Verification and Analysis of Flowing Gas Discharge – Part II

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ABSTRACT

Using an artificial wind tunnel, the three basic preconditions presented in the preceding article by Kang *et al* are experimentally verified and systematically analyzed. The experimental results confirm that, in a discharge of flowing air, the breakdown path of an air gap deflects at an angle along the direction of the airflow. Some of electrons and ions are blown away by the airflow, and the mean free path of electron increases with increasing airflow velocity. In addition, the physical essences of the effects of flowing air on the discharge are revealed, and the differences in flowing air discharge between the uniform and non-uniform electric fields are discussed.

Index Terms — **wind tunnel, gas discharge, flowing air, path deflection, electron free path**

1 INTRODUCTION

IN a preceding article [1], which is referred to hereafter as Part I, we presented a physical model of the flowing gas discharge. This model extends Townsend's discharge model for static gases to flowing gases and can be applied to a wider range of gas discharge situations.

In the presented theory, we made three basic preconditions in the modeling process for flowing gas discharge. Therefore, their rationality affects the correct application of the presented discharge model. In addition, the physical essences of flowing gas discharge and its difference between the uniform and non-uniform electric fields are also unclear.

In this part, we examine the three basic preconditions and substantiate those points; we also reveal the physical essences of the effects of flowing air on discharge and the differences using appropriate experimental results.

2 EXPERIMENTAL SETUP

An artificial experimental wind tunnel, designed to simulate an airflow environment (the airflow velocity can be up to 120 m/s), was composed of a centrifugal fan, a steady section, a test section and an extended section. The anemometer (FC-002A) with the measurement range of 0 - 80 m/s was installed at the extended section, which is 1.78 times larger than the test section (the cross-sectional area at the test section is 240 mm × 180 mm). The experimental samples (a needle- plate electrode and a plate-plate electrode) were installed in the test section, as shown in Figure 1. The gap distance between electrodes could be altered using a slide adjuster. A DC high-voltage power source (ZGF-120) with an output voltage of 0-120 kV was applied to the needle and plate electrode. A high-voltage probe (Tektronix P6015A) was used to monitor the applied voltage between the needle electrode and grounded plate with the signal output to an oscilloscope (MDO3000 Tektronix) and get the breakdown voltage value. The leakage current was calculated by measuring the voltage of a non-inductive resistor of 0.4 MΩ connected between the plate electrode and ground, with the signal output to an oscilloscope (Tektronix M DO3000). In the experiment, the occurrence of breakdown was defined as the appearance of spark, as judged by observation of a sudden change of the leakage current. The discharge images were obtained by using a camera (Canon EOS) from the observing window (the purple area in the test section stands for the observing window shown in Figure 1, which is composed of a piece of quartz glass).

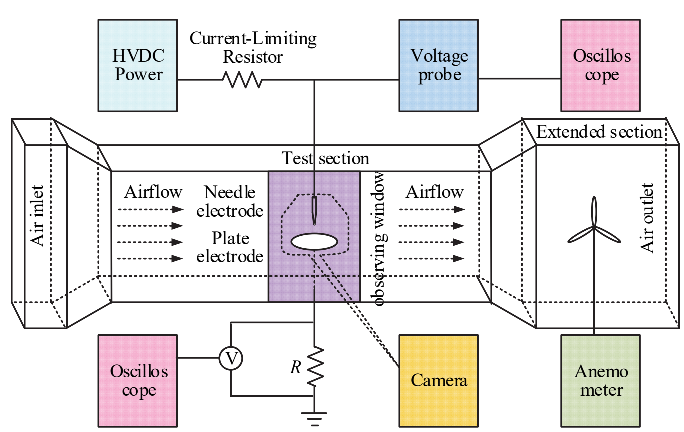

Figure 1. Schematic of experimental measurement.

In the experiment, the temperature, humidity and pressure of air were approximately 20 °C, 65% and 96 kPa, respectively.

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The increasing voltage method was adopted according to the IEC standard [2]. In order to reduce the experimental errors, the same experiment was repeated five times.

3 VERIFICATION AND ANALYSIS

3.1 DEFLECTS OF DISCHARGE PATH IN THE AIRFLOW

In the discharge of flowing air with the horizontal airflow velocity, we know from Part I that the velocity of the charged particles consists of drift velocity and airflow velocity (here, the diffusion velocity is ignored). Therefore, we suppose that the trajectory of electron motion could undergo a deflection in the horizontal direction, especially when the applied electric field is low and the airflow velocity is high, which can also be called the deflection effect. As a result, the major discharge path and the breakdown path in flowing air can also generate deflection. To verify and observe the deflection phenomenon of the discharge path, we performed the following experiments. The effects of airflow on the corona and spark discharge of the needle-plate air gap were investigated as shown in Figure 2. The diameter and thickness of the plate electrode were 25 mm and 6 mm, respectively. The diameter of the needle electrode was 1 mm, with a tip curvature radius of 0.1 mm.

