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Dependence of dielectric barrier discharge jet length on gas flow rate and applied voltage

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Abstract The effect of gas flow rate of helium and argon on the length of dielectric barrier discharge (DBD) jet generated under atmospheric pressure using an AC source is investigated. It is found that as the flow rate increases, the jet length increases up to a maximum length. Upon further increase in flow rate, it will cause the jet length to decrease. Visual inspection shows the jet to be of laminar flow when its length was increasing, and gets turbulent when the jet length decreases with increased flow rate. There is an obvious increment in jet length of argon DBD system when the applied voltage is increased from 8.8 kV to 11.0 kV, but not in helium. Spectral analysis reveals the DBD jet to comprise of emission lines of its constituent flow gas. In addition to that, emission lines of component gases (N_2 and O) in ambient air and water vapour were also present. Upstream jet was obtained only in helium DBD jet at low flow rate but high applied voltage.

Keywords dielectric barrier discharge – atmospheric pressure plasma jet

INTRODUCTION

Atmospheric pressure discharge is an electrical discharge which can be generated and controlled under atmospheric pressure. Atmospheric pressure discharges attract much interest because it is inexpensive and easy to handle, and it can be an alternative for the low pressure discharges in many applications. Much investigation that involves the physical analytical study of the discharge regimes and plasma chemistry of these discharges with dielectric barrier configuration started to boost rapidly after the 1990s [1].

There are two types of atmospheric discharge, thermal and non-thermal ones. The thermal plasma sources included transferred arc, radio frequency (RF) inductively coupled and DC plasma torch. The temperature of thermal discharges is high ranging from 5000 K to 50,000 K [2]. It is widely applied in material processing, like plasma spray to produce layers of coatings on the film [3], metal cutting [4], plasma synthesis of fine powders down to nanometer size [5] and plasma welding [6].

Examples of non-thermal atmospheric pressure discharges include corona discharge, RF discharge, dielectric barrier discharge, plasma jet and microwave discharge. To generate the non-thermal plasma at atmospheric pressure, RF, microwave, pulsed, DC or AC excitation schemes can be used. Non-equilibrium or non-thermal plasma in which the total number density of charged particles (ions and electrons) is very much less than that of the neutral particles [7], usually has gas temperature close to room temperature. However, the electrons are expected to be energetic with temperature of several electron volts (eV).

Non-thermal plasma in the form of a jet is the main interest in this work. These atmospheric pressure non-thermal plasma jets differ from the thermal type such as the plasma torch that has already been developed and used for many decades. The non-thermal type was first reported by Koinuma and co-workers in 1992 [8]. Plasma jet is attractive because it is portable and can be designed into compact size and able to operate at atmospheric pressure. Its dimension and electrode shape is flexible depending on its applications. It also can be aligned in arrays to be applied in industrial processing to increase the production efficiency [9]. There exists a variety of configurations for the plasma jet. Some commonly used configurations are those with center needle electrode, hollow or rod electrode inside quartz or glass tube, while others have electrodes outside the tube. A modified Dielectric Barrier Discharge (DBD) arrangement with external co-planar electrodes is adopted in this experiment.

The DBD is a non-equilibrium high pressure gas discharge. The discharge occurs between two electrodes with at least one of them shielded by a dielectric layer when an AC high voltage is applied. The type of dielectric will decide the proper function of the discharge [10]. There are two ways to generate the discharge, either through surface discharge or volume discharge arrangement. For volume discharge arrangement, electrodes are separated by a gas gap. The discharge bridge the gap when a high enough voltage is applied across the electrodes. For surface discharge arrangement, there is no gas gap required for this arrangement; the dielectric layer is connecting the electrodes and the discharge area is on the surface of the dielectric layer. Surface DBD was introduced by Masuda and co-workers for ozone production [11]. Quartz and glass are commonly used as dielectric materials in DBD. Dielectric material plays an important role in the control the discharge current. It will avoid transition to arc discharge in which high current flows between the two metal electrodes. This is because the charged particles that accumulate on the dielectric surface will induce an electric field which opposes the applied voltage and thus the electric field strength decreases at the location of filament formation until the filament disappears [12], hence, avoiding arc formation.

In terms of accessibility, a longer jet would be more useful. Hence, parameters that affect the formation of the atmospheric pressure DBD jet are studied in this work. This will aid in better control of the plasma jet length.

