POLARITY EFFECT OF REPETITIVE NANOSECOND PULSE DISCHARGE ON SYMMETRIC ELECTRODE IN THE SUBSONIC AIRFLOWS

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Abstract: Nanosecond pulse discharge plasma has good prospect in aerodynamic flow actuation applications, which has attracted much attentions in the world. In this paper, the characteristics of repetitive nanosecond discharge between two symmetric line-line electrodes in the subsonic airflows are investigated experimentally. The results show that the area distribution of three different discharge modes changes with the variation of flow condition and pulse parameters. Especially, it is found that there is a polarity effect of repetitive nanosecond pulse discharge for symmetric electrode in the subsonic airflows. Comparing to the case that the negative electrode is on the upstream of the airflows, the promoted area becomes larger with the positive electrode located on the upstream, but the inhibited area smaller. The polarity effect of the symmetric line-line electrode is mainly contributed to the micro structure of the electrode surface, which is confirmed by the corresponding experiment results.

1 INTRODUCTION

Flow control by atmospheric pressure discharge plasma is a growing topic, which has received a great amount of interest for a number of years due to its ability to modify the flow field around an aerodynamic body [1-6]. The plasma actuators seem to be good candidates comparing to conventional control techniques limited by strict localization and slow response time. In addition, it has some other advantages such as no moving parts, low weight and small size. If combined with relatively low energy consumption, all the features allow the possibility of developing new systems of flight control at high velocities.

So far, there are a lot of researches about flow control based plasma technology. These typical methods include some plasma actuators based on sinusoidal high voltage dielectric barrier discharge, DC surface discharge and repetitive high voltage nanosecond pulse discharge. However, among these existing techniques, it has been proved that a voltage waveform consisting of high repetition rate short (nanosecond) pulses has a potential to produce a stronger effect on the flow than other plasma actuators. But up to now, there are only a few works involving pulse discharge plasma actuator. All the reported works were focused on how a discharge influenced the airflow. From this point, some researchers proposed the physical mechanism of the nanosecond pulse plasma actuator, which is the fast heating of the near-surface layer. However, all the experiments or simulation models were conducted in the quiescent air [7-10]. In practical, the plasma used for flow control should be generated in flowing air. It is entirely conceivable that the discharge characteristics and plasma shape will be changed under the action of an external airflow. The actuator performance relies greatly on the plasma shape [11,12]. Therefore, a question how an external airflow influences a pulse discharge is proposed.

The objective of this paper is to investigate the characteristics of a pulse discharge in the airflow. Some different discharge modes are described. In this paper, we also discuss the physical explanation about some new phenomenon.

2 EXPERIMENTAL SETUP

Figure 1 shows a simplified scheme of the experimental set-up. Experiments were carried out at room temperature in atmospheric pressure air with a gas flow perpendicular to discharge gap with a variable velocity ranged from 0m/s~40m/s. a copper wire was used as a high voltage (HV) electrode opposite to a grounded copper wire electrode. Both of the copper wires are with a length of 68mm and a diameter of 0.1mm. The distance between electrodes d=4mm. The symmetric line-line electrode was set on a PMMA board in a parallel manner. The electrode system was installed on the lower wall of subsonic wind tunnel exit.

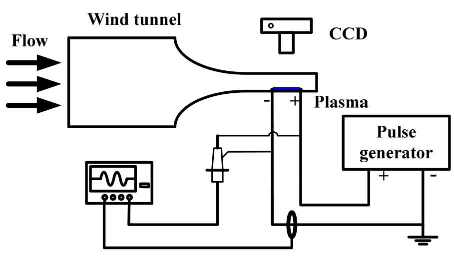


Figure 1: Schematic of the experimental set-up

A unipolar repetitive high voltage nanosecond pulse power supply connected via a series resistor R limiting the total current was used to generate pulse discharge plasma. All of the pulse parameters can be varied. Its repetition rate ranges from 100Hz to 5000Hz with the highest output voltage up to 40kV. The fastest rise time and shortest pulse duration can be 10ns and 30ns respectively.

