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ORIGINAL RESEARCH

Design, Construction and Characterization of AC Atmospheric Pressure Air Non-thermal Plasma Jet

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Abstract This paper presents the design and construction of non-thermal plasma jet device which was built in plasma phys. Dept., NRC, AEA, Egypt with a plasma application group. This design will be useful to initiate research in different fields such as low temperature plasma, polymer and biomedical applications. The experimental operation of this device is conducted with power supply of (10 kV, 30 mA, and 20 kHz). The discharge process takes place by using Air as input gas with different flow rates. The experimental results showed that the maximum plasma jet length of 7 mm is detected at air flow rate of 12 L/min. The electrical characteristics of discharge at different flow rates of Air such as discharge voltage, current, mean power, power efficiency, and energy have been studied by using potential dividers and Lissajous figure techniques. The results of plasma jet temperature along the jet length showed that the jet plasma has approximately a room temperature at the end of jet column.

Keywords Plasma jet · Neon power supply · Lissajous figure · Power efficiency

Introduction

Atmospheric-pressure plasmas has attracted much attention in recent years as a promising source for various industrial applications due to their advantages such as the ability to provide a vast array of chemically active species without elevating gas temperature and operating without expensive vacuum equipment [1].

Devices that generate discharges at atmospheric pressures face problems with heating and arcing within the gas and/or the electrodes. To overcome these problems, several schemes have been devised such as the use of pointed electrodes in corona discharges [2], insulating inserts in dielectric barrier discharges [3], and a plasma jet has been developed which uses flowing helium and a special electrode design to prevent arcing [4].

Over the past 3 years, many plasma jet devices that produce a non-thermal atmospheric-pressure plasma plume have been investigated. The interest in this topic is dictated by a potential economic benefit from numerous non-thermal plasma technologies [5].

The major advantage of atmospheric pressure plasma jets (APPJs) is the small plasma dimensions in combination with the ability of penetrating into narrow gaps with high aspect ratio [6].

This makes APPJs particularly interesting for applications involving complex geometries with micro structured cavities or capillaries. Likewise, the small dimensions of the blown out discharge are advantageous for the precise treatment of sensitive spots. Thus, APPJs are often used for biomedical applications [7, 8].

Nonthermal plasmas generated at reduced pressure are well established for broad applications in material science. Nonthermal atmospheric plasmas get much attention lately because they can provide a cheaper and more convenient alternative in comparison with low-pressure plasmas [9].

The plasma jet operation depends on the electrical excitation which can vary from DC power to sine-wave power with frequency from tens of Hz to MHz (radio frequency)

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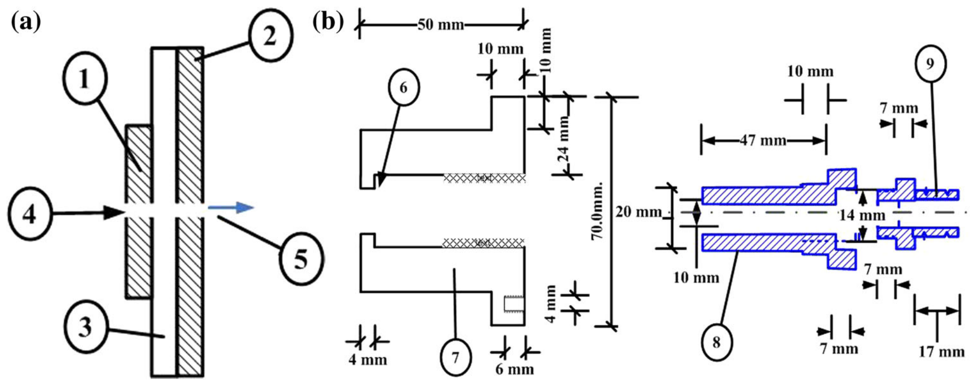

Fig. 1 **a** Electrodes structure **b** schematic of simple Air non-thermal plasma jet device at atmospheric pressure. *1* Anode, *2* Cathode, *3* Teflon insulator, *4* Gas inlet, *5* Plasma jet, *6* Electrodes location, *7* Envelope, *8* Artelone dielectric, *9* Gas feeding

and to GHz (microwave). For different jet sources applying specific working conditions, i.e., device configurations, carrier gases, and driven powers, the generated plasma effluents may display distinct characteristics [10–12].