EXPERIMENTAL SETUP

Figure 1 is a schematic of the experimental setup. The plasma jet was designed with DBD configuration where both electrodes were made of copper foil, wrapped around a quartz tube (dielectric layer) in co-planar arrangement, similar to that by Xiong *et al*. [13]. One of the electrodes was connected to high voltage while the other electrode was grounded. Internal diameter of the quartz tube was 4 mm while the outer diameter was 6 mm. The width of the high voltage (HV) electrode was 10 mm while the width of the grounded electrode was 2 mm. The distance between electrodes was set at 5 mm. Distance from the edge of the quartz tube to the grounded electrode was 5 mm. Gas was continuously flowed into the quartz tube and the DBD jet was forced out from the open end of the quartz tube. The flow rate was controlled by a variable area flowmeter (Dwyer Ratemaster RMA-21) and the gases used in this experiment were Argon and Helium. The flow rate reading was corrected for different gas density as the scale was factory calibrated in air.

A home-built MOSFET driven HV generator at approximately 11 kHz was used to excite the discharge. The electrical signal was recorded by a digitizing oscilloscope (Tektronix TDS2024B), the discharge voltage was measured by a HV probe (Tektronix P6015A) while the current was measured by a current transformer (Pearson 4100). A ruler was mounted parallel to the quartz tube and Canon EOS40D camera equipped with Tamron 90 mm F/2.8 macro 1:1 lens was used to capture the image of the jet. The emission spectra of the DBD plasma jet was obtained using Ocean Optics USB2000 spectrometer which was connected to the computer for spectral display via SpectraSuite software.

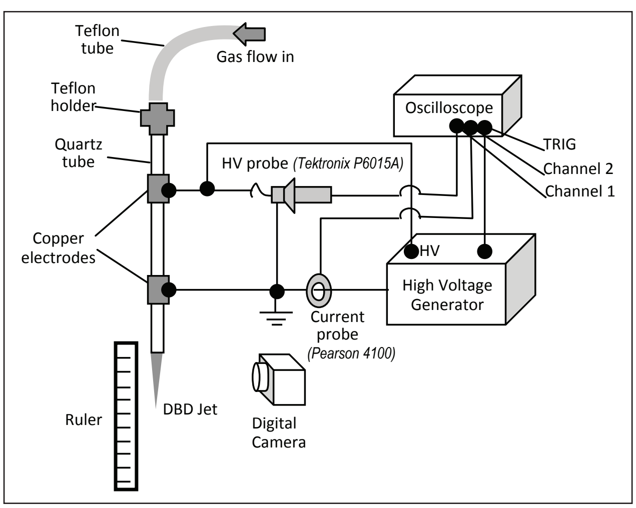


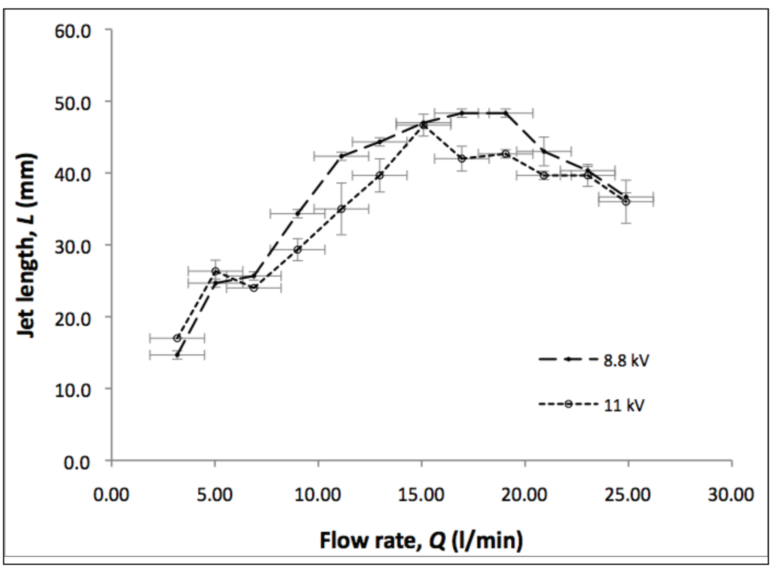
Figure 1. Schematic of experimental setup.

