Comparing the Effects of Different Dielectric Materials on Atmospheric Pressure Plasma Jet by Experiments and Simulations

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Abstract: This study aims to investigate the effects of different dielectric materials on atmospheric pressure plasma jet using numerical simulations and experimental measurements. In current research, the method of discussing the effect of dielectric materials on atmospheric pressure plasma jet is mainly based on simulation results, so there is a lack of experimental measurement results to verify. This study focuses on the comparison of experiments and simulations to gain an in-depth understanding of the influence of different dielectric materials on atmospheric pressure plasma jet.

Keywords: Atmospheric pressure plasma jet, The Boltzmann plot, The power balance method, dielectric barrier discharge, Lissajous figure

1. Introduction

Considered the fourth state of matter, plasma is a fully or partially ionized gas with ions, electrons, and uncharged particles such as atoms, molecules, and free radicals [1]. Atmospheric pressure plasma (APP) is one of the widely used plasma classifications. APP has a place in plasma medicine, agriculture, material surface treatment, catalysis and aerospace engineering [2]. The application of APP in the field of biomedicine is the main focus on this study. At present, many studies have shown that APP has a significant effect on wound healing [3, 4], cancer treatment [5, 6], and dental stain removal [7-10]. Since it operates in an atmospheric environment, APP is not limited by the plasma in the vacuum environment [9], and the reactive oxygen species (Reaction oxygen species, ROS) generated by the plasma can also eliminate bacteria through strong oxidative stress groups [10]. At the same time, the short-lived chemical substances contained in ROS will not remain in the body after plasma treatment, which is a major advantage of plasma in biomedical treatment [9].

Generally, the generation of plasma is usually accompanied by the generation of high temperature. For the application of atmospheric pressure plasma in the biomedical field, how to avoid the generation of high temperature is a very important key. Dielectric barrier discharge is a form of discharge. Putting at least one dielectric between two electrodes can reduce the plasma temperature. Because the dielectric is an insulator that can be electrically polarized, due to the characteristics of the dielectric insulator. DC voltage cannot pass through the dielectric, and an alternating current is required to make the dielectric polarized and conduct. In the process of electric polarization of the dielectric, the charge will be confined in the dielectric, and micro-discharges will be continuously generated at different positions on the surface of the dielectric. Microdischarges create weakly charged plasma channels with properties similar to transient high voltage glow discharges. Due to charge accumulation on the dielectric surface, within a few nanoseconds after breakdown, the electric field at the location of the microdischarge decreases to such an extent that the current flow at that location is interrupted. This effectively avoids gas heating due to the short duration and limited charge transport and energy dissipation [11]. Common dielectric materials are glass, quartz, ceramics or polymers [12]. Different dielectric materials have different dielectric permittivity. The larger the permittivity, the greater the electric polarization tendency of the dielectric material. When the dielectric material has a larger permittivity, the plasma discharge will become stronger and more unstable, and the surface charge density will increase. Chemical The efficiency of the reaction will also be improved [13].

The influence of the dielectric constant on the DBD has been widely discussed, and some studies have pointed out that electrostatic attraction is the main reason that affects the propagation of positive streamer discharges on the dielectric surface. The attractive force is caused by the net charge in the streamer, which polarizes the dielectric, enhance the electric field between the streamer and the dielectric, while a higher permittivity accelerates the streamer propagation [14]. There are also studies using ICCD cameras and simulations to observe the formation of primary streamer and secondary streamer. According to the research results, a higher permittivity is conducive to enhancing the formation of primary streamer and secondary streamer. Many studies have also discussed the point-to-plane configuration of dielectric materials under normal pressure [16-18]. The point-to-plane electrode configuration can more effectively simulate the discharge situation of the cathode plane. Research results have shown that the propagation of streamers has a great relationship with the surface properties. For the dielectric of the surface-coated conductive plate, when the surface charge density is low, the effect of secondary electron emission is visible. When the streamer is suppressed due to the high surface charge density, the front end of the streamer will diverge along the dielectric surface [16]. Studies have shown that the discharge rate of the dielectric surface depends on the capacitance value of the dielectric layer and decreases with the increase of the capacitance. The amount of deposited surface charge will also increase the capacitance value with the increase of the dielectric layer [17]. There are also studies that apply a constant voltage for different permittivity, and find that the permittivity affects the voltage distribution ratio between the anode and the dielectric surface and between the cathode and the dielectric surface. When the permittivity increases, the voltage distribution ratio between the anode and the dielectric increases, which leads to an increase in the electric field of the streamer head and an increase in the propagation speed of the mainstream light [18]. At last, there are also literatures that change the dielectric material of APPJ, and find that as the permittivity increases, the speed of ionization to the surface, the speed of electrons, and the ion density in the plasma column will increase. A larger permittivity can increase the production of key neutral particles for biomedical applications during the discharge process, a lower permittivity can allow plasma ionization waves to travel farther along the surface of the dielectric and allow more electrical penetration into the material [19].