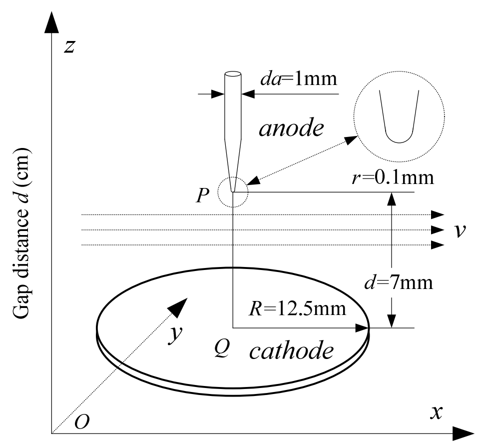
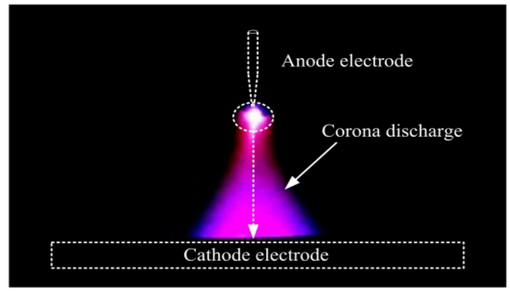


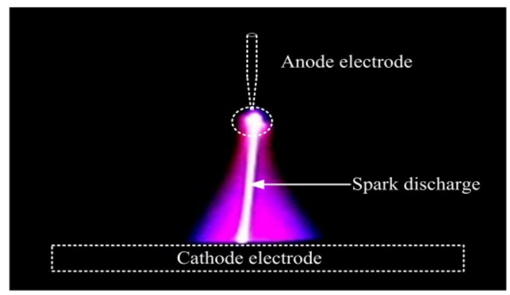
Figure 2. Discharge of the needle-plate air gap in flowing air with a horizontal airflow velocity.

The experimental results of the discharge of the needle-plate air gap under various conditions are shown in Figures 3 and 4.

Figure 3a shows the corona discharge of the needle-plate air gap in static air under an applied voltage of 20 kV and a gap distance of 7 mm. The light region of the corona discharge symmetrically distributes on both sides of the needle-plate electrode space, and the major discharge path is also in the vertical direction. In addition, we find that two strengthened discharge regions appear at the center of the needle electrode as a spherical shape and at the plate electrode as a coniform shape. When the applied voltage is increased to 20.4 kV, the leakage current increases suddenly and a large pulse current is observed. At this moment, breakdown of the air gap occurs and a spark is observed between the two strengthened discharge regions, as shown in Figure 3b. The breakdown path is approximately perpendicular to the axis of the needle and plate electrodes, even has a left deflection with an offset angle of approximately 5°, which may be caused because of the random breakdown path near the axis line and the defects on the surface of electrode. These results indicate that the major discharge path is almost perpendicular to the axis of the needle and plate electrodes under the case without airflow.



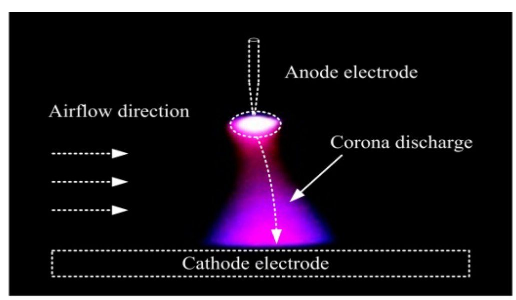
(a) Image of corona discharge (U = 20 kV, d = 7 mm, v = 0 m/s)



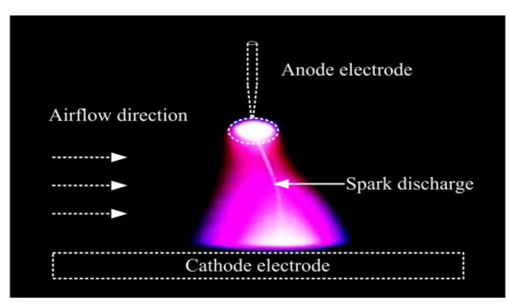
(b) Image of breakdown (U = 20.4 kV, d = 7 mm, v = 0 m/s)

Figure 3. Images of corona discharge and breakdown without airflow.

Figure 4 shows the experimental results for the flowing air discharge with an airflow velocity of 82 m/s.



(a) Image of corona discharge (U = 20 kV, d = 7 mm and v = 82 m/s)



(b) Image of breakdown (U = 24.3 kV, d = 7 mm, v = 82 m/s)

Figure 4. Images of corona discharge and breakdown with the airflow velocity of 82 m/s.

Figure 4a shows that the major discharge path exhibits a deflection along the airflow direction compared with the path in static air (Figure 3a); this deflection is clearer when we observe the strengthened coniform discharge region located at the plate electrode due to shifts rightward. When the applied voltage is increased to 24.3 kV, the first-time breakdown of the needle-plate air gap occurs and a spark is observed, as shown in Figure 4b. The breakdown path obviously deflects at an angle (approximately 15°) along the airflow direction, and the breakdown path connects the two strengthened discharge regions located on the needle and on the plate electrode, respectively. These results indicate that, in the discharge of flowing air, both the major discharge path and the breakdown path will exhibit a steady deflection angle along the airflow direction.