The discharge voltage was measured by a high voltage probe (Tektronix P6015A) at the end of the two electrodes. A Rogowski coil (Pearson Electronics 4100) with a response time of less than 1ns was used to measure the discharge current. The voltage and current signals were recorded by a 500MHz digitising oscilloscope (Tektronix DPO4054) with a sampling rate up to 2.5Gs/s. a digital differential pressure sensor was used to measure the pressure difference of the total pressure and static pressure in the wind tunnel. Therefore, the velocity of the airflow can be calculated by the Bernoulli equation:

$$P + \frac{1}{2}\rho v^2 = P_0$$

Where: P = Static pressure in Pascal (Pa)

$\frac{1}{2}\rho v^2$ = Dynamic pressure in Pascal (Pa)

P_0 = Total pressure in Pascal (Pa)

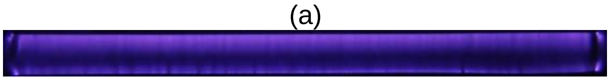
The camera of NIKON D300 was used to take the pictures for investigating the spatial characteristics of pulse discharge. The exposure time was set to 1s in the experiment. To examine and analyze the effect of flow on the discharge, three pictures were taken before, during and after the air flow in the wind tunnel. The corresponding voltage and current waveforms were also recorded at the three different stages. Fortunately, the electrical signals and discharge phenomenon seemed to keep relative stable in different stage respectively. So it is feasible to compare these different waveforms and images, although these electrical signal and discharge images may be not synchronous in the strict sense.

3 EXPERIMENT RESULTS AND DISCUSSION

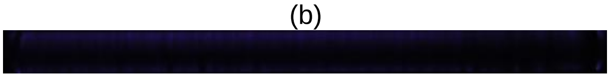
3.1 Different discharge modes in the airflows

In our experiment, the pulse discharge plasma formed between the two parallel copper wires. Firstly, the corona discharge appeared near the wire electrodes due to the concentration of electric field around the electrodes. With the pulse voltage increased, the discharge moved forward along the surface of PMMA board. The pulse discharge images seem to be multi-channel regime. But during the experiment, it was found that the discharge modes varied with the changes in flow condition and pulse parameter, which are shown in Fig.2. Fig. 2(a) illustrates a pulse discharge that was generated in the quiescent air. And the pulse voltage is 7.8kV with a rise time of 120ns, a repetitive frequency of 500Hz and a pulse width of 200ns. When the flow velocity was increased to 15m/s, interestingly, the discharge was promoted by the airflows, which was reflected in the discharge images and current (shown in Fig. 2(b) and Fig.3). This phenomenon is named as promoted mode under the action of the airflows. When the flow velocity was increased to 40m/s, the discharge was inhibited by the airflows (shown in Fig.2(c) and Fig.3). From Fig.2(c), it can be seen that the discharge was almost extinguished. If the flow condition and pulse parameter are limited to a specific range, the discharge kept unchanged or only changed slightly. The above mentioned regimes in the airflows are named as promoted mode, inhibited mode and transitional mode respectively.

(a)



(b)



(c)

Figure 2: The different discharge modes in the different airflow condition. Pictures in Fig(a), (b) and (c) are corresponding to the flow velocity 0m/s, 15m/s and 40m/s respectively.

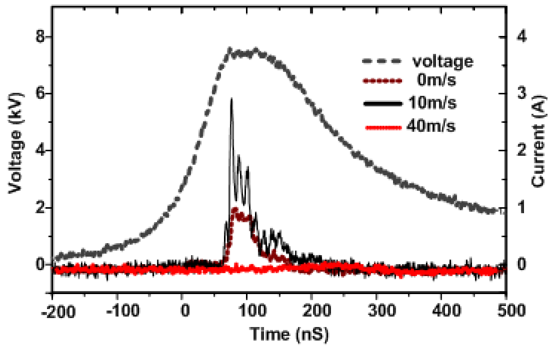
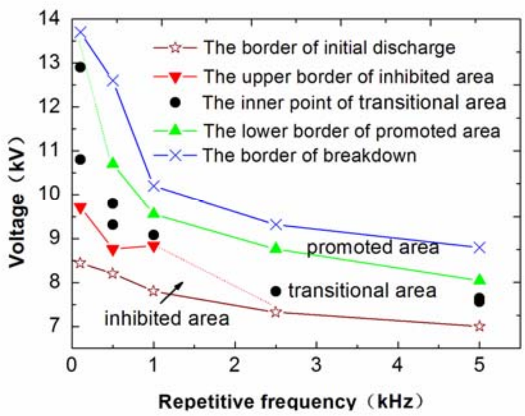


