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Pulsed cold plasma jet generated at atmospheric pressure

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Abstract

Non-equilibrium cold plasma jets generated under atmospheric pressure by means of high voltage pulsed power generator are extended up to a few centimeters long in the surrounding air. The generator is consisting of a negative dc source, a Blumlein-type pulse-forming network (E-PFN), and a dynamic spark gap switch. The plasma jet generated by the device using helium as the operating gas depends on the applied voltage and the gas flow rate. It is found that the plasma jet width and the radiant intensity depend on the discharge current. The experimental results show that the average velocityof the plasma bullets is estimated to be about 5.5×10^{6} cm/s. The magnetic field radiated from an atmospheric pressure room temperature plasma plume is measured. It's found that the peak value of the magnetic field strength about 900 gauss at 1cm away from the nozzle.

Key Words

Cold plasma; Atmospheric pressure; Spark gap switch; Discharge current.

INTRODUCTION

Atmospheric pressure non-equilibrium plasmas have become powerful experimentaltools for many applications in areas such as micro fabrications in microelectronics[1],surface modifications[2], light sources[3-4], and environmental processing[5]. Cold atmospheric pressure plasma jet devices have recently attracted significantattention for food preservation[6-7]. The most important devices for generating atmospheric pressure nonthermalplasmas can be considered: atmospheric pressure plasma jet[8-9], plasmaneedle[10], plasma pencil[11-12], miniature pulsed glow-discharge torch[13], oneatmosphere uniform glow-discharge plasma[14], resistive barrier discharge[15] anddielectric barrier discharge[16].

Atmospheric pressure non-equilibrium plasmas, which have an electron temperature that is much higher than gas temperature, have recently come to play an increasing role in several novel applications, such as biological applications[17-18].

Non-thermal plasmas, operated at ambient atmospheric pressure and temperature, are very efficient sources for the production of highly reactive neutral particles, for example, reactive oxygen and nitrogen species (RONS) (such as atomic oxygen, atomic nitrogen, hydroxyl radical, superoxide, singlet delta oxygen, and nitrogen oxides), charged particles, UV-radiation, and electromagnetic fields. Non-thermal plasmas are frequently called,"non-equilibrium" plasmas because they arecharacterized by a large difference in the temperature of the electrons relative to theions and neutrals. Since the electrons are extremely light, they move quickly and havealmost no heat capacity. In these plasmas, $T_e >> T_i \approx T_n$. Ionization is maintained by theimpact of electrons (which may have temperatures ranging from 0.1 to more than 20eV) with neutral species, producing additional electrons and ions. These plasmas aretypically maintained by the passage of electrical current through a gas.

Due to the high collision frequency at atmosphericpressure, it is not easy to generate a long nonequilibrium plasmaplume at atmospheric pressure. Furthermore, studies on the fundamentals of plasma plumes show that plasma plumes are nota continuous volume of plasma; rather, plumes are more likea bullet formed by a small and well-confined plasma volumethat travels from the exit aperture and terminates somewherein the surrounding air. The propagation velocities of plasmaplumes vary from~10^4 to10^5 m/s, which are several orders ofmagnitude higher than gas velocities[19]. In order to obtain the plume propagation velocities, costly high-speed intensified charge-coupled device(ICCD) cameras are currently used in most of the experimentsreported[20-21]. Somehow, the price of an ICCD is prettyhigh, and not every plasma laboratory has an ICCD. In orderto find relatively simple and cheaper method for estimatingthe plasma plume propagation velocity, charge methodis investigated in this paper.

Experimental setup

The plasma generator is consisting a negative DC source, Blumlein-type pulse-forming network (E-PFN)and a dynamic spark gap switch. A triggered spark gap switch was used as a closing switch of E-PFN. The APPJ is consists of4 inductor, each inductor equal 5μH and 5 capacitoreach capacitor equal 5nF. Acharging resistance value of 100k & Ω is chosen in the present case which corresponds to a charging RC time constant of 1.0ms. A schematic of the pulsed atmospheric-pressure plasma jet (APPJ) discharge and of the experimental set-up is shown in Figure 1. The gas is fed through an annular region between the two metal electrodes 15 cm in length. The inner electrode is 5 mm in diameter and is powered with a pulsed high voltage power supply, while the grounded outer electrode is separated from the inner electrode by a gap of a few millimeters. The APPJ device operates using 5-20 kV power supply with a gap between two electrodes of 2-3 mm under atmospheric pressure[17]. The spark gap between rotating grounded electrode and fixed high voltage electrode is adjusted at required breakdown voltage. Hence the gap gets triggered in each rotation, which gives the repetition frequency of order 25 Hz (pulses/s). As the voltage on the capacitors reached the spark-over voltage of the spark gap electrode, the capacitors discharged, producing a high voltage pulse.