2. Method

A DBD-configured APPJ is mainly used in this research. First, the numerical simulation of the 2D model will be used to calculate the electric field distribution and electron density of the APPJ. In the experimental part, the light emission spectrum of the plasma will be measured and compared with the simulation results. In order to deeply understand the influence of different dielectric materials on the discharge of APPJ, and further explore whether the plasma discharge can be made more stable by changing the dielectric material.

2.1 Experiment Setup

Our self-made atmospheric plasma beam device is shown in Figure 1. A quartz tube (SiO_2 tube, TOCHANCE Technology, Taoyuan, Taiwan) with a dielectric coefficient of 3.74 and an alumina tube (Al_2O_3 tube, TOCHANCE Technology, Taoyuan, Taiwan) with a dielectric coefficient of 9.8 were used as dielectric materials with an outer diameter of 5 mm. The inner diameter is 3 mm, the length is 12 cm, the gas flow rate is 3 slm, and the working gas is argon (Argon, 99 %). A high voltage power supply (High voltage power source, NAIO DING Technology, Tainan, Taiwan) with an output voltage of 2.5 kV and a sinusoidal voltage with a frequency of 20 kHz was used to ignite the plasma.

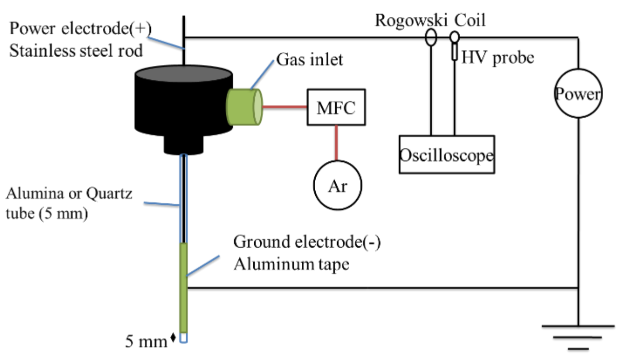

Fig. 1. DBD-configured APPJ Setup.

2.2 Measurement Instruments

In terms of simulation, the ultraFM software is used, and the initial conditions and grid models are substituted into the simulation software for numerical simulation calculation; in the experiment, high-voltage probes (P6015A, Tektronix, State of Oregon, United States) are used to measure plasma voltage and active A current probe (TCP312, Tektronix, State of Oregon, United States) was used to measure the plasma current. An oscilloscope with a bandwidth of 100 MHz and a sampling rate of 2 GSa/s was used to record the voltage and current waveforms (DSOX2012A, Keysight, Santa Rosa, United States). A spectrometer to detect the presence of chemical species; use a thin-film capacitor (CT-MEF, Cheng Tung Industrial, Taiwan) as a measurement capacitor connected in series with a plasma device to draw a Lissajous figure.

2.3 Governing equation

First, in order to simulate the movement of particles in the plasma, this study uses the Boltzmann Equation to perform calculations, and the equation is as follows:

$$\frac{\partial f(r,v,t)}{\partial t} + v\frac{\partial f(r,v,t)}{\partial r} + a(r,t)\frac{\partial f(r,v,t)}{\partial v} = 0 \qquad (1)$$

In the above formula, f refers to the distribution equation, r represents position, v represents velocity, t represents time, and a represents acceleration. When considering the collision, the right term of the equation will have a collision term $(\frac{\partial f}{\partial t})_{col}$ to be considered. When we consider that the motion of the particle is affected by an external electromagnetic field, we can express the acceleration term a(r,t) by the Lorentz force:

$$\mathrm{F} = \mathrm{m}a = \mathrm{q}(\mathrm{E} + \mathrm{v} \times \mathrm{B}),\ a = \frac{q}{m}(E + v \times B) \qquad (2)$$