The main purpose of this paper is to describe the design and construction of an atmospheric pressure non-thermal plasma jet device as well as investigation of its characteristics.

Design and Construction of Plasma Jet Device

A drawing of the experimental device configuration parts used to produce the atmospheric non-thermal plasma jet is shown in Fig. 1a, b. The device was designed and constructed from two parallel Aluminum electrode discs, Teflon insulator, Copper envelope and Artelone dielectric. The electrodes (Fig. 1a (1, 2)) have diameters of 21, 9 mm respectively with thickness of 3 mm separated by Teflon insulator (Fig. 1a (3)). This insulator has diameter of 21 mm and thickness of 1.5 mm. The assembled electrodes and the insulator have a hole of 0.8 mm diameter, through which Air gas is flowing as shown in Fig. 1a (4). They were stacked and fixed together using super glue adhesive material. The whole system is inserted in a cylindrical copper envelope for support it as shown in Fig. 1b (6, 7). This envelope is also used to connect with the plasma jet cathode. The inner electrode (anode) is connected to the copper tube for gas feeding shown in Fig. 1b (9) via electrical cable. This cable is isolated from the envelope by an Artelon dielectric shown in Fig. 1b (8). The plasma is ejected outside the cathode surface as shown in Fig. 1a (5).

The Artelon dielectric is also used to push the electrodes and the insulator for good contact between the cathode and the envelope. The plasma jet device is energized by using a commercially AC power supply for neon light with output of 10 kV, 30 mA and 20 kHz. This power supply is connected to the anode via 5 nF capacitor and 25 Ω resistor as shown in Fig. 2.

The discharge voltage, $V_d(t)$, is measured by a voltage probe (1000:1) that connected between the cathode and anode. The discharge current waveform, i(t), is measured by measuring the voltage across the 25 Ω resistor terminals ($V_R(t)$) while the capacitor voltage, $V_c(t)$, is measured by using a voltage probe (21:1). An electronic digital Tektronix oscilloscope TDS1002 is used to view the voltage and current output waveforms. A Variac 220/250 V, 50 Hz, 12 A is used to adjust the input voltage of the neon power supply. Diagnostic devices arrangements are shown in Fig. 3.

A flow meter with valve is connected to Shamal Air compressor (with volume and pressure of 270 L and 11 bar respectively), to feed the plasma jet device under consideration with Air flow rate ranging from 0 to 25 L/min. The plasma jet device can be hand held, and the plasma can be touched by human bodies without any harm as shown in Fig. 4.

The total weight of the device, including power supply, is <1 kg and the overall cost of the device is about 200 $.

Experimental Results

Jet Plume Configuration

Figure 5 shows images of plasma jet plume operated with Air for different flow rates from 3 to 25 L/min, fixed input voltage of 6 kV.

The experimental results indicated that, the length of the plasma jet plume increases with increasing flow rate from 3 up to 12 L/min.

For Air flow rate from 9 to 15 L/min, the jet plume is more comparable. After that, the jet plume becomes shorter in length and less luminous until flow rate of 25 L/min. It is observed that maximum jet plume length of 7 mm is detected at flow rate of 12 L/min.