3.2 BLOWING AWAY OF CHAGRED PARTICLES IN THE AIRFLOW

In the discharge process of the flowing air, the neutral molecules from the airflow frequently collide with electrons and ions in the airflow direction; as a result, some of the electrons and ions involved in discharge could be blown away by the airflow. This phenomenon is also known as the blowing away effect [3] and is confirmed in the following section.

Compared with the discharge without airflow, the discharge regions with airflow mainly focus on the right side of the electrode space, which indicates that the charged particles (electrons and ions) are mainly distributed on the right side of the electrode space. Therefore, we suppose that, if the electrons and ions can be blown away by the airflow, we should be able to collect some of the electrons and ions (blown away by the airflow) using a metal mesh installed on the right side of the electrode space in the vertical direction. To do so, we designed the experiment shown in Figure 5.

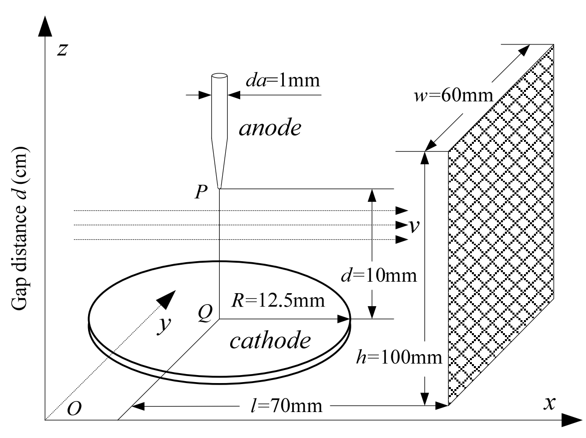


Figure 5. Collection of charges blown away by the airflow.

In this experiment, the applied voltage between the needle and plate electrodes is 10 kV and the gap distance is 10 mm. The metal mesh with a size of 100 mm × 60 mm, a mesh number of 100 and a wire thickness of 0.1 mm, is positioned 70 mm from the axis of the needle and plate electrodes. Because the metal mesh is far away from the electrode and the diameter of wire is very small, the metal mesh almost does not affect the wind property near the discharge path. In addition, the maximum wind speed is 120 m/s, which is much less than the velocity required by collision ionization (approximately 10^5 m/s) between gas molecules and metal mesh (the work function of iron is approximately 4.7 eV). Thus, collisions between gas molecules and metal mesh do not produce new charged particles. To study the effect of the metal mesh on the electric field distribution near the electrode space, the simulation of electric field is carried out. It is difficult to simulate completely field because the cell of metal mesh is very small and the calculation of all cells is complicated. To simplify the simulation, we replace the metal mesh with the metal plate with the same size. Figure 6 shows the electric field distribution between the needle and the grounded plate, which indicates that the electric field concentrates mainly on the needle-plate electrode space and the electric field near the metal mesh is approximately zero. Figure 7 shows the comparison of the electric field along the axis of the needle and plate electrodes between with metal mesh and without metal mesh. We see from Figures 6 and 7 that the application of the metal mesh almost does not affect the original electric field distribution between the needle and the grounded plate. In fact, the aim of the experiment is to verify the effect of the airflow on charged particles. Therefore, when other conditions remain constant, we only need to confirm the difference of the current pulses between with airflow and without airflow.

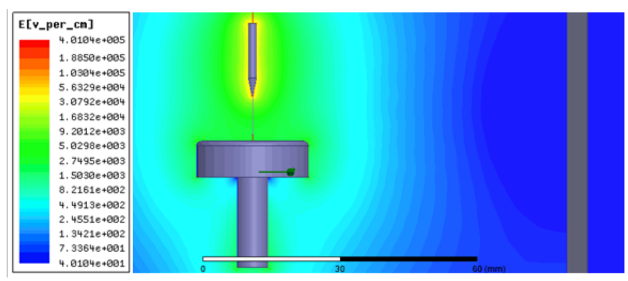


Figure 6. Electric field distribution of the needle-plate electric space with the metal mesh (the applied voltage between the needle and plate electrode is 10 kV).

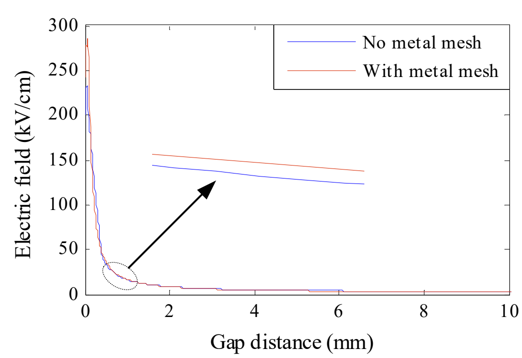
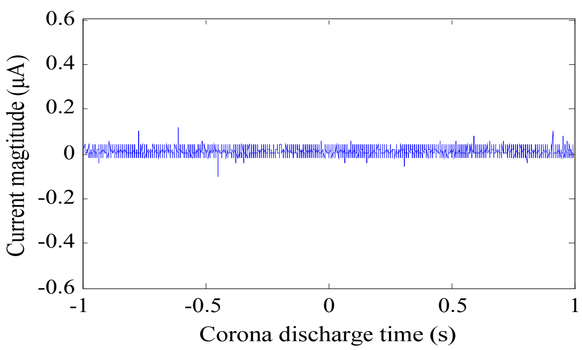