Figure 3: The voltage and current waveforms for different flow conditions

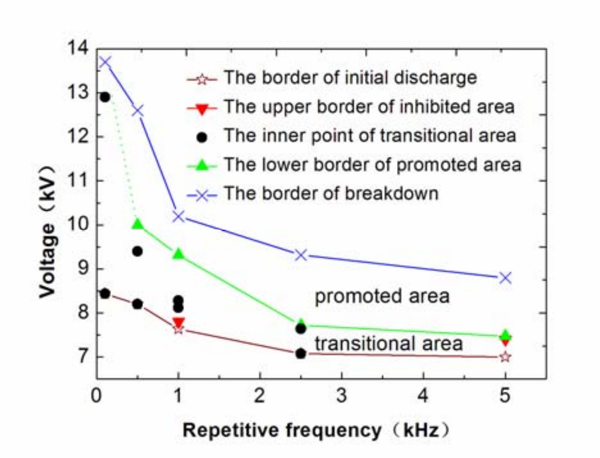
3.2 Area distribution of discharge modes and polarity effect

From the experiment results, it can be summarized that an external flow can not only promote the discharge but also inhibit the discharge. So a series of experiments were conducted to aim at determining the influence of pulse parameter and flow condition on the discharge modes. Based on a lot of experiment results, the area distribution of different discharge modes can be illustrated in the figure. These different areas named promoted area, inhibited area and transitional area are corresponding to the modes which have been mentioned in front section. Figure 6 and Figure 7 show the area distribution under different flow condition. And the borders of initial discharge and breakdown are both obtained in quiescent air. As the flow velocity increased, the inhibited area increased especially at the low frequency. This is due to the increase of inhibited effect resulted from the external flow. But the area distribution only changes slightly or almost unchanged at 4k Hz and 5k Hz. With the increase of repetitive frequency, the energy transferred to the gas gap increases. From the point of energy balance, the lost energy by external flow with cooling effect is so small that the inhibited effect is not obvious. Besides that, due to the memory effect of active particle and electron at high frequency, the quantities of these particles becomes larger, which is involved in the discharge process of the next pulse. And the interval between two adjacent pulses becomes smaller for a high repetitive frequency. During the interval time, the active particles diffused without the influence of electric field. Lots of particles can not be dispersed by the external flow in the short time.

Another important feature to be pointed out is that the area distribution is obviously different when the positive or negative electrode was on the upstream of the airflows respectively. With the positive electrode located on the upstream, the promoted area is much larger especially at high repetitive frequency when the flow velocity is 15m/s. Moreover, there is no inhibited area, which is different from the situation with the negative electrode on the upstream. When the velocity of the airflow is increased to 40m/s, the difference between them become more obvious. For the negative electrode on the upstream, the promoted area almost disappears with an increase of inhibited area and transitional area. However, there is almost no inhibited area as before when the positive electrode was on the upstream even at flow velocity=40m/s.

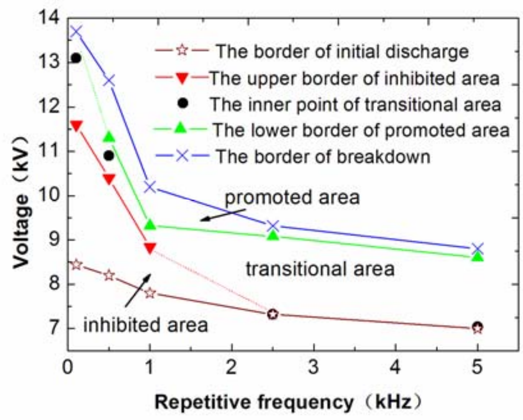


(a) Negative electrode at the upstream

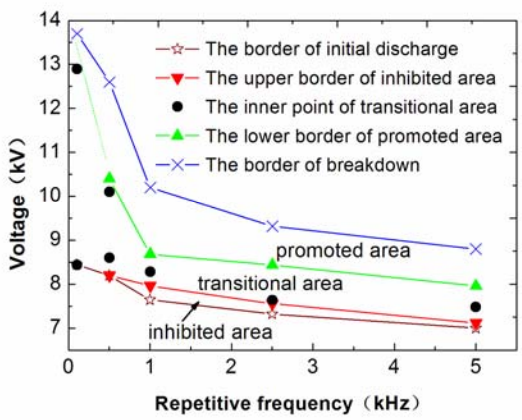


(b) Positive electrode at the upstream

Figure 4: The discharge area distribution at flow velocity=15m/s



(a) Negative electrode on the upstream



(b) Positive electrode on the upstream

Figure 5: The discharge area distribution at flow velocity=40m/s

3.3 Discharge characteristics of point-line electrode in airflows

For the differences of area distribution between the above two cases, it can be defined as polarity effect of symmetric electrode in the airflows. It is an interesting question that how the polarity effect generated for a symmetric line-line electrode. The discharge often occurs at the structural bulge or the defect of the electrode. In fact, a line-line electrode can be approximately equivalent to a parallel connection of many point-line electrodes from the view of microstructure. Therefore, it is necessary to investigate the pulse discharge characteristics of a point-plate electrode. A point-line electrode which is shown in Fig.6 was used in this section. It is a copper film electrode was plated on a PMMA board.