Charge method

The charge method is simple andcan be used to obtain the spatiallyresolved plume propagation velocity by collecting charges onan equivalent capacitor. Figure 2 shows the schematic of the "charge method." Asshown in Figure 2, the plasma plume is in contact with thequartz tube. The contacting point of the plume with the quartztube is covered by a 2-mm-wide conducting ring made of thinaluminum foil. Another conducting ring with the same widthis added to the inner surface of the quartz tube opposite tothe outer ring. The inner ring is connected to the ground. The charge deposited on the outer aluminum foil is obtainedthrough integration of the current flowing through the groundwire[19].

RESULTS AND DISCUSSION

The high voltage pulses are applied between the needle electrode positioned inside adielectric cylinder (a simple

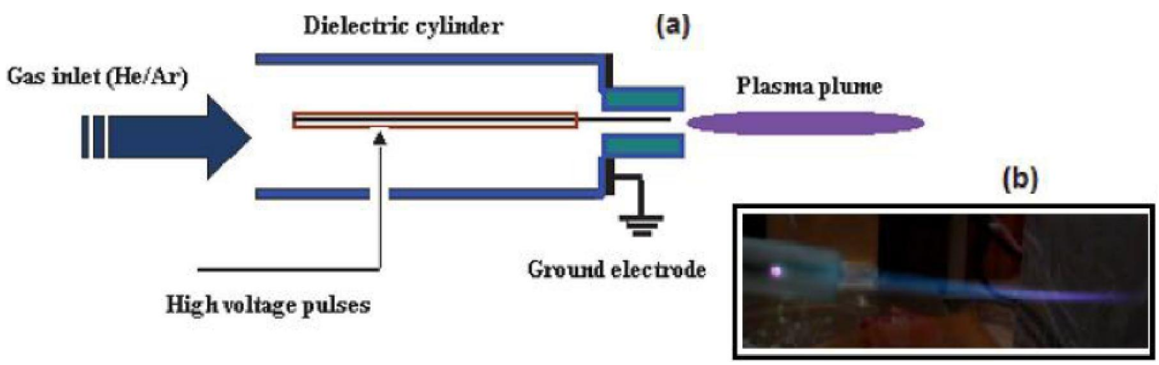

Figure 1 : (a) Schematic diagram of the plasma jet generator. (b) Image of the plasma jet with helium gas

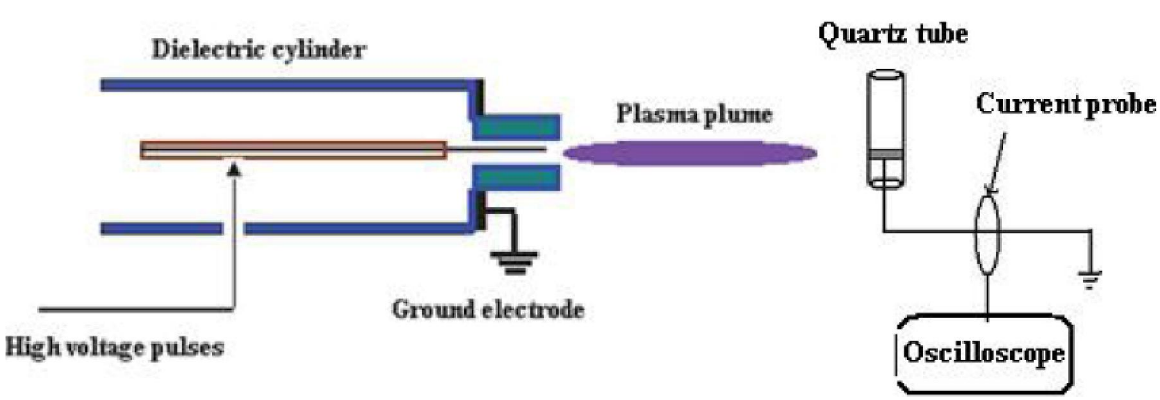

Figure 2 : Schematic of the "charge method." The quartz tube could move alongthe plasma plume