The Electrical Characteristics

The electrical characteristics of the plasma jet device including the discharge parameters such as the discharge voltage, discharge current, consumed power, energy and

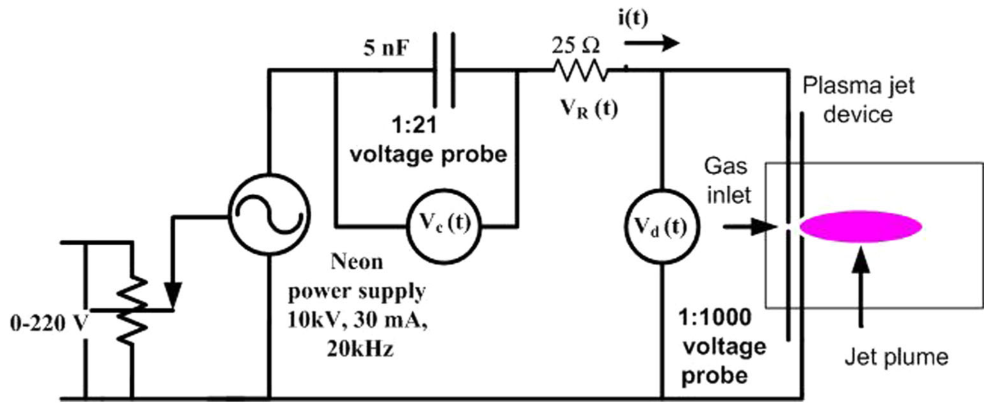

Fig. 2 The electric circuit of the non-thermal plasma jet device

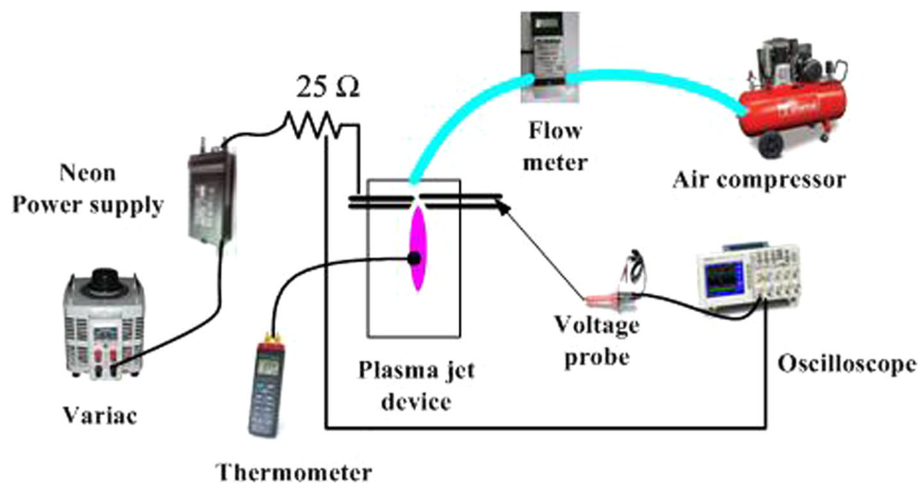

Fig. 3 Experimental arrangement and the diagnostic techniques of plasma jet device

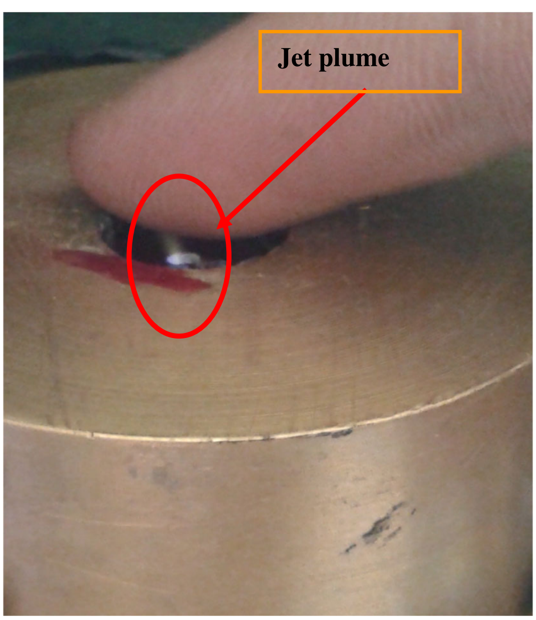

Fig. 4 Photograph of Air plasma jet in contact with human hand

power efficiency were investigated at different Air flow rates in the range from 3 to 25 L/min.

The discharge could not be maintained at voltage values smaller than 6 kV. The discharge voltage, $V_d(t)$, is measured between the two electrodes using the 1000:1 voltage probe.

