Non-Thermal Equilibrium Atmospheric Pressure Glow-Like Discharge Plasma Jet*

CHANG Zhengshi (常正实), YAO Congwei (姚聪伟), ZHANG Guanjun (张冠军)
State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi’an Jiaotong University, Xi’an 710049, China

Abstract Non-thermal equilibrium atmospheric pressure plasma jet (APPJ) is a cold plasma source that promises various innovative applications, and the uniform APPJ is more favored. Glow discharge is one of the most effective methods to obtain the uniform discharge. Compared with the glow dielectric barrier discharge (DBD) in atmospheric pressure, pure helium APPJ shows partial characteristics of both the glow discharge and the streamer. In this paper, considering the influence of the Penning effect, the electrical and optical properties of He APPJ and Ar/NH\textsubscript{3} APPJ were researched. A word “Glow-like APPJ” is used to characterize the uniformity of APPJ, and it was obtained that the basic characteristics of the glow-like APPJ are driven by the kHz AC high voltage. The results can provide a support for generating uniform APPJ, and lay a foundation for its applications.

Keywords: APPJ, glow-like, Penning effect

PACS: 52.25.−b, 52.80.−s

DOI: 10.1088/1009-0630/18/1/04

(Some figures may appear in colour only in the online journal)

1 Introduction

Uniformity and controllability of plasma are vital technical parameters for its applications in some special areas, such as materials process and bio-medicine, etc. However, the generation of a uniform non-thermal equilibrium atmospheric pressure plasma is a bottleneck in this field. Therefore, how to generate the uniform plasma and avoid heterogeneous filamentous discharge is also hot issue.

The glow discharge, as is well known, is firstly a method for obtaining the uniform discharge. Under low pressure, the direct current glow discharge, as a self-maintained discharge formed by positive ions bombarding the cold cathode, has been well known [1]. However, the discharge will transform into a filamentous mode with pressure increasing. Roth et al. [2,3] reported that, in open gas ambient, the One Atmospheric Uniform Glow Discharge Plasma (OAUGDP) could be obtained if an appropriate frequency of applied voltage was selected and the ions were captured between two electrodes. Since then, a word “atmospheric pressure glow discharge” has been widely used. Meanwhile, it is pointed out that the discharge is usually operated in a DBD structure in which at least one electrode was covered by insulation dielectric, whose surface will accumulate charges. It would help the discharge to transit successfully from a half period to the next half period without an arc. In the subsequent research works [4−7], several deep and detailed investigations were conducted through experiments and simulations. The plasma structure and characteristic of OAUGDP were obtained. Successively, the study on the mechanism of glow discharge in parallel plate DBD was also performed [8−10].

Certainly, plasma generated by using DBD glow discharge has great advantages in processing thin film; however, it cannot be used to treat the bigger size objects or those with an irregular shape, because of the short gap (<5 mm) of DBD. However, the discharge zone and work area of the atmospheric pressure plasma jet (APPJ) are separate, and the length of APPJ is usually longer than a few centimeters. It is a good and promising low temperature plasma source for use in treating remote objects with different shapes [11−14]. Furthermore, researchers in several special fields, such as skin disease therapy and sterilization etc., are eager for a homogeneous APPJ. The research results show that He APPJ is completely different from the glow discharge, showing the characters of not only the streamer but also the glow discharge. The phenomena presented in He APPJ are thought to be mainly because of the Penning effects between metastable atom He and molecular N\textsubscript{2}. To highlight the uniformity of APPJ, a word “glow-like APPJ” is employed in this paper. Then, the characteristics of the glow-like APPJ are researched by comparing optical and electrical properties of the APPJs. “Glow-like mode” was found in the paper about atmospheric pressure DBD of Chai et al. in 2002 [15], in which they pointed out that plasma has a

*supported by National Natural Science Foundation of China (Nos. 51307133, 51125029, 51221005) and the Fundamental Research Funds for the Central Universities of China (Nos. xj2012132, xjkc2013004)
good radial uniformity under glow-like discharge mode and only one current pulse per half cycle. In 2011, in the research on the homogeneity of glow-like DBDs at near-atmospheric pressure in helium, Li et al. [16] employed the glow-like discharge to judge the homogeneity of discharge, and proposed a streamer coupling theory to interpret the generation mechanism of this discharge. In 2014, Li et al. [17] further investigated the discharge current waveforms and images of He APPJ and Ar APPJ, and they thought that the Ar APPJ worked in the filament mode but the He APPJ worked in the glow-like mode. However, further interpretations were not obtained. Moreover, considering the Penning effect, the investigation of Chang et al. [18] showed that filamentous discharge for pure Ar APPJ will transform into the same discharge morphology of pure He APPJ if a little ammonia (NH$_3$) is added into pure Ar. Therefore, electrical and optical properties of He APPJ and Ar/NH$_3$ APPJ are investigated in the present paper to generate a glow-like APPJ, and then the basic characteristics of glow-like APPJ are summarized. The results can provide a uniform plasma source for some special applications and build a foundation for further researches.

