1(a), are simulated. As indicated in Section 1, the modeling is divided into two parts corresponding to the discharge region and the jet region as shown in Fig. 1(b), where the electrode gap spacing is fixed at 2.4 mm, while the height and length of the plasma jet region are 5.0 mm and 20.0 mm, respectively.

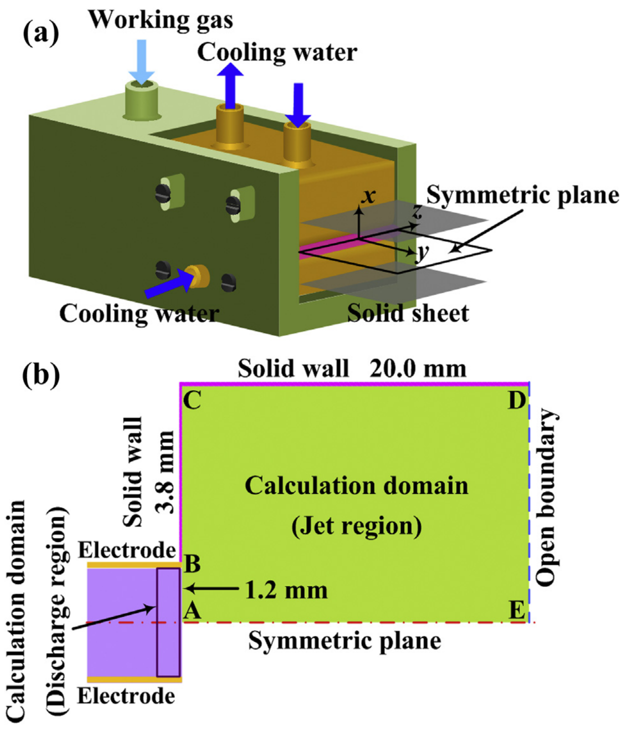

Fig. 1. Schematic diagrams of the planar-type plasma generator (a) and of the calculation domains for the modeling of the discharge region and the plasma jet region (b).

2.1. Assumptions

In this study, the high-purity helium (with 0.5 ppm nitrogen as an impurity) is used as the plasma forming gas. Thus, seven species involved in thirteen chemical reactions as listed in Table 1 [7,14–19] are considered in the modeling, including electrons (e), helium metastables (He^*, He_2^*), helium ions (He^+, He_2^+), nitrogen molecules (N_2) and nitrogen molecular ions (N_2^+). The number density of helium atoms (He) is assumed to be constant and determined by the ideal-gas law since its number density is much higher than those of the other species. The major assumptions used in this study are as follows: (i) The variation of the gas pressure in the discharge region and the jet region is negligible, i.e., $p = 1$ atm during the whole discharge process. (ii) In the discharge region, all the metastable species and ions are quenched or neutralized at the electrode surfaces and return back to the inter-electrode space as stable neutral species; the drift-diffusion approximation is employed for calculating the number fluxes of the charged species. (iii) In the plasma jet region, the plasma flow is in a quasi-steady, incompressible and laminar regime; the values of the mass density, viscosity, specific heat at constant pressure and thermal conductivity of the plasmas are constant; and the electric field is negligible, and thus no drift process is considered for the charged particles.

2.2. Governing equations in the discharge region

Based on the preceding assumptions, the governing equations in the discharge region include the species continuity equation, Poisson equation, electron and heavy-particle energy conservation equations.

(i) Species continuity equation:

$$\partial n_i/\partial t + \nabla\cdot \vec{\Gamma}_i = S_i \tag{1}$$

where n_i, $\vec{\Gamma}_i$ and S_i represent the number density, number flux and the homogeneous production/destruction rate of species i, while t is the time. The drift-diffusion approximation is used for calculating the species number flux as

$$\vec{\Gamma}_i = \mathrm{sgn}(q_i)\mu_i n_i \vec{E} - D_i \nabla n_i \tag{2}$$

Table 1
Elementary reactions, the corresponding rate constant, and the energy loss due to the inelastic collisions[a].

No.	Reaction	Rate constant (m, molecules, s)	ΔE_i^e(eV)	Refs.
R1	$e + He \rightarrow He^* + e$	$1.3 \times 10^{-14}\varepsilon^{-1.7}\exp(-6.0 \times 10/\varepsilon)$	19.8	[7,14,15]
R2	$e + He \rightarrow He^+ + 2e$	$2.1 \times 10^{-7}\varepsilon^{-3.8}\exp(-1.3 \times 10^2/\varepsilon)$	24.6	[7,14,15]
R3	$e + He^* \rightarrow He^+ + 2e$	$7.1 \times 10^{-12}\varepsilon^{-0.9}\exp(-1.7 \times 10/\varepsilon)$	4.8	[7,14,15]
R4	$He^* + 2He \rightarrow He_2^* + He$	2.5×10^{-46}	/	[16,17]
R5	$He^+ + 2He \rightarrow He_2^+ + He$	1.1×10^{-43}	/	[7,18]
R6	$He_2^* + M \rightarrow 2He + M$	1.0×10^4	/	[7,19]
R7	$2He^* \rightarrow He_2^+ + e$	1.5×10^{-15}	−17.4	[16,18]
R8	$2He_2^* \rightarrow He_2^+ + 2He + e$	1.5×10^{-15}	−13.7	[16,18]
R9	$e + He_2^+ \rightarrow He^* + He$	$8.9 \times 10^{-15}(T_e/T_h)^{-1.5}$	ε	[7,18]
R10	$He^* + N_2 \rightarrow N_2^+ + He + e$	5.0×10^{-17}	−4.2	[7,18]
R11	$He_2^* + N_2 \rightarrow N_2^+ + 2He + e$	3.0×10^{-17}	−2.5	[7,18]
R12	$He_2^+ + N_2 \rightarrow N_2^+ + He_2^*$	1.4×10^{-15}	/	[7,18]
R13	$N_2^+ + e \rightarrow N_2$	$4.8 \times 10^{-13}(T_e/T_h)^{-0.5}$	ε	[7,19]

[a] In this table, ε is in the unit of eV, while T_e and T_h are in the unit of Kelvin; the symbol M stands for an arbitrary heavy collision partner.

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