The discharge current i(t) is obtained from the measurement of the voltage across the resistance of 25 Ω. The consumed power (W) is obtained (traditional method) by the following equation [13]:

$$P = \frac{1}{T}\int V_d(t).i(t)dt \tag{1}$$

where T is the period time of the discharge voltage. The energy (J) is estimated by multiplying the consumed power by the period time or by calculating the area under curve of the obtained power as a function of time.

At flow rate of 12 L/min which corresponds to maximum length of plasma jet plume, the discharge voltage, the discharge current signals and the consumed power are shown in Fig. 6a, b.

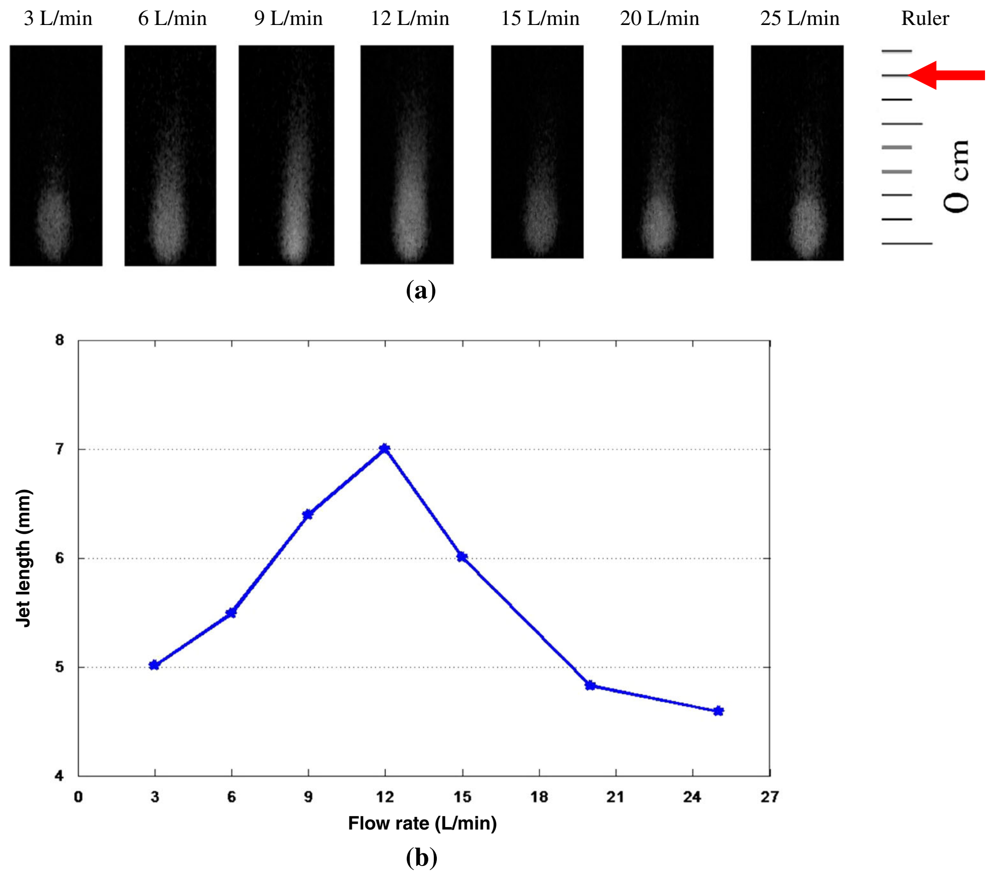

Fig. 5 **a** Photographs of Air plasma jet plume at different flow rates and **b** variation of jet length with Air flow rates at 6 kV input voltage

The experimental measurements showed that the signals of $V_d(t)$ and i(t) have sinusoidal signal form with frequency of 20 kHz. From the measurements, it can be seen that the discharge current leads the discharge voltage by phase shift angle of 86°. The discharge voltage, current and mean consumed power values are 3.4 kV, 31 mA and 33.6 W respectively.