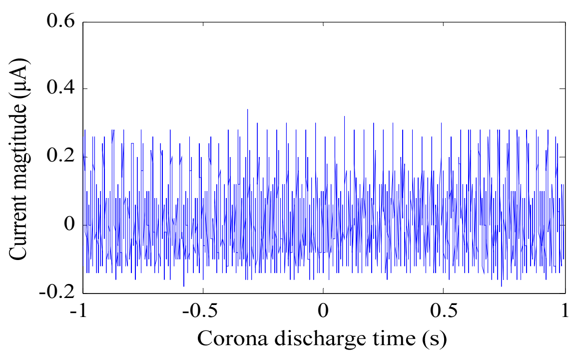
Figure 7. Comparison of the electric field strength along the axis of the needle and plate electrodes between with metal mesh and without metal mesh (the applied voltage between the needle and plate electrode is 10 kV).

Some of electrons and ions (blown away by the airflow) could migrate to the metal net because of the airflow, which can cause current pulses that can be measured using a non-inductive resistor of 10 kΩ connected between the metal net and ground and recorded using an oscilloscope.

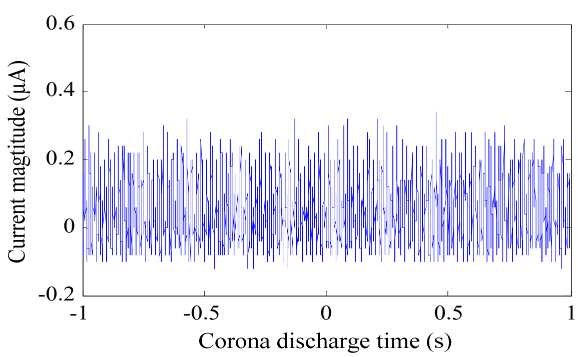
The measurements of current pulses are shown in Figure 8. We find that the collected current is approximately zero when the applied voltage is zero. When the applied voltage is 10 kV, we find that the collected current pulses in the case with airflow, shown in Figures 8b to 8f (with the airflow velocity of 30 m/s, 65 m/s, 82 m/s and 120 m/s, respectively), are greater than in the case without airflow (shown in Figure 8b), which directly confirms that, for the discharge of the flowing air, some of electrons and ions are blown away by the airflow. We also find that the average value of the collected current from the metal mesh increases gradually with increasing airflow velocity, as shown in Figure 8g. In addition, we see that there are many pulses found in Figures 8b to 8f. The reason causing the result may be as follows: (i) the current pulses or charges collected by the metal mesh are the difference of charges between the positive charges and the negative charges (here, we only consider the electrons) blown away by the airflow at



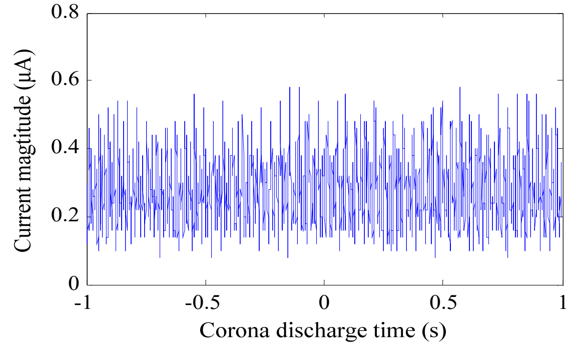
(a) Collected current waveform (U = 0 kV, d = 10 mm and v = 0 m/s)



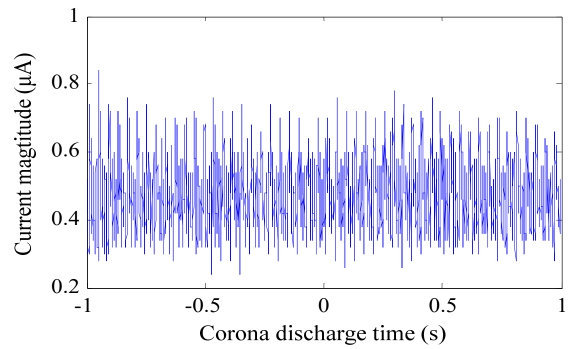
(b) Collected current waveform (U = 10 kV, d = 10 mm and v = 0 m/s)



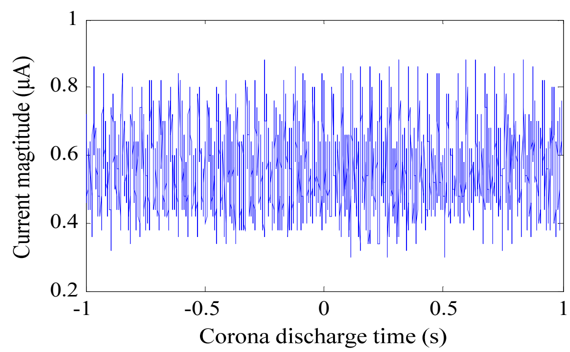
(c) Collected current waveform (U = 10 kV, d = 10 mm, v = 30 m/s)