RESULTS AND ANALYSIS

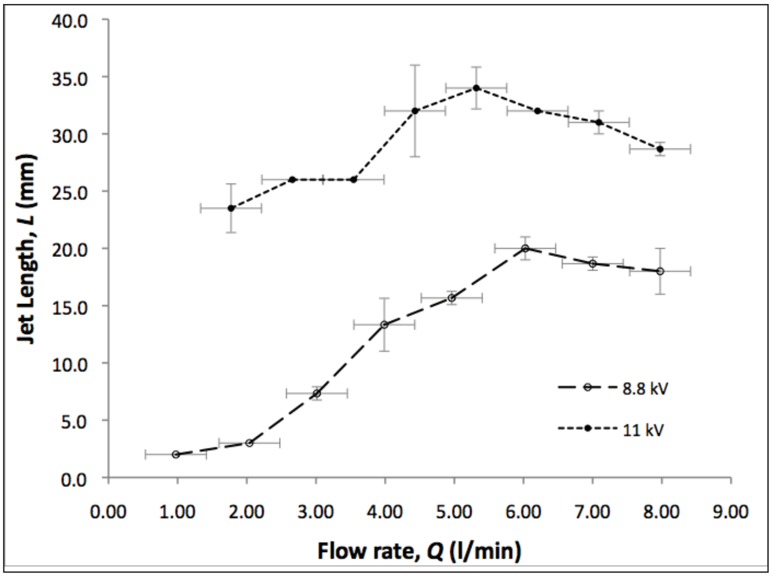
The gas flow rate, Q is one of the important parameters that can affect the DBD jet length. For both He and Ar gas, it is observed that as the flow rate, Q increases, the downstream jet length L also increases until a maximum length before decreasing with further increase in Q. In He DBD plasma jet (Fig. 2a), the longest length of the downstream jet at applied voltage (peak-to-peak), $V_{pp} \cong$ 8.8 kV occurs in the range of flow rate of 17-19 l/min. This maximum length is 48.3 mm. At $V_{pp} \cong$ 11.0 kV, maximum jet length of 46.7 mm occurs at about 15 l/min. In Ar DBD plasma jet (Fig. 2b), the longest jet length at applied voltage, $V_{pp} \cong$ 8.8 kV occurs at 6.0 l/min, with length of 20.0 mm. When excited at $V_{pp} \cong$ 11.0 kV, the maximum jet length occurs at flow rate of 5.3 l/min, with length of 34.0 mm. On visual inspection, the shape of the downstream jet is slim and tapers to a pointed end (Fig. 3a) during the length increase region. After the maximum length, the jet became wider and the end is less pointed.

It is found that only He DBD plasma jet has both downstream and upstream discharge, occurring at V_{pp} = 11.0 kV and Q = 3 l/min (Fig. 3b). The upstream discharge disappears when Q is further increased or when V_{pp} is decreased.

Emission spectra from both He and Ar DBD plasma jets (downstream) collected just outside the edge of the quartz tube exhibit emission lines from hydroxyl molecules, nitrogen molecules and oxygen atoms in addition to those from the operating gas itself. The wavelengths of these emission lines are identified and shown in Figure 4.



(a)



(b)

Figure 2. The length of DBD plasma jet, L at different flow rate, Q for (a) Helium, and (b) Argon, at applied voltages (peak-to-peak) ~8.8kV and ~11.0kV. Frequency of the AC voltage is f~11.0kHz.

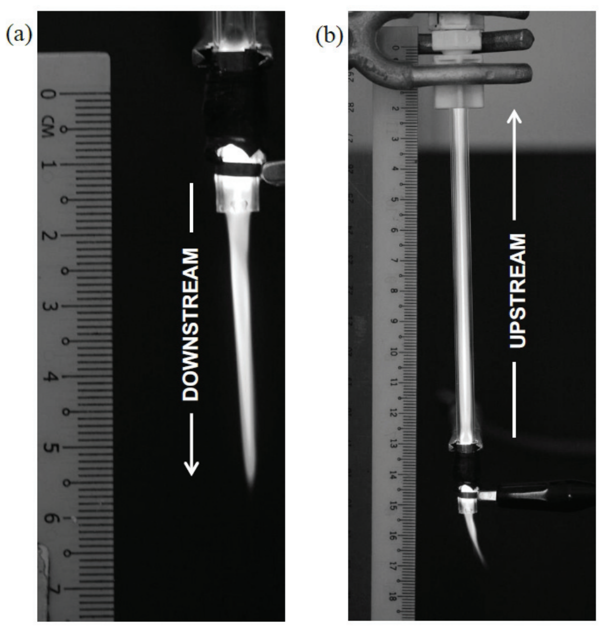


Figure 3. He DBD jet at V_{pp} ≅ 11.0 kV. (a) Only the downstream jet is present at flow rate, Q = 11 l/min. (b) Both the downstream and upstream jets occur simultaneously at lower flowrate, Q = 3 l/min with all other parameters the same.