The mean consumed power at the same discharge conditions mentioned above can be also obtained by using Lissajous figure (V–Q figure) [14–16] which includes the data of the discharge voltage $V_d(t)$ and charge Q(t) on the 5 nF capacitor shown in Fig. 2. The charge Q(t) on the capacitor is obtained using the following equation:

$$Q(t) = CV_c(t). \tag{2}$$

The mean power consumed is determined by employing V–Q Lissajous figure shown in Fig. 7 by multiplying the area of this figure by the frequency of the discharge voltage. The power efficiency of the plasma jet device can be obtained by dividing the measured consumed power by the input power (48 W of this device).

The mean consumed power, the power efficiency, and the mean energy by using Lissajous figure have values of 32.1 W, 67 %, 1.68 mJ per each voltage period respectively. It can be seen that Lissagous figure gives the same result for the mean consumed power of the traditional method with a difference of about 5 %.

At Air flow rates of 3, 6, 9, 15, 20, 25 L/min, the mean consumed power, power efficiency, and energy are measured as described previously for Air flow rate of 12 L/min. Figure 8 shows the variation of the mean consumed power, power efficiency and mean energy as a function of Air flow rate in the range from 3 to 25 L/min. It is observed that the mean power consumed increases from 6.61 to 32.1 W with increasing Air flow rate from 3 L/min until 12 L/min correspondingly. After that, the mean consumed power is decreased from 32.1 to 11.2 W with increasing Air flow rate after 12 L/min until 25 L/min.

The power efficiency and the mean energy consumed per voltage period have the same behavior like the mean consumed power. They have a maximum value of 67 % and 1.68 mJ respectively, at Air flow rate of 12 L/min.

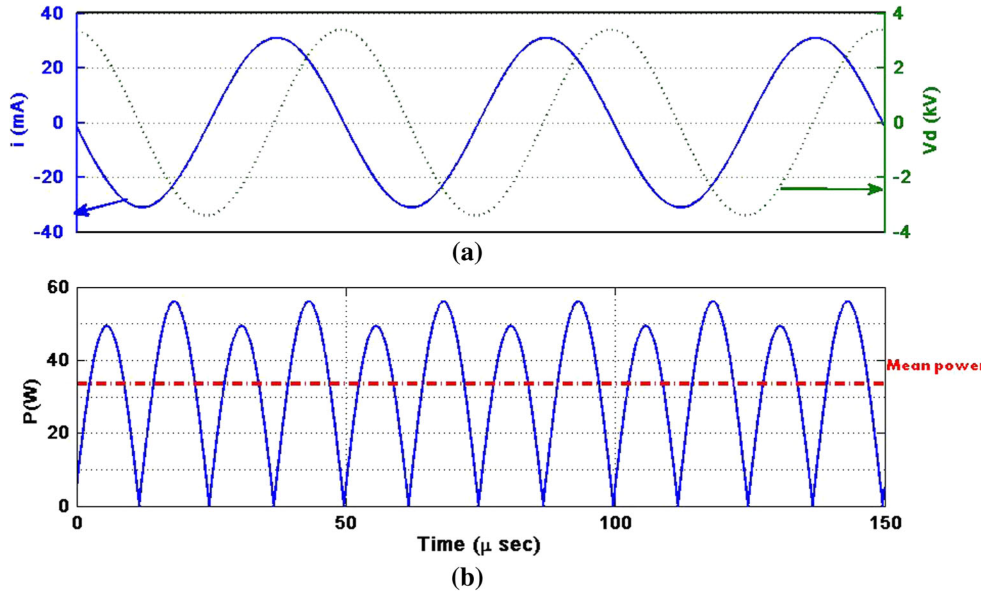

Fig. 6 waveforms of discharge parameters at Air flow rate of 12 L/min: **a** the discharge current and voltage, **b** the consumed power