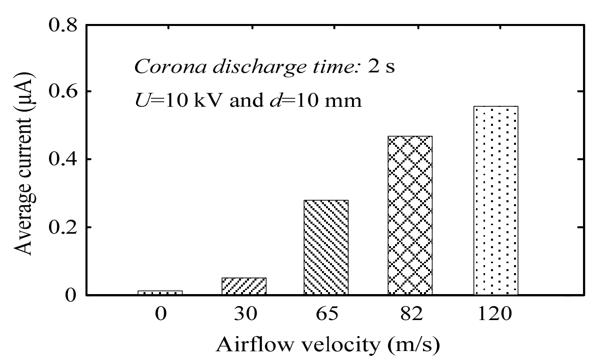
(d) Collected current waveform (U = 10 kV, d = 10 mm, v = 65 m/s)



(e) Collected current waveform (U = 10 kV, d = 10 mm, v = 82 m/s)



(f) Collected current waveform (U = 10 kV, d = 10 mm, v = 120 m/s)



(g) Average current value (U = 10 kV, d = 10 mm, t = 2 s)

Figure 8. Collected current waveforms and average value under different airflow velocities.

some point. When the positive charges collected by the metal mesh at some point are greater than the collected negative charges, the current is positive, and vice versa, which is a random process. Thus, the current collected by the metal mesh contains many pulses. (ii) the measurement waves contain background noise. In addition, we find that the average current is positive, which indicates that the positive ions collected by the metal mesh are greater than the collected electrons. The reason causing this result may be that the positive ions have greater cross section and lower drift velocity compared with the electrons, which results in that the positive ions are more easily blown away by the airflow. For Townsend discharge, we consider mainly the effect of electrons. Thus, the discharge process will be affected by the airflow because of the blowing away of some of electrons.

The cumulative charges of the discharge are calculated using the following expression:

$$Q(t)=\int_{t0}^{t} i(t)\mathrm{d}t \tag{1}$$

The cumulative charges of the collected current in two seconds under different airflow velocities were calculated and are shown in Figure 9. In the case with airflow, the cumulative charges are much greater than in the case without airflow (almost zero), which further indicates that the number of charged particles reaching the metal net obviously increases because of the blowing away effect. In addition, the cumulative charges in the case with high airflow velocity are greater than that with low airflow velocity, which indicates that the blowing away effect is strengthened with increasing airflow velocity.

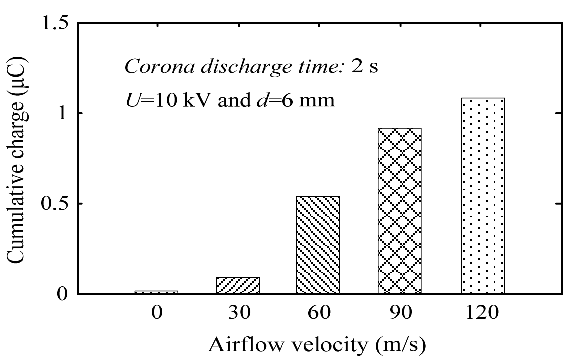


Figure 9. Cumulative charges under different airflow velocities.

3.3 CHANGE OF MEAN FREE PATH OF ELECTRON IN THE AIRFLOW

The compressibility of the fluid as a basic property of the flowing gas had already been confirmed in the field of fluid dynamics [4]. This property may indirectly influence the discharge in flowing gas because of the relationship between the airflow velocity and the electron free path.

In the present work, airflow can be regarded as a one-dimensional steady and isentropic flow. Therefore, the airflow density ρ is given by:

$$\rho=\rho_0\left[1+\frac{\gamma_a-1}{2}\left(\frac{v}{s}\right)^2\right]^{-\frac{1}{\gamma_a-1}} \tag{2}$$

We know from Equation (2) that airflow density decreases with increasing airflow velocity. When the airflow velocity v is 120 m/s (the maximum airflow velocity in the experiment), the airflow density ρ decreases by 7%.

The relationship between the airflow velocity and the mean electron free path is obtained by considering the compressibility of the fluid and utilizing the relationship between the molecular number density and the airflow density (described by Equation (23) in Part I), as shown in Figure 10. Figure 10 shows that the mean electron free path increases with increasing airflow velocity. Therefore, we conclude that the compressibility of the fluid affects the discharge of the flowing air by influencing the mean electron free path.

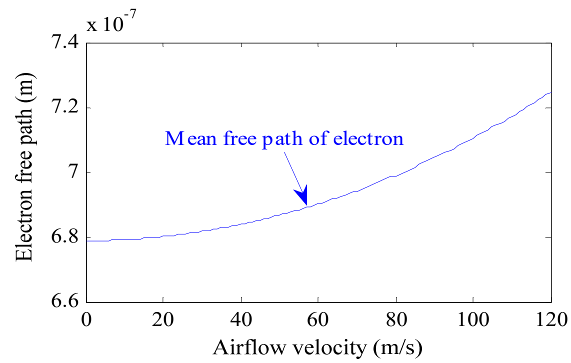


Figure 10. Airflow velocity-mean free path of electron curve.

3.4 *Q*(d*x*)∝(*v/E*)*n*d*x*

In Part I, we assumed that $Q(\mathrm{d}x) \propto (v/E)n\mathrm{d}x$, where $Q(\mathrm{d}s)$ denotes the probability that an electron is blown away by the gas flow in ds when the electron at s crosses through ds along the electric field direction. We attempt to explain the appropriateness of this assumption in the following section.

