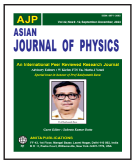

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Development of cold atmospheric pressure plasma jet sources for biomedical application

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Dedicated to Prof B N Basu

Characterization of dielectric barrier discharge (DBD) based cold atmospheric pressure plasma jet (C-APPJ) source has been carried out. The effects of the operating parameters have been analyzed on the effective formation and characteristics of the plasma plume. The emission spectra of the C-APPJ source have been measured to determine the presence of the reactive species generated from the developed sources. The discharge analysis and the plasma dynamics at higher flow rate of 3 SLM have been investigated. The discharge image shows that the plasma is emanated from the nozzle up to the distance of ~2.0 cm. The strongest spectral line centered around 308 nm shows the formation of the hydroxyl radical in the region of the plasma plume. A simulation has also been carried out to determine the velocity distribution of the gas at different flow rates in the C-APPJ source, and it was observed that the flow is turbulent in nature at higher gas flow rates (~3 SLM). The obtained results are expected to be useful for the design and development of C-APPJ sources for their potential utilisation in surface and biomedical applications. © Anita Publications. All rights reserved.

Keywords: Cold Plasma, Plasma Plume, Turbulence, Plasma medicine.

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1 Introduction

Cold atmospheric pressure plasma (CAP) sources provide many solutions in the medical field due to their therapeutic nature [1]. Production of the reactive radicals at low temperature opens up the avenues towards new area of research called "plasma medicine" [2-4]. In fact, cold atmospheric pressure plasma jet (C-APPJ) sources have received much attention for their utilisation in the medical application due to their capability of delivering the reactive oxygen and nitrogen species (RONS) in the narrow regions of the spectra [5,6]. However, the complexity of the interaction mechanism of plasma with the living cells demands attention toward the design and development of C-APPJ sources by optimising the operating and geometrical parameters, as per the requirements [7,8]. In the characterisation of the C-APPJ sources, the study is mainly focused on the characteristics of the plasma plume emanating into the atmospheric environment. For the design and development of suitable C-APPJ sources generally dielectric barrier discharge based mechanism is used [9].

In the present work, the characterisation of different dielectric barrier discharge based C-APPJ sources have been carried out. The discharge characterisation and the plasma formation have been investigated

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at an applied voltage of 8 kV, frequency of 25 kHz and gas flow rate of 3 SLM. The simulation analysis has been performed to determine the velocity distribution for analysing the gas flow dynamics in the C-APPJ sources. The discharge characteristics include the electrical and optical characterisation of the C-APPJ source. The plasma plumes generate different reactive species, which are identified by using optical emission spectroscopy. The investigation has also confirmed the formation of low temperature plasma plume and the generation of metastable, hydroxyl (OH), nitric oxide (NO), low plume current, etc. The paper is organised in four sections. In section 2, details of the experimental setup and procedure are explained, and the results are presented in section 3. Finally, the work is concluded in section 4.

2 Experimental Setup

Block diagram of the experimental setup of one of the designed and developed atmospheric pressure plasma jet (C-APPJ) for the analysis and characterisation of the discharge phenomenon is shown in Fig 1. The geometry of the plasma jet is similar as discussed in earlier work [10]. The working gas is injected inside the tube from the gas inlet at a fixed flow rate of 2 SLM, which is controlled by the mass flow controller (Matheson). The ignition of the gas takes place through the electrode wrapped over the nozzle of the tube making the distance of 7 mm to each other, Fig 1. The high voltage electrode is powered by high voltage pulsed DC supply with pulse repetition rate up to 50 kHz that results in the axial electric field in the direction of gas flow. The current transformer (CT) (Pearson Model 110; 0.1VA–1) and the high voltage probe (Tektronix P6015 A) are used for measuring the total current and the applied voltage at the electrode, respectively. The voltage probe and current transformer are connected to the Tektronix DPO 4054 digital oscilloscope for recording the voltage and current data.

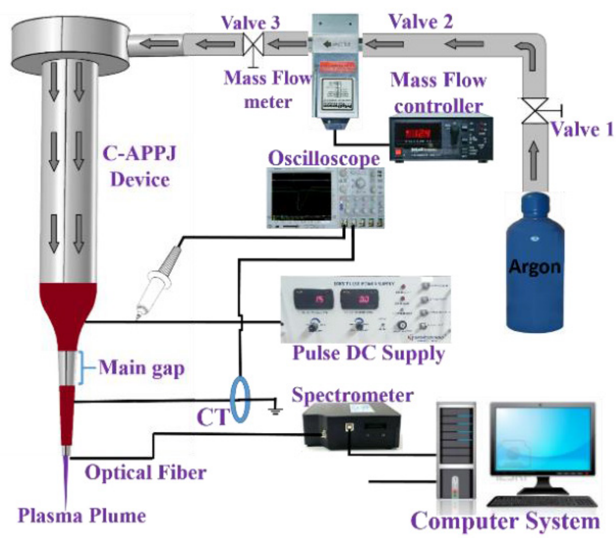


Fig 1. Schematic of the experimental setup for the characterization of C-APPJ source.