Substituting the acceleration affected by the Lorentz force into the Boltzmann equation, the following formula can be obtained:

$$\frac{\partial f(r,v,t)}{\partial t} + v\frac{\partial f(r,v,t)}{\partial r} + \frac{q}{m}(E + v \times B)\frac{\partial f(r,v,t)}{\partial v} = \left[\frac{\partial f(r,v,t)}{\partial t}\right]_c \qquad (3)$$

This study also uses the continuity equation to describe the density of electrons and ions. The general continuity equation is as follows:

$$\frac{\partial n_{e/i}}{\partial t} + \frac{\partial \Gamma_{e/i}}{\partial x} = S \qquad (4)$$

$n_{e/i}$ represents the number density of electrons or ions, $\Gamma_{e/i}$ represents the flux of charged particles, S represents the source term (Source term), and the continuous equation represents the change of electrons and ions over time The situation, plus the flux change in the direction, will be related to the chemical reaction formula we input, $\Gamma_{e/i}$ can be expressed by the following formula:

$$\Gamma_{e/i} = sign(q_{e/i})\mu_{e/i}n_{e/i}E - D\nabla n_{e/i} \quad (5)$$

$q_{e/i}$ represents the amount of charge replaced by ions or electrons, $\mu_{e/i}$ represents the mobility of electrons or ions, E represents the electric field, and the first item on the right side of the equal sign in the equation is a charged particle The component drifting along the direction of the electric field, the second term on the right side of the equal sign is the diffusion term, which represents the particle flow caused by the concentration gradient, and D represents the diffusion coefficient. The right term of the continuous equation is mainly related to the chemical reaction formula, which can be expressed by the following formula:

$$\mathrm{S} = m_i k_i n_i n_j \quad (6)$$

m_i is the mole number of particles being generated, and k_i is the chemical reaction rate of particles of exponential density n_i with target particles of number density n_j.

The momentum equation is mainly used to describe the state of motion of the particle. We can obtain it by multiplying the Boltzmann equation by mv and integrating the velocity. The momentum equation is as follows:

$$\mathrm{mn}\left[\frac{\partial v}{\partial \mathrm{t}} + (v \cdot \nabla)\mathrm{u}\right] = \mathrm{qn}(\mathrm{E} + \mathrm{v} \times \mathrm{B}) - \nabla \cdot \mathrm{P} + \mathrm{M} \quad (7)$$

m represents the mass, n represents the number density, u represents the average velocity, B represents the magnetic field, P represents the stress tensor, the momentum equation can describe the force situation of the particles in the plasma, The left side of the equation represents the change in velocity of the particle after the force is applied, while the right side represents the Lorentz force, the influence of the stress.

The electron energy conservation equation can be used to describe the energy change of the electron after the collision motion. With the calculation result of the energy, we can also calculate the change of the electron temperature in the whole plasma simulation process.

$$\frac{\partial(n_\varepsilon)}{\partial t} + \nabla \cdot \left(\frac{5}{3}\mu_e E n_\varepsilon - \frac{5}{3}D_e \nabla n_\varepsilon\right) = -\Gamma_e \cdot E - \sum \Delta E \cdot K_{inel} \quad (8)$$

n_ε represents the energy density of electrons, μ_e and D_e represent the mobility and diffusion number of electrons, respectively, Γ_e represents the flux of electrons, ΔE and K_{inel} represent the energy loss of inelastic collisions and the related chemical reaction rates, respectively.

The Passon equation is mainly used in the plasma simulation to simulate the change of the electrostatic potential and the electric field between the electrodes. The Passon equation is as follows:

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0} \quad (9)$$

V is the electric potential, ρ is the bulk charge density, and ε_0 is the vacuum permittivity.

2.4Chemical Reaction

In this study, the input reaction of argon is used as the main chemical reaction gas in the fluid simulation of the atmospheric plasma beam. In the simulation process, we consider three chemical species as follows: Ar, Ar^+, Ar^* and the reactions of electrons. The chemical reaction formulas used in this study are mainly from the LXCat website platform and literature [20-22], while the electron mobility, electron diffusion coefficient, and electron transport coefficient are all from the software named BOLSIG+ [23]. BOLSIG+ is a Boltzmann solver for calculating electrons in weakly ionized plasma. According to the cross-section of the input particles, the transmission coefficient and collision coefficient of electrons can be calculated to evaluate the energy function of electrons.

3. References

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