(1) When an electron moves from A to B along the field direction in flowing air (as shown in Figure 4 of Part I), the electron is always in the same condition regardless of position because the electron encounters the same electric field force and collision force from the airflow wherever it is. Therefore, the probability that the electron is blown away by the airflow in unit distance in the field direction is the same. That is, it is irrelevant to the position of the electron. Thus, the probability is reasonably assumed to be proportional to the distance of electron motion in the field direction, i.e., $Q(\mathrm{d}x) \propto \mathrm{d}x$. In addition, we know that the reason an electron is blown away by the airflow is the frequent collisions between molecules and electrons. Thus, we propose that the probability is proportional to the collision frequency f. From the theory of gas discharge [5], the collision frequency $f \propto$ molecule number density n. Thus, we deduce that the probability is proportional to the molecule number density n and, thus, that $Q(\mathrm{d}x) \propto n\mathrm{d}x$.

(2) The probability p that the electron is blown away by the airflow can be calculated as n_b/n_t, where n_b denotes the number of electrons blown away by the airflow and n_t denotes the total number of electrons. We then have $p = n_b/n_t = f_p(v)$.

As shown in Figure 11, the number of charged particles collected by the metal net (i.e., the charged particles blown away by the airflow) exhibits an approximately linear relationship to airflow velocity v. Thus, we estimated that $n_b = f_b(v) = kv$ and, thus, that $p = f_p(v) = kv/n_t$, i.e., p is proportional to airflow velocity v. Therefore, we can estimate that $Q(dx)/dx \propto v$.

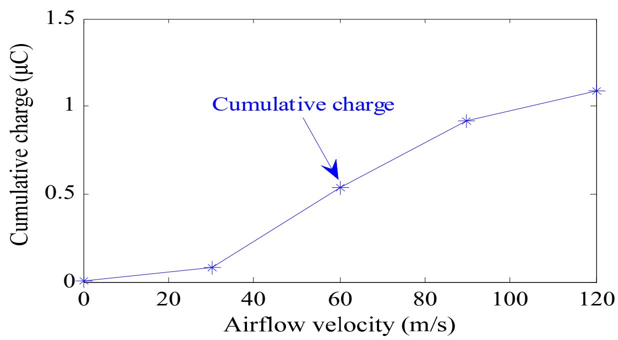


Figure 11. Cumulative charges – airflow velocity curve.

(3) Accurately estimating the effect of the applied electric field on the probability that the electron is blown away by the airflow is difficult. We know that an electron is more difficult to be blown away by the airflow under higher electric field strength because of the huge electric field force in the vertical direction. In addition, we know that the electrons are dragged by the airflow because of a horizontal average force F_d ($F_d \propto v$) imposed by the collision between molecules and electrons. Analogously, the electrons are drifted by the electric field force F_e ($F_e \propto E$) along the electric field direction, which, compared with the horizontal force, inhibits the probability. Thus, we propose that the two behaviors are similar, i.e., the horizontal force is positive ($F_d \propto v \propto Q(dx)/dx$) and that the electric field force is negative to the probability. Therefore, we can experientially estimate that $Q(dx)/dx \propto 1/E$.

(4) We find, based on the aforementioned discussions, that $Q(dx)/dx \propto (v/E)n$, where $Q(dx)/dx$ denotes the change in probability in unit distance, which is also called the change velocity of probability. When v tends to zero, the change velocity tends to zero; when v tends to infinity, the change velocity tends to infinity. Similarly, for the electric field E, we can obtain the same conclusion. These results are consistent with experiential laws. Thus, we can estimate experientially that $Q(dx) \propto (v/E)n\, dx$.

Although we have attempted to establish some evidence to support $Q(dx) \propto (v/E)n dx$ as soon as possible, it is not enough. In practice, $Q(dx)/dx = f(v, E, n)$. More evidence should be collected and verified by obtaining the exact distribution of the electron number density in the discharge of flowing gases.

4 DISCUSSION

Figures 3 and 4 show the typical light of corona and spark discharge at the needle-plate air gap under different airflow velocities. We find the discharge characteristics in flowing air are obviously different from those in static air. The breakdown path exhibits an obvious, steady deflection angle along the direction of the airflow. In this case, the projection distance of the mean electron free path along the direction of the applied electric field decreases because of the deflection of breakdown path. Therefore, for the discharge of flowing air, the electrons receive less energy from the applied electric field in a mean electron free path compared with that in static air because of the decrease in projection distance of the mean electron free path in the field direction, which results in a lower electron collision ionization probability.

In the discharge process of the flowing air, the neutral molecules from the airflow collide frequently with electrons and ions in the airflow direction. The electronic and ionic energy required from applied electric field rapidly transfers and decreases because of the inelastic or elastic collision, and the velocity direction is also varied instantaneously. As a result, some of the electrons and ions could deviate from the major discharge path or be completely blown away by the airflow due to frequent neutral molecular collisions in the airflow direction. Thus, the effective electron number involved in collision ionization decreases due to some of the electrons are blown away, which results in fewer final electrons created by collision ionization.