Spectral characteristics of the DBD based C-APPJ have been analysed by taking the emission spectra using the Ocean Optics spectrometer (HR4000). The radiations from the plasma plume formed outside the nozzle have been accumulated using the optical fibre of diameter 400 µm, which is placed at a location 10 mm radially away from the axis of the tube. The optical fibre transmits the light signal to the input of the spectrometer having diffraction grating of grooves 300 lines/mm that provides the spectral range of 200-1000 nm. The spectra have been recorded for the accumulation of the light for 100 milliseconds and fed to the computer for the post processing and data analysis.

3 Result and Discussion

The discharge characteristics of the C-APPJ have been analysed by the measured voltage-current waveform as shown in Fig 2. The unipolar pulse of amplitude 8 kV has been applied, which results in the strong current pulse formed during the rising edge of the applied voltage. The current reaches its maximum value at a voltage of 5.6 kV due to the direct ionization of Argon gas. The charged particles migrated and diffused toward the wall and accumulated on it, so that the induced electric field is found to be in opposite polarity. Hence, the ionization process is stopped, and the current is decreased. During the discharge in the C-APPJ source, very narrow current pulse is generally formed having smaller value of full width at half maximum (FWHM) as compared to that of the applied voltage pulse.

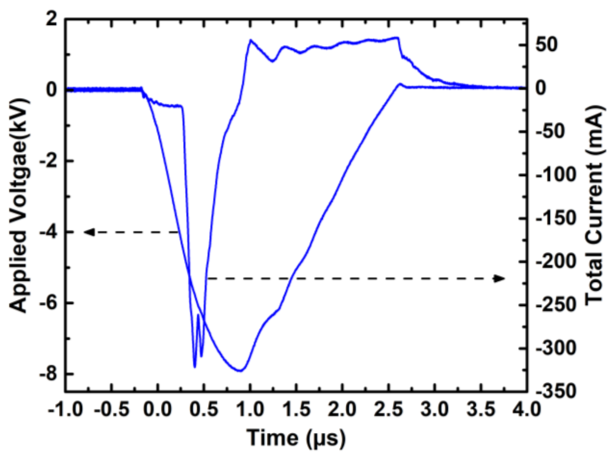
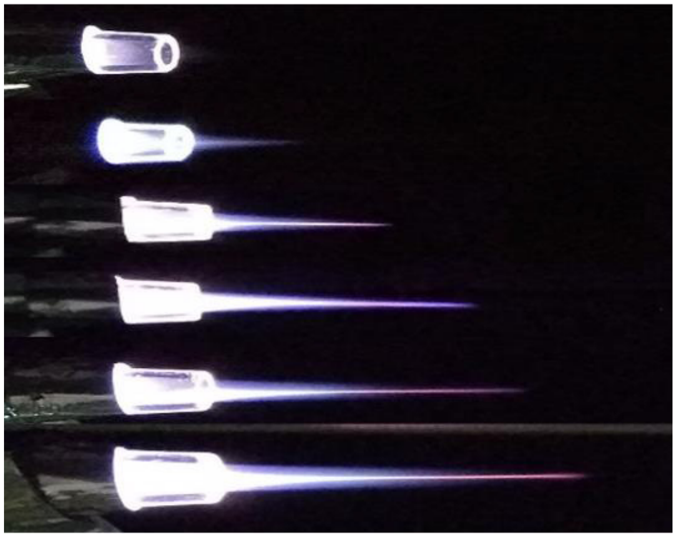


Fig 2. V-I characteristics of the developed C-APPJ source.

The strong current pulse during the rising phase shows that the maximum power is dissipated in the gas discharge. Multiple current pulses of small amplitudes are also formed during the falling phase, which is resemblance of the secondary discharge. The applied voltage pulse ignites the discharge and plasma is formed that propagates and emanates outside the tube of the C-APPJ source. Figure 3(a) shows the operation of C-APPJ source and formation of plasma plume at different magnitudes of applied voltage pulse having frequency of 25 kHz and flow rate of 1 SLM for Argon gas. The plasma plume is basically a fast propagation of ionization wave or say plasma bullet, and due to this reason, it is continuously visible with the naked eyes. The generated plasma plume of C-APPJ source using noble gas is mainly driven by electric field, and because of this an increase in the applied pulse width of the voltage pulse increases the duration of the plasma plume. Also, it is found that there is a deflection in the plasma plume due to distortion in the electric field if a conducting material is placed nearby, as shown in Fig 3(b).