2 Experimental arrangement

An electrode configuration with co-axial and double ring electrodes is employed in this paper, and the widths of the two electrodes (1 and 2) are fixed at 10 mm. Work gases are selected as pure helium and the mixture of argon and ammonia, and the gas flow is controlled and adjusted by using a mass flow controller. The APPJ is driven by a high voltage power with 23 kHz in frequency, as the experimental diagram shows in Fig. 1. A quartz tube acts as a dielectric and guides the gas flow channel, whose inner and outer diameters are 2 mm and 4 mm, respectively. The distance between electrode 2 and the nozzle of the tube is 10 mm. A digital camera (Canon 60D/700) and an intensified charge coupled device (ICCD, Andor iStar DH334T) are used to capture the images of APPJ in various exposure time scales. The discharge current and voltage waveforms are measured by using a current transformer (Pearson 2877) and a high voltage probe (Tek P6015A), respectively.

3 Results and discussions

3.1 $I$-$V$ Characteristics

For He APPJ driven by a high voltage with 23 kHz in frequency, Chang et al. [19] divided the discharge mode into five groups according to discharge current waveforms under various applied conditions, such as the peak-peak value of applied voltage, gas flow of helium, etc. The results are shown in Fig. 2, the embedded blue numbers represent the serial number of the modes. It can be seen that only one discharge (one current pulse) per half cycle appears in most of the cases (Modes 1-3) and the current pulse width is about 5-10 $\mu$s. The discharge behavior under the three discharge modes has a good repeatability, and the He APPJs previously reported basically belong to these three modes. Taking the Mode 3 as an example, Fig. 3 shows its typical voltage and current waveforms.

The published research indicates that Ar APPJ is usually a heterogeneous filament discharge. Just like the research results from Shao et al. [20], the discharge morphology of the Ar APPJ is an unstable and unrepeatable filament. The current amplitude is more than 10 mA. The speed of the plasma bullet is about $10^3$ m/s, which is one order of magnitude lower than that of He APPJ, and the radial shape of the plasma bullet is solid.

Considering the contribution of the Penning effects, by adding a little ammonia into pure argon, Chang
et al. [18] found that the discharge morphology becomes uniformity instead of maintaining the filament in pure argon. On the basis of these researches, the voltage and current properties of Ar/NH$_3$ APPJ under various NH$_3$ ratios are investigated in detail, and the results are shown in Fig. 4. If the gas flow rate of argon is fixed at 3 slm and that of ammonia is 0.4 sccm, it can be seen that only one current pulse per half applied voltage cycle appears in the voltage range of $V_{pp}=6$-13 kV. Both the positive and negative current pulses are symmetrical. It is similar to the case of Mode 3 of He APPJ. From the results of long time and continuous discharge, it is obtained that the discharge current waveforms have the same stability and repeatability.

Similarly, fixing the gas flow rate of argon at 3 slm and the peak-peak value of applied voltage at 7.6 kV, the behavior of only one current pulse per half applied voltage cycle is found during the range of the ammonia gas flow rate 0.1-5 sccm, when the gas flow rate of added ammonia is changed. The corresponding positive and negative current pulses are symmetrical, similar to the case of Mode 3 of He APPJ. Finally, the same stability and repeatability of the discharge current waveforms are also obtained from the results of long time and continuous discharge. The voltage and current properties are shown in Fig. 5.

The aforementioned researches indicate that the discharge current behavior of Ar APPJ transforms from the filament into the morphology similar to He APPJ when a little NH$_3$ is added into pure Ar. The uniformity of Ar/NH$_3$ APPJ is improved greatly and the amplitude of the current decreases remarkably. Fig. 6 provides the typical voltage and current waveforms of Ar/NH$_3$ APPJ.