The mean electron free path increases with increasing airflow velocity (Figure 10). Therefore, the electron collision ionization probability will increase because an electron will acquire more energy from the applied electric field in an increasing mean electron free path. Meanwhile, the number of electron collision per unit distance in the field direction decreases because of increasing mean free path. Therefore, the Townsend's first ionization coefficient first decreases and then increases with increasing airflow velocity under the two competitive effects (the electron collision ionization probability and electron collision number per unit distance), which can also be explained using Paschen's law [5].

Based on the experimental results and aforementioned aspects, the discharge of the flowing gases presents three basic performances. The first one is the deflection of the major discharge path and the breakdown path (precondition 1 in Part I). The second one is that some of the electrons and ions are blown away by the airflow (precondition 2 in Part I). The third one is the decrease in air density or the increase in mean electron free path (precondition 3 in Part I). In the experimental airflow velocity range, both the first and the second performances increase breakdown voltage and the third decreases it with increasing airflow velocity. Their combined effects determine the final variation trend in the breakdown voltage with airflow velocity.

The experimental results in section 3 show that, for the needle-plate electrode, the breakdown voltage value (24.3 kV) in the case with an airflow velocity of 82 m/s is greater than that (20.4 kV) in the case without airflow, which indicates that the breakdown voltage value of the needle-plate air gap substantially differs under conditions with and without airflow. Based on it, we carry out the breakdown experiments. The experimental results of the breakdown voltage of the needle-plat and the plat-plat air gap under different airflow velocities with a gap distance of 10 mm are shown in Figure 12.

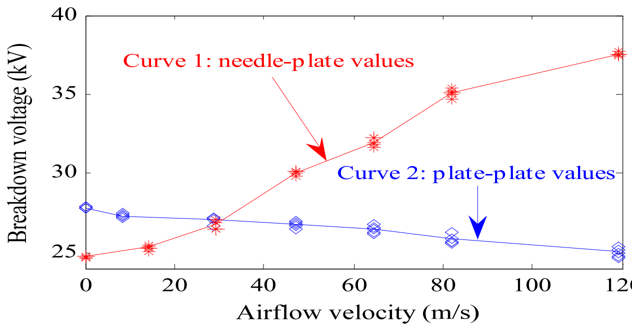


Figure 12. Breakdown voltage values of needle-plate and plate-plate air gap under different airflow velocities (results of experimental test).

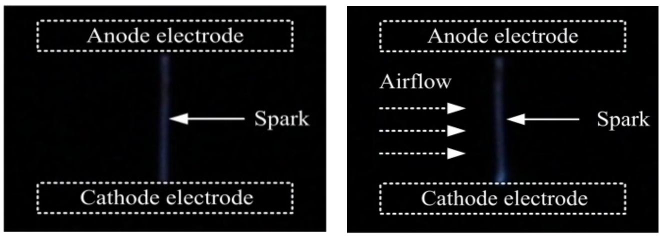
The change rate of breakdown voltage is defined as $R = (U-U_0)/U_0$, where U_0 is the breakdown voltage value at v=0 m/s. The change rate of breakdown voltage is shown in Table 1.

Table 1. The change rate of breakdown voltage in flowing air.

Airflow velocities (m/s)	Needle-plat values (kV)	Rate (%)	Plate-plate Values (kV)	Rate (%)
0	24.74	0%	27.84	0%
9	25.32	2.34%	27.34	-1.80%
30	26.78	8.25%	27.08	-2.73%
48	30.02	21.34%	26.78	-3.81%
65	31.98	29.26%	26.48	-4.89%
82	35.08	41.79%	25.84	-7.18%
120	37.52	51.66%	25.02	-10.13%

Figure 12 and Table 1 show that the breakdown voltage of the needle-plate air gap gradually increases with increasing airflow velocity. The breakdown voltage is 24.74 kV at v = 0 m/s and reaches 37.52 kV at v = 120 m/s, which is an increase of 51.66% compared with the voltage at v = 0 m/s. These results indicate that, for the discharge of the needle-plate gap in flowing air, the effects of the deflection of discharge path and the blowing away of some of electrons on the breakdown voltage are substantial and much stronger than the effect of the decrease of air density. However, for the plate-plate electrode, the breakdown voltage continues to decrease with increasing airflow velocity, which is obviously different behavior than that exhibited by the needle-plate electrode (Figure 12). That is, for the discharge of the plate-plate gap in flowing air, the effects of the deflection of discharge path and the blowing away of some of electrons on the breakdown voltage are weaker than the effect of the decrease of air density. The difference in the verification trend in the breakdown voltage with airflow velocity between the needle-plate gap and the plate-plate gap is caused mainly due to the difference in the breakdown processes between them. According to the theory of gas discharge, for the discharge of a needle-plate gap that is a typical non-uniform field, the corona discharge begins before breakdown occurs. Therefore, the transition of the discharge of the needle-plate gap from the corona to the breakdown in flowing air is a continuous process. That is, because of the non-uniform electric field, many electrons and ions created by the corona discharge have existed in the space of the needle-plate electrode before the breakdown occurs, which is very important to affect the final breakdown voltage values and the breakdown path. Meanwhile we also get a hint that these electrons and ions (have existed in the electrode space) suffer the obvious and continuous effects from the airflow because of the frequent neutral molecular collisions in the airflow direction before the breakdown occurs, which results in the strengthening of the effects of the deflection of discharge path and the blowing away of some of electrons on the breakdown voltage. In addition, the drift velocity of electrons and ions in most areas is relatively slow, especially in the middle of the needle-plate electrode due to the weak field. In this case, the electrons and ions are more easily deflected or blown away by the airflow because of the slow drift velocity. The deflection effect and the blowing away effect are more significant in this case. Thus, the breakdown voltage of the needle-plate gap increases because of the obvious effects of the deflection of the discharge path and the blowing away of some of electrons, which are consistent with the experimental results shown in Figures 4, 8 and 12. Based on the experimental results and the above discussions, we conclude that, for the discharge of the needle-plate gap in flowing air, the discharge process is strongly influenced by the effects of the deflection of discharge path and the blowing away of some of electrons. As a result, the airflow could cause a very large increase in the breakdown voltage value in the non-uniform electric field.