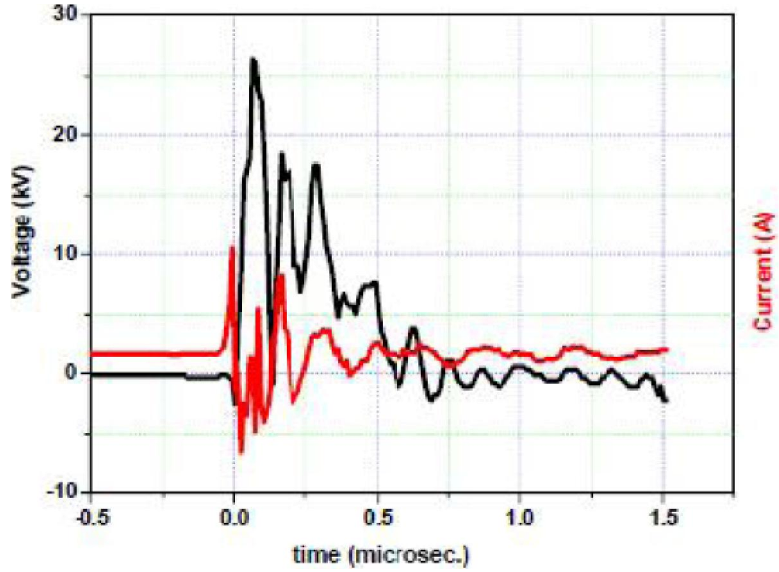

Figure 3 : Typical discharge current and the voltage waveforms

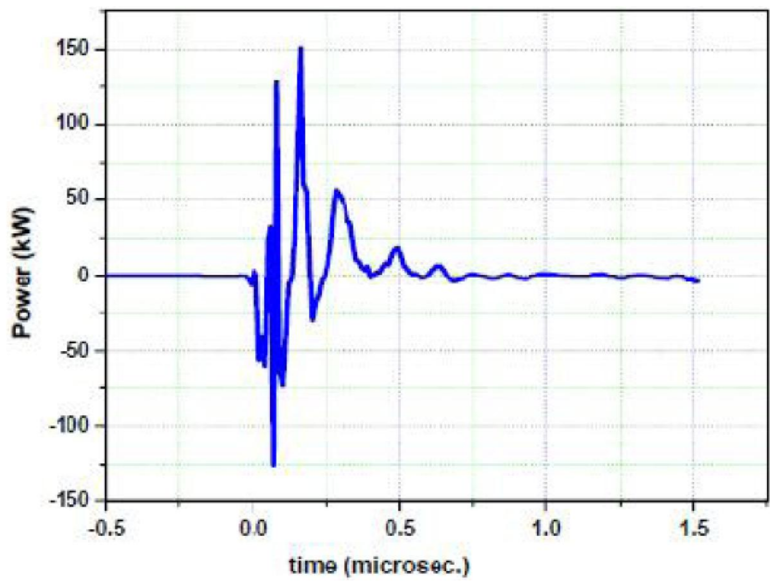

Figure 4 : The power waveform of the device

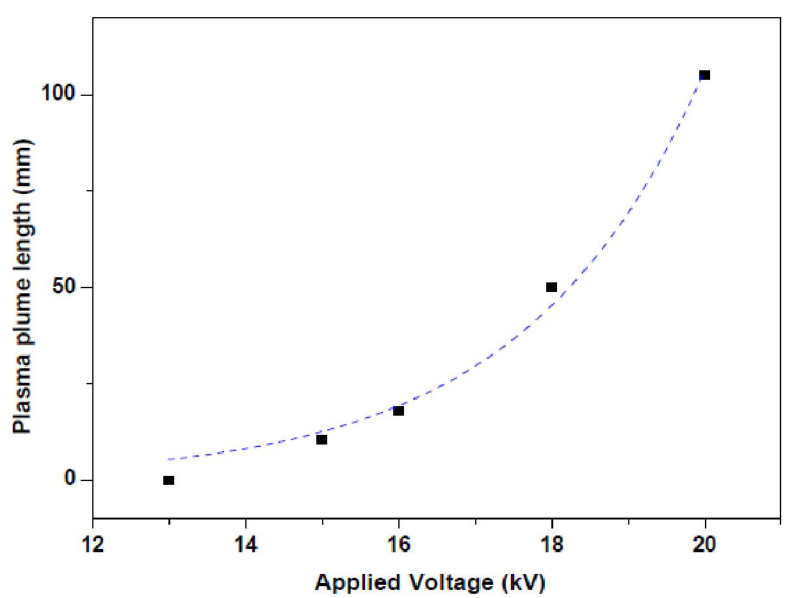

Figure 5 : Dependence of plasma plume lengthon applied voltage

medical syringe) and a metal ring placed on the exterior ofthis cylinder. In order to obtain electric discharges at atmospheric pressure, a highvoltage pulses (tens of kV) which have limited duration (hundreds of nanoseconds) andare repeated (tens of pulses per second), in addition to an inert gas (helium) isintroduced in the cylinder. The gas flows were in the range 0.5–10 liter per minute. The dischargetakes place between the metallic needle top and a metallic ring fit on the outer surfaceof the syringe. Under optimal conditions, plasma is emitted as centimeter-long jets, justmillimeters in diameter or even smaller.

The working gases are supplied by high-pressure cylinders. Gas pressure regulators areused to reduce the pressure of gases to a workable level. Then, gas flow controllersdeliver the gases with the desired flow. For voltage amplitudes of 15–18 kV, the plasmajet is very weak. The plasma jet disappears for voltage amplitudes lower than 15 kV. When helium is injected from the gas inlet and high voltage pulses 26 kV voltage isapplied to the electrode, the plasma jet is generated and a plasma plume reachinglength of 21 mm is launched through the end of the tube and in the surrounding air. Theplasma has a cylindrical shape. The length of the plasma plume can be adjusted by thegas flow rate and the applied voltage.

A Lecroy 200 MS/s 4-channel digital storage oscilloscope model (9304c) was used torecorded voltage and current waveforms, via a high voltage probe and a pulse currenttransformer, respectively; and to calculate the discharge power. The measured peakvalue of the discharge current was approximately 10.5 A during the pulse. Figure 3 showsthe current and voltage waveforms measured as a function of time at an input energy of6.76 J (maximum