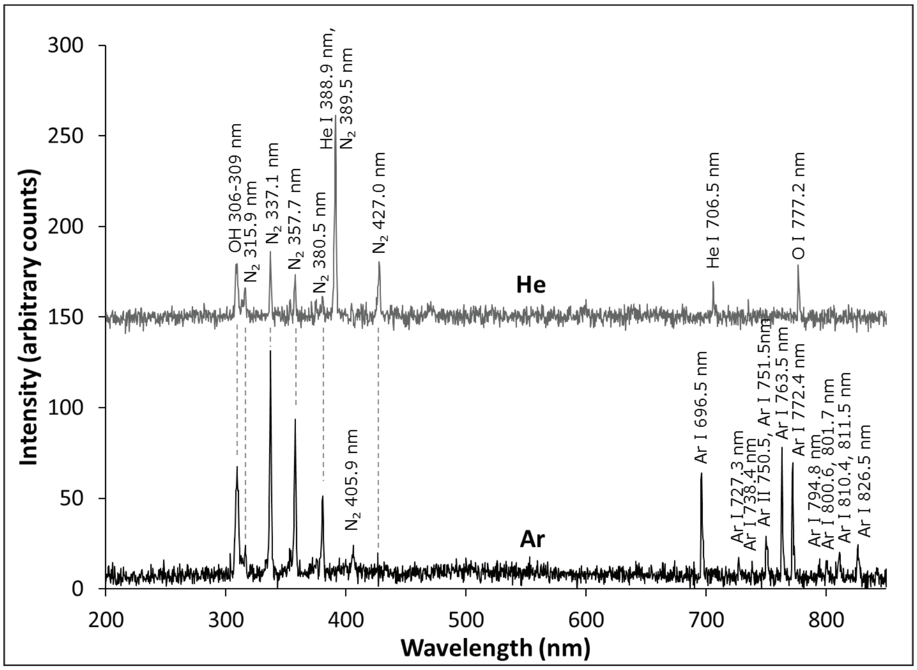


Figure 4. Emission spectra from He and Ar DBD plasma jets at V_{pp} ~ 11.0 kV, frequency, f ~ 11.0 kHz with all other parameters the same as stated earlier.

DISCUSSION

In this experiment, the frequency of the AC source was fixed at 11.0 kHz but two different voltages were applied, V_{pp} = 8.8 kV and 11.0 kV. At higher V_{pp}, the electric field strength is higher and more electrical excitation energy is applied. This will cause more ionization and thus brighter jet emission and longer jet occurs. This is very clear in Figure 2b for the case of DBD jet in Ar where L is distinctly longer when operated at V_{pp} = 11.0 kV. However, when operated in He, the jet length does not depend on applied voltage, as the DBD is operated in the glow mode (no multiple current spikes were observed in the current signal) at both voltages. The Townsend's first ionization coefficient in Ar is much larger and increases more steeply with electric field compared to He, hence, increasing the electric field tends to push the Ar DBD into filamentary mode (current spikes were observed) producing more intense discharge.

At low flow rate region, when Q is increased gradually, more gas particles are available to be ionized and number of charged particles forced out from the quartz tube would be higher, and thus a longer L is observed (Fig. 2). This is characteristic of laminar flow [14]. After achieving a maximum length, L becomes shorter when flow rate is further increased. This is most likely due to turbulence flow of the gas in quartz tube which causes lesser particles to be ejected out from the mouth of the tube. When flow rate is very high, the gas particles flowing in would be more than the number flow out from the quartz tube. This causes the velocity of gas particles to continuously change in magnitude and direction. The gas swirls and eddies but the overall bulk of the gas still moves along a specific direction which is forced out from the mouth of the quartz tube.

It is found that only He DBD plasma jet exhibits both downstream and upstream discharge at V_{pp} = 11.0 kV and low flow rate, Q = 3 l/min. However, upstream discharge no longer exists when flow rate is further increased or when the V_{pp} is decreased to 8.8 kV. The upstream jet is longer than the downstream jet because the downstream discharge diffuses into ambient air that quenches it. The upstream discharge is due to electric discharge process such as streamer mechanism in which photoionization plays an important role and not the gas flow phenomenon [15].

The presence of OH, N_2 and O emission bands/lines in the spectra of both Ar and He DBD plasma jets can be explained by the interaction of the Ar or He plasma that exits the quartz tube with the ambient air particles through excitation and de-excitation collisions. The second positive system of N_2 and O emission lines come from component gases in air while the OH band arises from water vapour content in humid air. The presence of reactive species, OH and O, will be useful for surface oxidation of polymer surfaces to increase wettability [16].

CONCLUSION

In summary, the effect of flow rate of the operating gas and applied voltage on the DBD jet length has been investigated. Jet length increases with flow rate initially up to a maximum length under laminar flow; and then the jet length decreases when the flow rate is further increased as the flow becomes turbulent. Ar DBD jet length increased markedly when applied voltage, V_{pp} is increased from 8.8 kV to 11.0 kV but not in He DBD jet. Upstream discharge occurs only in He DBD jet system when operated at flow rate of 3 l/min and V_{pp} = 11.0 kV. When the DBD jet plasma diffuses into the ambient air, N_2 molecules and O atoms as well as water molecules are also excited producing reactive species. In the present configuration, the longest jet in He is obtained at 17-19 l/min and 8.8 kV while in Ar, it is operated at 5.5 l/min and 11.0 kV.

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