Comparison of point-to-plane corona in different gases

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Abstract. The point-to-plane DC corona discharges at atmosphere pressure have been investigated experimentally in different gases including argon, helium, N₂, O₂ and air in a needle-to-plate configuration. The breakdown voltage (the onset voltage of corona and the inception voltage to spark), current-voltage characteristics and the corona images have been measured in the gases under positive and negative polarity. Generally, the breakdown voltage of the positive corona is higher than the negative in the gases except O₂ in which the results is reversed. The current of the negative corona discharge is much higher than the positive in all gases. There exists a stable negative corona glow in the gases except air or O₂ before the spark occurs, while the pulsed positive corona will transit into the spark directly when the voltage increases, without the stable glow stage.

1. Introduction
Corona discharge is a partial discharge where the geometry confines the gas ionizing processes to high-field ionization region around the active electrode [1]. The field near the discharge electrode is much stronger than the rest of the gap. This situation typically arises when the characteristic size of the electrode radius is much smaller than the inter-electrode distance [1, 2]. Corona discharge is also one of the common low-temperature, non-equilibrium plasmas. Because it is easy to generate, stable at atmospheric pressure, and operate at low currents (on the order of several micro-amperes) and power consumption [3], and also rich in the active radicals, excited and ionized species, corona discharge has been widely used for many traditional applications such as spray coating copy machines, drying separation systems and radiation detectors, surface treatment, electrostatic precipitators [4-6], as well as in some new fields such as probe of microwave (MW) plasma jet, treatment of skins diseases and airflow control [6-8], etc.

The electrode configuration has great influence on the characteristics of the corona discharge. The typical configurations include point-to-plane or point-to-point, wire-to-wire, wire-to-plane or wire-to-cylinder, etc. Among them, the point-to-plane (or needle-to-plate) is the most typical and popular configuration. The corona discharge with the point-to-plane configuration has been investigated widely in air under various conditions. In this paper we investigate the DC corona discharges in different gases at atmospheric pressure. The aim is to make a comparison of characteristics of the point-to-plane corona in air and other gases.
2. Experimental set-up
The experimental setup of the discharge system is shown in figure 1.

![Figure 1. Schematic of experimental setup.](image)

The discharge electrode is made of stainless steel with a diameter about 0.05 mm in tip. A copper plane is used as the grounded electrode through a resistor $R_S$ (1 MΩ) which is also the current sampling one. The gap distance between the needle and plane is 5 mm. A high voltage (HV) DC power supply was used as the power source and connected to the needle through a protection resistor $R_0$ (2 kΩ). The output of the power source may be positive or negative. The applied voltage was measured by using a digital oscilloscope (Tektronix TDS3054B, 500 MHz) with a voltage probe P6015A. The discharge current was measured by a micro-Ampere-meter. It was also monitored by the voltage drop $V_R$ across sampling resistor $R_S$ which was measured with the same oscilloscope. A digital camera (Canon EOS 550D) was used to record the corona images.

3. Results and discussion
There are two breakdown voltages for the corona discharge, i.e., the onset voltage of the corona, named as $V_C$ in this paper and the inception voltage of spark, named as $V_{spark}$ in this paper. We tested the corona discharge under different gases at atmospheric pressure and different voltage polarity.

3.1. The breakdown voltage in different gases
Table 1 gives out the measured onset voltage $V_C$, the inception voltage of spark $V_{spark}$ and the corresponding transition current $I_{spark}$.

|          | Ar   | He   | Air  | N₂   | O₂   |
|----------|------|------|------|------|------|
| $V_C$ (kV) | 1.91 | 1.23 | 2.37 | 1.02 | 3.10 |
| $V_{spark}$ (kV) | 3.24 | 2.15 | 5.07 | 2.24 | 5.42 |
| $I_{spark}$ (μA) | 6.00 | 32.0 | 50.0 | 101.0 | 20.0 |

Generally, the onset voltage is much higher for the positive corona than the negative in all the investigated gases. For instance, the onset of positive corona is 1.91 and 3.10 kV in Ar and air, larger than that of negative corona (1.23 kV and 2.05 kV, respectively). This is also true for the breakdown voltage to spark except in O₂ in which the result is reversed. This unexpected result might relate to the existence of the electronegative oxygen molecules. The attachment of electrons on O₂ might cause a
decrease of the avalanche under negative polarity and cause increase in breakdown voltage. This is also evidenced by the result in air that the breakdown voltage under negative polarity is close to the positive. The corresponding transition current to spark is also different for the positive or negative corona. The transition current of the negative corona is much larger than the positive in all the investigated gases.