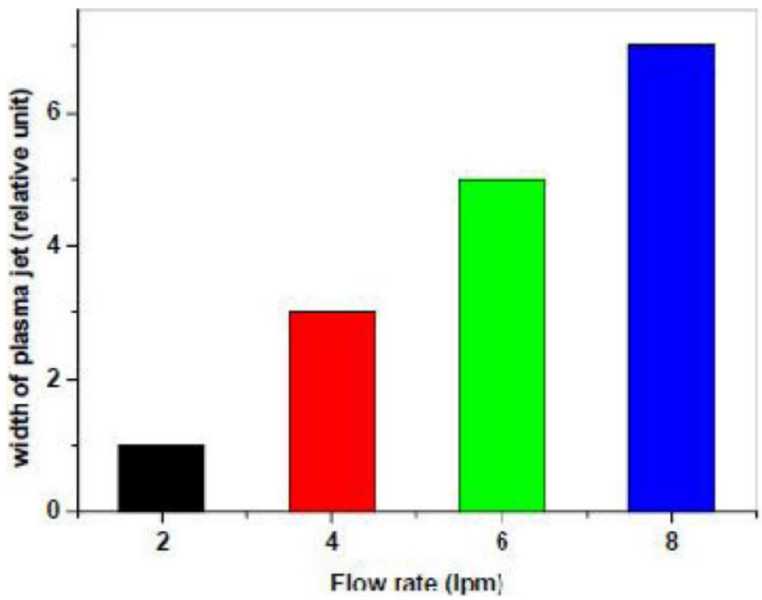

Figure 6 : Dependence of the plasma jet width on helium flow rate

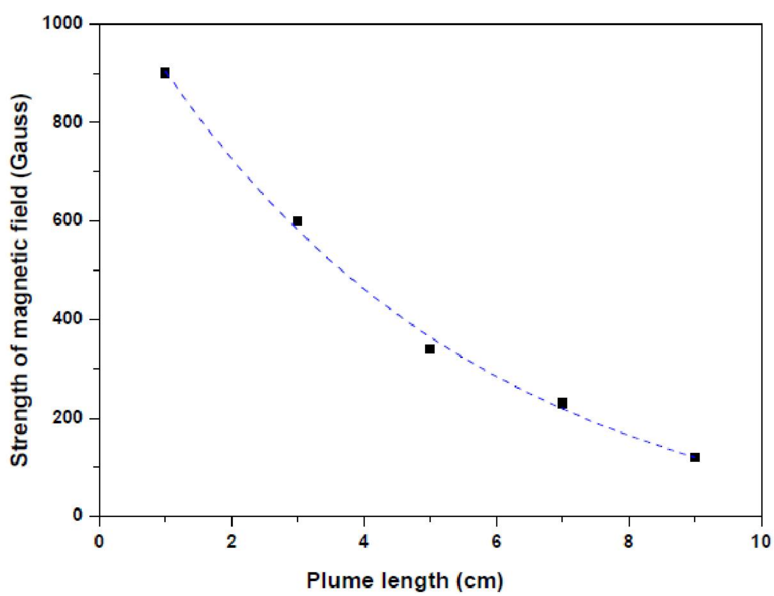

Figure 7 : The peak value of the magnetic field strength for different plume length (probe is mounted 3cm below the plasma plume)

applied voltage 26 kV). Figure 4 shows the power input as a function oftime, the maximum power approximately 150 kW at time 167 ns.

Figure 5. indicates the dependence of plasma plume length on applied voltage. As the result with increasing applied voltage, the plume lengthincrease exponentially. It is found that the maximum plasma plume length about 105 mm at 20 kV of applied voltage and there is no plasma plume inopen air at 13 kV of applied voltage.

Figure 6 indicates the dependence of the plasma jet width on helium flow rate, theminimum width at 2 liter per minute and maximum at 8 liter per minute. With increase gas flow rate, dischargevoltage increased. This is because a higher energy is necessary to get larger amounts ofgas into excited states.

The Model 5080 Gauss/Tesla-meter is a portable instrument that utilizes a Hall probe to measure magnetic flux density (magnetic field strength) in terms of gauss, tesla or ampere-meter is used to measure themagnetic field radiated by the plasma plume. The magnetic field probe is mounted 3cm and 5cm below theplasma plume to avoid disturbing the discharge. The magnetic field probe is usedto measure the magnetic field strength at different distances along the plasma plume. Essentially, the magnetic field radiated by the plasma plume is caused by the transient currentpulse, which is mainly electron current since electrons movemuch faster than ions due to the difference of their mass. Thus, the current carried by the plasma plume

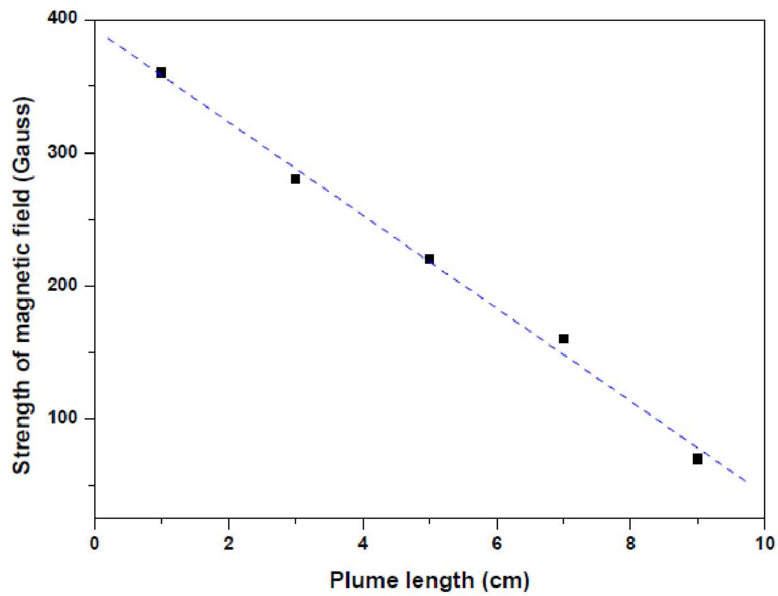

Figure 8 : The peak value of the magnetic field strength for different plume length (probe is mounted 5cm below the plasma plume)