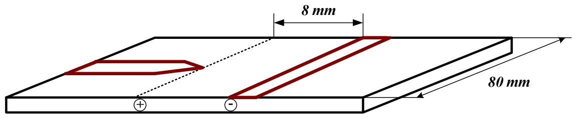
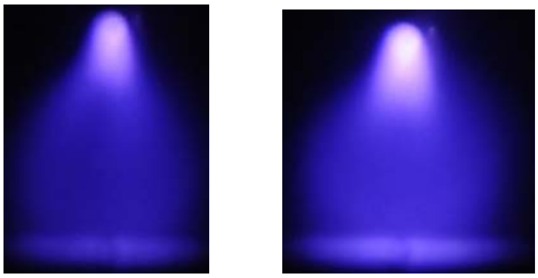


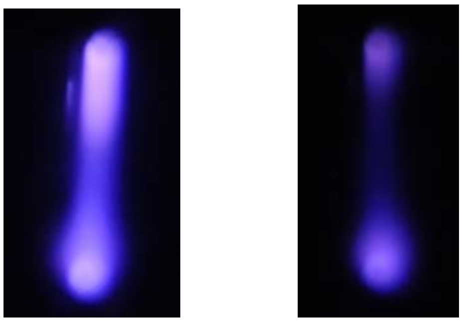
Figure 6: The structure of a point-line electrode

Figure 7 shows the discharge images for a pulse voltage of 7.7kV, with a rise time of 120ns, a pulse width of 200ns and a repetitive frequency of 5k Hz. And the positive electrode was on the upstream of the airflows (the point electrode is positive). The surface pulse discharge can also be promoted in the airflow, which is consistent with a line-line electrode. The discharge looks like a glow regime. The anode glow, positive column and cathode glow can be seen in the image. Comparing to Fig. 7(a), the brightness of anode glow and cathode becomes higher for Fig. 7(b). The luminous anode glow moves forward under the action of airflow. On closer examination, this phenomenon can also be found for a line-line electrode (shown in Fig.2). Figure 8 shows the discharge images when the negative electrode was located on the upstream (the point electrode is negative). The discharge was generated by a pulse voltage of 12.5kV, with a rise time of 80ns, a pulse width of 160ns and repetitive frequency of 5k Hz. The difference of the pulse voltage can be explained as the polarity effect for a point-plate electrode according to the classic theory of gas discharge. The corona discharge is easy to be initiated for a negative point electrode. However, it needs a higher voltage to generate an obvious glow-like discharge. Because the equivalent radius of the point electrode is enlarged by a diffused plasma which is generated around the negative point electrode. The electric field of the streamer head is inhibited due to the shield effect of plasma so that the discharge can not develop easily for the case of negative point electrode. Even the amplitude of the pulse is up to 12.5kV, the discharge is also inhibited by the airflow, which can be seen from Fig. 8(b). Therefore, it can be deduced that the polarity effect of symmetric electrode in the airflows may be mainly caused by the micro-structure of the electrode surface. Moreover, with a negative point electrode, the discharge looks like a thin channel, which is unfavourable for the generation of large area plasma.



(a) flow velocity=0m/s (b) flow velocity=40m/s

Figure 7: The discharge images for different flow conditions when the positive point electrode was on the upstream



(a) flow velocity=0m/s (b) flow velocity=40m/s

Figure 8: The discharge images for different flow conditions when the negative point electrode was on the upstream

4 CONCLUSION

The discharge characteristics of repetitive nanosecond pulse on a line-line electrode and a point-line electrode were investigated. For the line-line electrode, the discharge behaved as three regimes in the airflows. The discharge was easy to be promoted with high repetitive frequency at low velocity. For symmetric line-line electrode, the area distribution of discharge regimes was different when the negative electrode or positive electrode was on the upstream. From the experiment results, it can be concluded that the stable plasma was easier to be generated with a positive electrode on the upstream and a high repetitive frequency.

The discharge phenomenon of the point-line electrode was very similar to the local feature of the line-line electrode in the airflows. So it is considered that the polarity effect of symmetric electrode may be resulted from the micro-structure of the line-line electrode.

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