3.2. Current-voltage characteristics
The current-voltage ($I$-$V$) characteristics were measured in all the tested gases under applied voltage between the corona onset $V_C$ and the spark breakdown $V_{spark}$.

![Figure 2. I-V curves of negative corona in various gases.](image)

![Figure 3. I-V curves of positive corona in various gases.](image)

It is seen that the $I$-$V$ is similar to the previous results [10, 11]. The corona current increases with the applied voltage in case of negative (see figure 2) or positive polarity (see figure 3). The $I$-$V$ dependence of negative corona in all gases is nearly according with the Townsend’s relation [2] for a stable corona, or $I = kV (V - V_C)$ where $k$ is constant that depends on the geometric parameters. The plot of $I/V$ as a function of $V$ is almost a linear. For the positive corona, the $I/V$ curve is nearly linear in large range of current but not true in the whole measured range.

The discharge current of negative corona is much larger than the positive, showing a significant polarity effect. For example, the current under negative polarity can reach as large as 100 A before spark in gases except Ar, while the current under positive polarity is generally less than 30 A except in He. This strong polarity effect would come from the asymmetry of the electrode geometry.

As expected, the voltage should be higher in N$_2$, air and O$_2$ to create the same discharge current voltage as the noble gases. But the operation voltage in N$_2$ is lower under negative polarity, close to that of the noble gases (see figure 2). This might relate to the electronegativity of oxygen, which has large electron-attachment cross section to make large probabilities of loss of electrons [1, 2].

Moreover, the current pulse (if occurs) is generally random under positive polarity. But the negative corona shows a regular repeat of the current pulse in air and O$_2$, known as Trichel pulse [1, 2]. The electronegative oxygen molecules are suggested to play an indispensable role for the Trichel pulse [1, 2]. But the Trichel pulses could also be observed in nitrogen as well as the noble gases in our experiments. This would be confirmed in the future.

3.3. Images of corona
The images of corona discharge in different gases at various voltages are shown in figures 4-8, where frames (a-c) are the negative corona, while frames (d-f) are the positive. All the images were recorded from side-view, with exposure time of 0.8 s. The electrodes are also shown in the figures.
It is seen that the negative corona occurs firstly around the tip of needle at lower voltage. As the voltage increases, the corona area increases, until a stable glow forms between the electrodes before the spark bridges the gap. Only in O₂, the glow discharge has not been observed in experiments. This would also relate to the role of electronegative oxygen. The stable glow has 3 characterized regions of DC normal glow, i.e., the light negative glow near cathode, the Faraday dark space and the followed positive column, as shown in figures 4-7. The glow discharge may diffuse outside toward the anode, forming a bell-shaped plasma region.

Figure 4. Images of (a-c) negative corona and (d-f) positive corona in Ar.

Figure 5. Images of (a-c) negative corona and (d-f) positive corona in He.

Figure 6. Images of (a-c) negative corona and (d-f) positive corona in N₂.

Figure 7. Images of (a-c) negative corona and (d-f) positive corona in air.

Figure 8. Images of (a-c) negative corona and (d-f) positive corona in O₂.

Under positive polarity, the corona generally occurs in small region around the tip of the needle. The bright area is 0.5-1 mm in diameter, and it is very similar in all the gases. In this case, the positive corona is generally pulsed, and will directly transit into the spark as the voltage increasing without stable glow. However, a positive corona glow may also be seen in air or O₂ sometimes, but the current is smaller than the negative.
4. Conclusion
We have investigated the DC corona discharge with different gases at atmospheric pressure in a needle-to-plane configuration. The results show a significant polarity-effect. In all gases the onset voltage of positive corona is much higher than the negative corona. The breakdown voltage of positive corona to spark is also higher than the negative except in O₂ that the result is inversed. The current of the negative corona is much larger than the positive in all gases. The current-voltage dependence of negative or positive corona shows the Townsend’s relation. The negative corona has a large luminous area than the positive in all gases and shows a stable bell-shaped glow before spark, except in case of O₂ in which the negative corona exists near the tip of the cathode. The positive corona in all gases occurs only in a small region around the anode needle. The electronegative oxygen is suggested to play an important role in the characteristics of negative corona discharge.

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