Generation of plasma plume outside the nozzle of the developed C-APPJ source comprises of different species of Argon and energetic electrons. These species interact with the N_2/O_2 molecules of ambient air and produce the reactive oxygen and nitrogen species (RONS) such as OH, NO, H_2O_2, etc., which have biological importance. Generally, the spectroscopic methods are used for the investigation of the reactive species formed in the C-APPJ [11-12]. In this study, optical emission spectroscopy is performed to diagnose the different species produced by the C-APPJ source. The measured emission spectra of the C-APPJ source operated at an applied voltage of 8 kV, frequency of 25 kHz and gas flow rate of 3 SLM are shown in Fig 4. The spectral lines suggest the occurrence of excited species of Ar, N_2 and OH. In Fig 4, 600-900 nm emission lines resemble with the 4p-4s transition of the Ar atom. The second positive system (SPS) of N_2 ($C_3\prod_u \rightarrow B_3\prod_g$) were also observed in the optical emission spectra. The spectral lines and their peak wavelengths have been shown in Table 1.



(a)

(b)

Fig 3. Discharge in the C-APPJ source and the formation of plasma plume (a) at different amplitude of applied voltage pulse (5-8 kV) having pulse repetition rate of 25 kHz and a gas flow rate of Argon of 1 SLM, and (b) interaction with a conducting material placed nearby (graphite)

Table 1. Spectral lines obtained in the emission spectra of C-APPJ

Species	Wavelength (nm)
OH ($A^2\Sigma - X^2\Pi$)	308.42
O(^5P ^5S)	777.23
$N_2(C_3\Pi_u N_2 - B_3\Pi_u)$	336.26
Ar ($2p_2$-$1s_5$)	696.17
Ar ($2p_3$-$1s_5$)	706.26
Ar ($2p_2$-$1s_4$)	726.90
Ar ($2p_3$-$1s_4$)	737.94
Ar ($2p_1$-$1s_2$)	750.23
Ar ($2p_2$-$1s_5$)	762.99
Ar ($2p_7$-$1s_5$)	771.99
Ar ($2p_4$-$1s_3$)	794.42
Ar ($2p_6$-$1s_4$)	800.04
Ar ($2p_7$-$1s_4$)	810.83
Ar ($2p_2$-$1s_2$)	825.96
Ar ($2p_8$-$1s_4$)	841.55

Figure 4 clearly indicates the formation of hydroxyl (OH) radical, which is proportional to the intensity of the spectral line of peak wavelength at 308 nm ($A^2\Sigma^+ \rightarrow X^2\Sigma_g^+$). In Fig 4, the 308 nm line is the most significant and intense. The hydroxyl radical is formed due to the interaction of the plasma plume with the H_2O molecules present in the ambient air. The main reaction possibly generates the OH radical as shown below:

$$H_2O + Ar\ (^3P_2\,,\,^3P_0) \rightarrow OH\ (A^2\Sigma) + H + Ar \quad (1)$$

$$e + H_2O \rightarrow e + H + OH\ (A^2\Sigma) \quad (2)$$

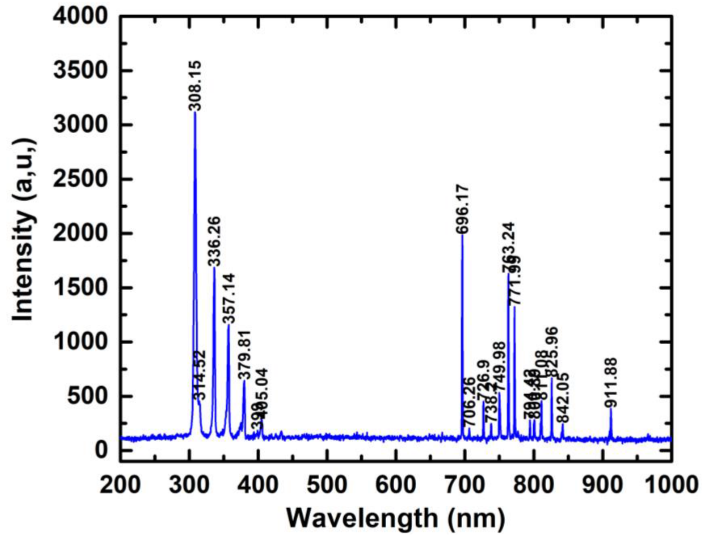


Fig 4. Optical emission spectra of C-APPJ source and the formation of plasma plume at an applied voltage of 8 kV, frequency of 25 kHz and a gas flow rate of 3 SLM.