However, for the breakdown of the plate-plate gap in flowing air, because of the uniform applied electric field, few electrons are created in the electrode space before breakdown occurs. That is, some electrons exist in the electrode space only when the breakdown occurs. Therefore, for the breakdown of the plate-plate gap in flowing air, the deflection effect and the blowing away effect only influence the discharge process at the moment of breakdown. That is, the effects of the deflection of discharge path and the blowing away of some of electrons on the breakdown voltage are only effective in the transitory breakdown process. According to the theory of gas discharge, when the breakdown of the plate-plate gap occurs, the electrons encounter a huge electric field force and obtain an ultrafast drift velocity imposed by the applied electric field force, but their horizontal velocity transmitted by the airflow because of frequent neutral molecular collisions is relatively small compared with their drift velocity. Therefore, we infer that for the breakdown of the plate-plate gap in flowing air, the deflection effect and the blowing away effect are weak and that their influences on the breakdown voltage are also very limited. The reason for this is two fold; first, the drift velocity of electrons is much greater than their horizontal velocity, which weakens the deflection effect, especially when the airflow velocity is low. Second, few electrons exist in the space of the plate-plate electrode before breakdown occurs and the breakdown process is transitory, which weakens the blowing away effect, especially when the gap distance is short (e.g., the experimental distance is only 10 mm). The aforementioned inference can be verified by the following experiment. Figures 13a and 13b shows the breakdown paths of the plate-plate air gap without and with airflow, respectively. Under the two different conditions, the breakdown paths are approximately the same. Both are almost perpendicular to the plate-plate electrode, which is completely different from that exhibited in the needle-plate gap as shown in Figure 4. These results indicate that, for the breakdown of the plate-plate gap in flowing air, the effects of the deflection of discharge path and the blowing away of some of electrons on the breakdown voltage are very weak in the uniform electric field.



(a) Without airflow (b) With an airflow of 82 m/s

Figure 13. Spark images of plate-plate gap under different conditions.

Based on the aforementioned discussions, we conclude that the breakdown process of the needle-plate gap in flowing air significantly suffers the deflection effect and the blowing away effect from the airflow. However, the breakdown of the plate-plate gap is mainly influenced by the airflow density.

Notably, for the Townsend's discharge theory, the effect of the positive space charges on the breakdown process is relatively small and can be neglected. However, for the streamer discharge theory, the positive space charges are very important to the formation and propagation of the streamer. Therefore, for the discharge of flowing gases, it is needed to further study the influence of the positive space charges on the discharge, especially in a non-uniform electric field, where both the deflection effect and the blowing away effect are much greater than in a uniform electric field.

5 CONCLUSION

In this work, the three basic preconditions have been experimentally verified and systematically analyzed, and the physical essences of the effects of flowing air on discharge and the differences in flowing air discharge between the uniform and non-uniform electric fields have also been revealed. The following conclusions can be drawn.

(1) In the discharge of the flowing air, the breakdown path of the air gap deflects at an angle along the direction of the airflow; some of electrons and ions are blown away by the airflow, and the mean electron free path increases with increasing airflow velocity. These three laws are the basic characteristics of flowing air discharge, and the first two characteristics are more obvious in non-uniform field.

(2) The deflection of the breakdown path results in that electrons obtain less energy from the applied electric field within a mean electron free path. The number of electrons involved in collisions decreases because some of electrons are blown away by the airflow, which decreases the final electron number involved in discharge created by collision ionization. The decrease in air density due to the flowing air causes competition between the increase in the electron free path and the decrease in the electron collision number. These three aspects, as the basic mechanisms, influence synthetically the discharge of the flowing gases.

(3) The discharge of flowing air in the non-uniform electric field is greatly influenced by the deflection effect and the blowing away effect because of the continuous discharge process, which causes a large increase in breakdown voltage value (an increase of 51.66% at v = 120 m/s compared with that at v = 0 m/s). For the uniform electric field, the discharge of flowing air is mainly influenced by the increase in mean electron free path (the effects of the deflection of discharge path and blowing away of some of electrons on the breakdown voltage are weak because of the transitory breakdown process). The breakdown voltage continues to increase in the non-uniform field and decrease in the uniform field with increasing airflow velocity.

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