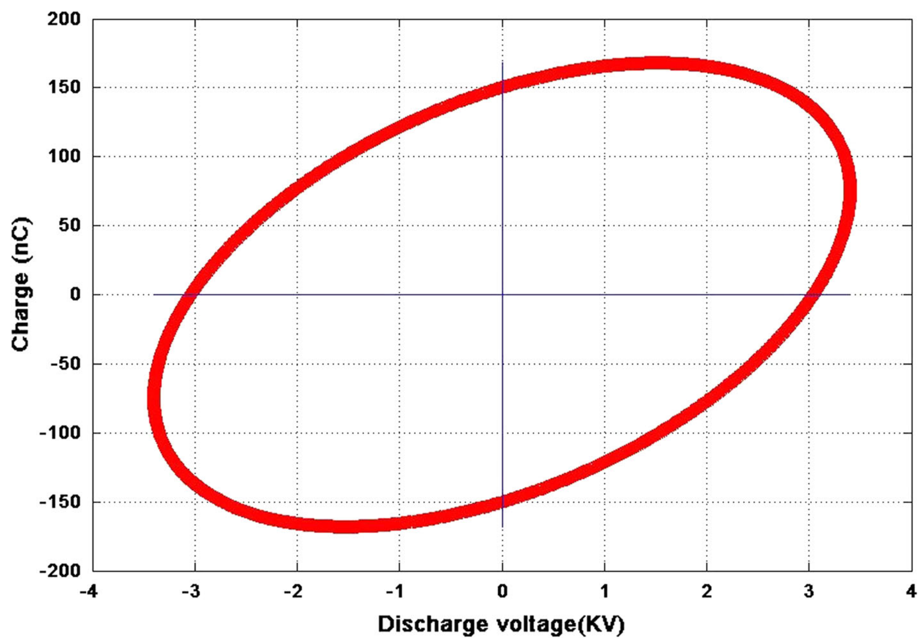

Fig. 7 Lissajous figure for the non-thermal plasma jet device at Air flow rate of 12 L/min

Measurement of Gas Temperature

The gas (heavy particles) temperature of the plasma jet liberated from the plasma jet device under consideration is measured by using dual probe type K thermometer model BK PRECISION 710. This temperature is found to be in the range of 100–50 °C from 2 to 7 mm.

Temperature is measured at different distances from the micro discharge channel in-between the two electrodes to 8 mm far away from the cathode surface at Air flow rate of 12 L/min as shown in Fig. 9. From this fig., it can be seen that the temperature decreases with the axial distance from the cathode surface. The temperature in between the electrodes is about 510 °C at −1 mm from the cathode surface (at the insulator between the anode and the cathode) and decreases to 380 °C at the cathode surface. Then it reaches 100 °C at 2 mm from the cathode surface. The temperature continues to decrease down to 50 °C at 7 mm distance from the cathode i.e., at the end of jet column.

At distance of 7 mm from the cathode surface, the jet's temperature becomes approximately close to the room temperature. The result confirmed that, the plasma jet