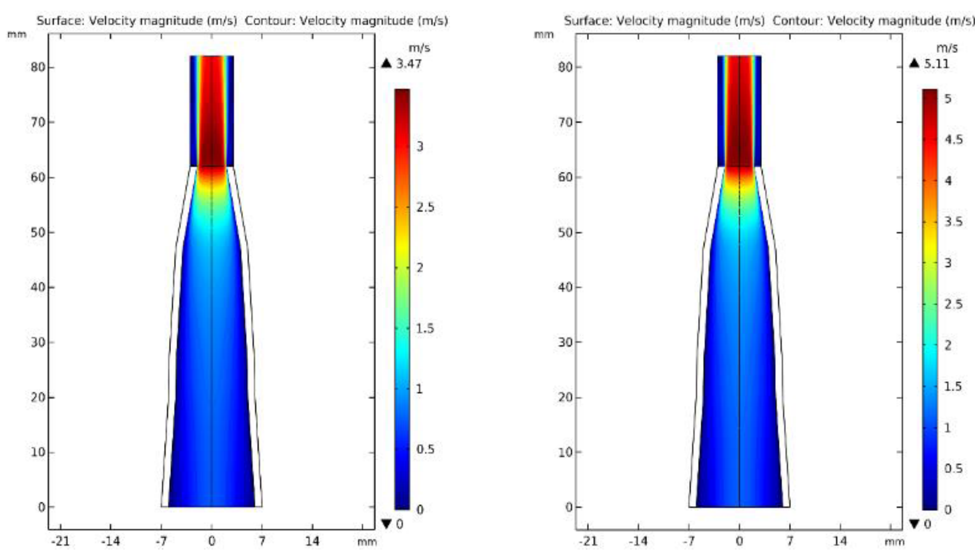


Fig 5. Surface and contour plot of Argon gas velocity in the annular region of C-APPJ source in which Argon flows at th rate of (a) 2 SLM and (b) 3 SLM.

The discharge dynamics and the emission characteristics have been analysed by experiment. The gas flow dynamics also has been found to play important role in the operation of C-APPJ sources. In this regard, simulation analysis has been performed using the COMSOL Multiphysics Software [13]. In the simulation study, 20 mm long rectangular region has been used to determine the velocity distribution of the gas emanated from the nozzle in the open environment. The inlet of gas flow has been maintained as required for the experiment. Figure 5 shows the velocity of the Ar gas flowing through the tube and ejected from the nozzle. The velocity distribution of gas has been calculated by solving Navier-Stokes equation along with the continuity equation. The geometry of tube has been fabricated in such a way that the gas velocity remains constant into the tube before reaching the opening of the nozzle. Due to tapered geometry of the nozzle, the velocity of the gas becomes higher at the exit of the nozzle. The velocity of the gas for the given flow rate of 2 SLM and 3 SLM have been shown in Fig 5(a) and 5(b), respectively. It has been observed that the velocity of the gas reached to 3.47 m/s at 2 SLM flow rate, and it acquires 5.31 m/s velocity for the 3 SLM flow rate, as shown in Fig 5. As the flow rate is increased, the gas starts ejecting from the nozzle at higher velocities that affects the characteristic length of the plasma plume.

4 Conclusion

The study presents the analysis of discharge dynamics and the gas flow dynamics of the developed C-APPJ source having ring electrode configuration and operated using Argon gas. The discharge characterisation including the electrical and optical characterisation of the C-APPJ source have been carried out. The gas flow dynamics has been analysed by evaluating the velocity of the gas in the nozzle and outside the nozzle using the COMSOL simulation tool. It has been found that the flow is turbulent in nature at the gas flow rate of 3 SLM. The higher rate of Argon flow (3 SLM) assisted the production of the suitable plasma plume to create the desired medium for enhancing the generation of different species. The emission spectra reveal the existence of large number of species such as excited argon, N_2 and OH. In fact, presence of these species demonstrates the potential of the developed C-APPJ source for food and biomedical applications. The simultaneous experimental and simulation studies for the characterization of C-APPJ source at wide range of operating and geometrical parameters are expected to be useful for the development of suitable cold atmospheric pressure plasma jet devices for various applications in biomedical and packaging industries.

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