![Fig.4 Voltage and current waveforms with different applied voltage amplitudes (Ar: 3 slm, NH$_3$: 0.4 sccm)](image1)

![Fig.5 Voltage and current waveforms with various gas flow rates of ammonia (Ar: 3 slm, $V_{pp}$: 7.6 kV)](image2)
3.2 Frequency spectrum of discharge current

For investigating the relationship between the uniformity and periodic behavior of the discharge, the Fast Fourier Transform Algorithm (FFT) is used to analyse the aforementioned discharge current waveforms of He APPJ and Ar/NH\textsubscript{3} APPJ. Take both the typical current waveforms in Fig. 3 and Fig. 6 as an example, the modulus value ($A_n$) of the harmonic is calculated by extracting the component of the discharge current, shown in Fig. 7. The discharge current includes the direct current component (marked as the blue number “0”), odd order harmonic components (marked as red numbers) and even order partner (marked as blue numbers). Whether for He APPJ or Ar/NH\textsubscript{3} APPJ, it can be seen from Fig. 7 that the peaks always present at the integral multiple driven frequency ($f_0=23$ kHz), and the same distribution of frequency is clearly found. In other words, the discharge currents of both the APPJs demonstrate the periodic behavior.

Similarly, under the same electrode structure with He APPJ, by fixing the carrier gas as the mixture of Ar (3 slm) and NH\textsubscript{3} (0.4 sccm), the macroscopical discharge images of Ar/NH\textsubscript{3} APPJ are captured with various applied voltages, as shown in Fig. 9. In this group of discharge images, the properties, such as the shape of APPJ, initial voltage and polarization effects etc., are similar to those of the aforementioned He APPJ, but are completely contrary to those of pure Ar APPJ\textsuperscript{[20]}. Discharge initiates at the downstream edge of the high voltage electrode and extends toward the outside of the tube when the applied voltage is low. Visual uniform plasma also presents in the DBD zone between both electrodes.
electrodes. With the increase of the applied voltage, the APPJ appears on the upstream side of the grounded electrode and extends against the gas flow. APPJs on both sides of the two electrodes are all cone in shape.

Fig.9  Macroscopical discharge images of Ar/NH$_3$ APPJ

To sum up, the macroscopical characteristic of the APPJ is a uniform discharge plasma whether in the DBD zone or on both sides.

3.4 Plasma bullet behavior

If the camera lens is focused on the downstream area of the nozzle, during positive discharge current pulse, APPJ’s evolutions in the two kinds of work gases are researched by using nanoseconds exposure images captured with ICCD.

For He APPJ, the results are shown in Fig. 10; it contains 10 images which are 1 digital image (2 s exposure) of the tube on the left and 9 ICCD images (10 ns exposure) on the right. The ICCD images from left to right are the spatio-temporal resolved plasma “bullet” in sequence. The plasma “bullet” on the downstream of the high voltage electrode propagates toward the grounded electrode or floating grounded electrode at the far end. It is similar to the cathode-directed streamer (CDS), which is an ionization wave. That is to say, the spatio-temporal He APPJ is an isolated plasma “bullet” (ionization wave).

Fig.10  ICCD images of He APPJ with 10 ns exposure

At the same time, the evolution of Ar/NH$_3$ APPJ (Ar(3 slm)+NH$_3$(0.4 sccm)) is studied by employing ICCD with 20 ns exposure time. The results in Fig. 11 also indicate that its behavior is a spatio-temporal isolated plasma “bullet” (ionization wave).

Fig.11  ICCD images of Ar/NH$_3$ APPJ with 20 ns exposure

4 Conclusions

He APPJ and Ar/NH$_3$ APPJ are driven by using an AC high voltage power with 23 kHz in frequency. The electrical and optical properties of the two kinds of APPJs are investigated by changing the applied voltage, gas flow rate and mixture ratio. It can be concluded that the two kinds of APPJs have many identical basic properties: (1) only one current pulse per half cycle of applied voltage, the peak value of the positive pulse is usually higher than or approximately equal to that of the negative pulse, and the amplitude of the positive current pulse ranges from 1 mA to 4 mA; (2) periodic frequency spectrum characteristic; (3) macroscopical uniform plasma; (4) plasma “bullet” behavior in ns magnitude; and (5) all of these discharge characteristics have very good stability and repeatability. These common points are different from the reported results of APPJ in other gas ambients such as pure Ar, N$_2$ and some mixture. Therefore, the APPJ, owning all the aforementioned characteristics, is defined as glow-like APPJ in the present paper.

References
10 Luo H Y. 2010, Study on homogenous dielectric barrier discharge at atmospheric pressure [Ph.D]. Tsinghua University, Beijing, China (in Chinese)


(Manuscript received 10 September 2015)
(Manuscript accepted 19 November 2015)
E-mail address of corresponding author ZHANG Guanjun: gjzhang@xjtu.edu.cn