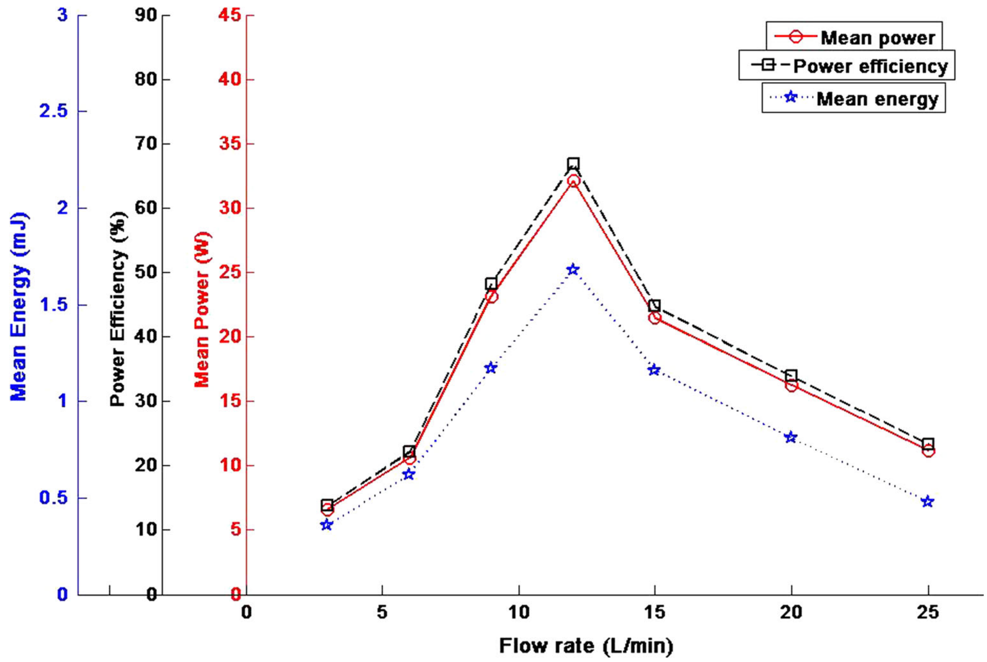

Fig. 8 Mean consumed power, mean energy and power efficiency of plasma jet at different Air flow rates

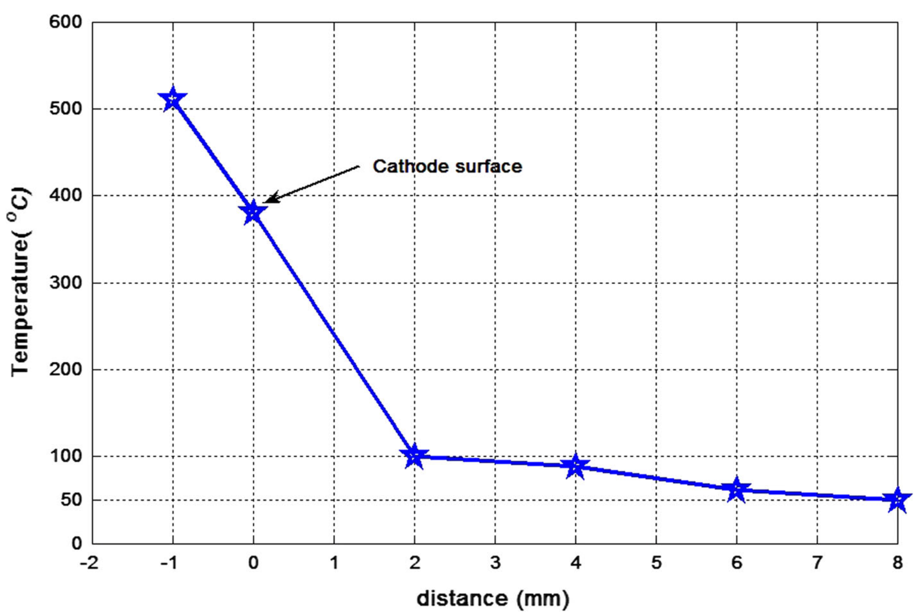

Fig. 9 Variation of temperature with different axial distances at Air flow rate of 12 L/min

device under consideration is a type of non-thermal plasma jet. Also, this temperature is suitable for polymer and biomedical applications [17].

Conclusion

An Air Atmospheric pressure non-thermal plasma jet device has been designed and constructed with low cost components.

Experimental data of the plasma jet column length and electrical characteristics of non-thermal plasma jet are taken at different Air flow rates in the range from 3 to 25 L/min and input voltage of 6 kV. Results showed that, the maximum jet plume length equals to 7 mm. The electrical parameters of the discharge such as discharge voltage, current, mean power, power efficiency, and mean energy have the maximum value of 3.4 kV, 33.6 mA, 32.1 W, 67 % and 1.68 mJ respectively at Air flow rate of 12 L/min. Thus, the performance of the device is found to be optimum at an Air flow rate of 12 L/min.

Results of plasma jet column temperature at flow rate of 12 L/min and along axial length (0–7 mm) illustrated that, the plasma jet temperature has approximately a room temperature (50 °C) at the end of jet column (7 mm), this result demonstrated that, the device under consideration is a type of non-thermal plasma and it is suitable in future for polymer and biomedical applications.

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