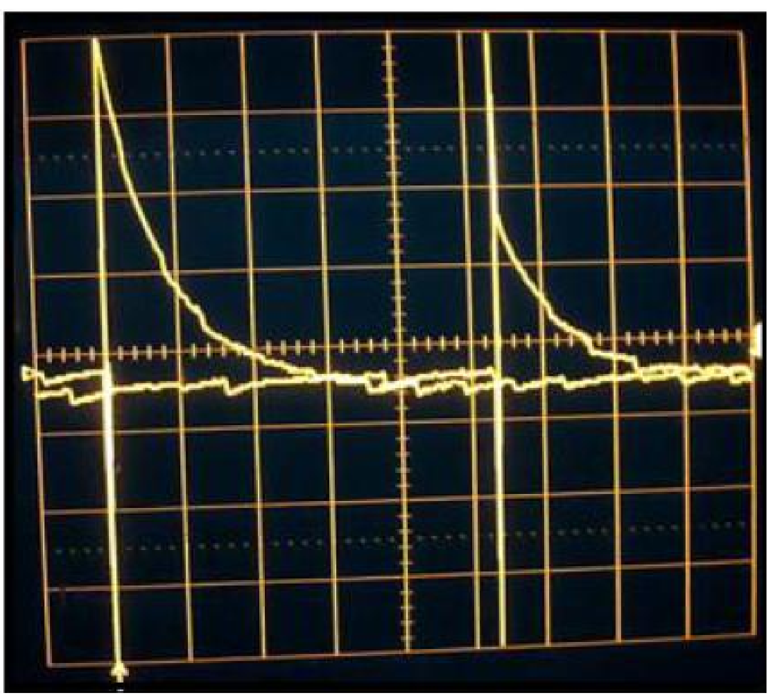

Figure 9 : Plume currentsat 2cm(left signal) and 5cm (right signal)from the nozzle versus time (0.1μs/division).

can be determined through the measurement of the magnetic field accordingly. For the magnetic field strength is sensitive with theprobe axis orientation and distance from the current axis, themagnetic field probe is installed at different locations below plasma plume. Figure 7shows the peak value of the magnetic field strengthabout 900 gauss at 1cm away from the nozzle (3cm below the plasma plume) and decrease along the plume length. Also, Figure 8 shows the peak value of the magnetic field strength at different distance away from nozzle (5cm below the plasma plume), the maximum magnetic field about 360 gauss at 1cm from nozzle.

The charge method is used directly to estimate the velocity of the plasmabullet. When the plasma plume is in contactwith the aluminum foil, as shown in Figure 2, the charges carriedby the plume are deposited on the aluminum foil surface. Thecharge deposited on the foil surface can be measured throughthe current probe. The two typical currentwaveforms correspond to the quartz tube placed at 2 and 5 cmaway from the nozzle. According to Figure 9, the average velocityof the plasma bullets is estimated to be about 5.5×10^{6} cm/s. It shouldbe emphasized that when the quartz tube is placed too closer tothe nozzle, the discharge is affected by the tube, and it probablyaffects the plasma plume propagation velocity.

CONCLUSION

It is found that the cold plasma jet using helium gas generated under atmospheric pressure by means of high voltage pulsed power generator radiates magnetic field. The magnetic field radiated from theplasma plume is measured by Hall probe to measure magnetic field strength in terms of gauss. By placing Hall probe at different position along the plasma plume, the magnetic field strength decrease away from the nozzle. It's found that the maximum value of the magnetic field strength about 900 gauss at 1cm away from the nozzle. The average velocityof the plasma bullets is estimated to be about 5.5×10^{6} cm/s using charge method.

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