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On the negative corona and ionic wind over water electrode surface

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ABSTRACT

The DC corona discharge in air and the induced ionic wind were investigated in the needle-to-water system at atmospheric pressure. The water deformation was measured under various conditions, and wind pressure and active areas were estimated accordingly. The effects of applied voltage, gap spacing and tip radius on the corona ionic wind were studied and the qualitative analysis was provided. Self-rotation of corona discharge was observed in experiments. The results show that higher voltage or electric field strength results in a stronger ionic wind. The active area increases with applied voltage below a voltage threshold. There is an optimal gap distance for a wider as well as stronger ionic wind and blunter needle we used leads to an enhancement on both the active area and the wind strength. The wind velocity reaches 7 m/s at optimized condition in the present system. The rotation of corona discharge helps to improve the active area and uniformity of the treating area which may be associated with the chemical reaction of the water surface.

1. Introduction

Corona discharges between sharp and blunt electrodes are one of the more common low-temperature, non-equilibrium plasmas because they are easy to generate, stable at atmospheric pressure, and operate at low currents ($\sim\mu$A) and low power consumption. For this reason they have been widely adopted for applications such as electrostatic precipitators [1], ion sources for mass spectrometers [2], waste water treatment [3], and as ionic wind blowers [4]. In the corona region, fast electrons ionize the neutral particles while slow electrons attach to the neutral particles forming the negative ions. These negative particles are also accelerated by the electric field and transfer momentum received from the field to the neutral particles thus creating the ionic wind. The ionic wind of corona has interesting potential on thermal cooling [4,5] benefited from non-moving components and micro scales, and recently the flow control [6,7] for purpose of reducing air drag, increasing lift, avoiding turbulence and rising fly accuracy. The researches on ionic wind have been reported in varieties of discharge conditions. For example, Colas et al. [8] used the wire-to-plate corona configuration and provided the ionic wind with maximal velocity about 8 m/s. After that, they realized the enhancement of the velocity to 10 m/s by adopting a pair of cylindrical ground electrodes but not by the adjustments of discharge conditions. Farnoosh et al. [9] developed three-dimensional numerical model and evaluated the electrical and electrohydrodynamics (EHD) characteristics of a single spiked wire-plate electrostatic precipitator. Bychkov et al. [10,11] made a series of researches on corona discharge over liquids. These works mainly focused on the appearance of the EHD impact, whereas the correlations between the impact and discharge conditions were only discussed in brief. Kawamoto et al. [12,13] reported the EHD deformation on water surface by ionic wind and the gap spacing was generally larger than 5 mm. The corona wind in small gas gap, however, was not investigated although it may be more preferable in practice to avoid high onset voltage and large energy consumption.

For many applications, the active area and strength of ionic wind are the two most important characters. The active area of the ionic wind indicates the region that can be treated by the flow and hence affects the efficiency of its applications. The wind strength represents the ability to control the air flow around the discharge part and determines the performance of ionic wind techniques. A stronger and wider ionic wind is more important for thermal cooling in integrated circuit. Several electronic devices can be covered by one corona at the same time which can significantly improve the treatment effect and the performance of the ionic wind techniques.

In this paper, we investigate the negative needle-to-water corona discharge at atmospheric pressure. In this configuration, a deformation can produce on water surface by the ionic wind of corona discharge. The wind pressure and velocity are estimated by measuring the radius and depth of the deformation. The effects of the operation parameters including applied voltage, gap spacing

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and tip radius on ionic wind were investigated. And a self-rotation of corona discharge was described.

2. Experimental details

2.1. Experimental set-up

The experimental set-up is schematically shown in Fig. 1. The needle with tip radius $\sigma = 50$ or 100 μm is above the glass vessel and perpendicular to the water surface. The gap spacing d between needle tip and water surface (noted in Fig. 1) ranges from 2 to 5 mm. A negative DC power supply is applied to the needle through a ballast resistance $R_b = 2$ kΩ while the water is grounded through a copper electrode with radius of 5 cm.

The applied voltage U is recorded by a digital oscilloscope (Tektronix TDS-3054B, 500 MHz-bandwidth and 5 G/s sampling rate) through a HV probe (Tektronix P6015A), while the discharge current I is measured by the Amperemeter (precision of 1 μA). A digital camera (Canon EOS 550D) is used to record the shape of water surface from horizontal position and 30° to the horizon.

2.2. Determination of wind pressure

The deformation of water surface was recorded by camera and samples are presented in Fig. 2. Fig. 2(a) was recorded at horizontal position with exposure time 1/6 s while (b) was recorded at inclined position and the asymmetry reveals the rotation. It is clear that the ionic wind impact makes a deformation (a “hollow”) on water surface. The active radius R (the radius of deformation) and the depth h of deformation (noted in Fig. 2(a)) depended on the applied voltage U, the gap spacing d and the tip radius of needle σ. R and h were measured at each position of the deformation to determine the active area and pressure of the ionic wind. The shape of the deformation shows a depression in the center but much flat nearby. Similar shape can be observed under different distances and applied voltages.

For calculation of the central pressure, the radius of infinitesimal surface r at each position is required. To determine r, the local shape is suggested to be spherical and fitting curves are obtained at various conditions as $h = h(X)$, where X is the distance from the deformation center. Fig. 2(c) shows the fitting curves for different voltage at gas gap $d = 2$ mm.

At any point of the deformation, the surface is assumed as sphere and has the balance of pressure represented by the following hydrodynamic formula [14]:

$$P = P_0 + \rho g|h| + \frac{2\alpha}{r} \tag{1}$$

where P represents the pressure above the water depression, P_0 is the atmospheric pressure, ρgh is the pressure induced by water level and the last part $2\alpha/r$ is caused by the water surface tension. The pressure difference between P and P_0 namely the wind pressure P_{wind}, which is determined as:

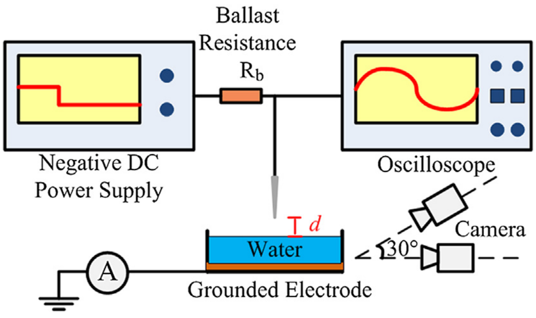

Fig. 1. Schematic of experimental setup.

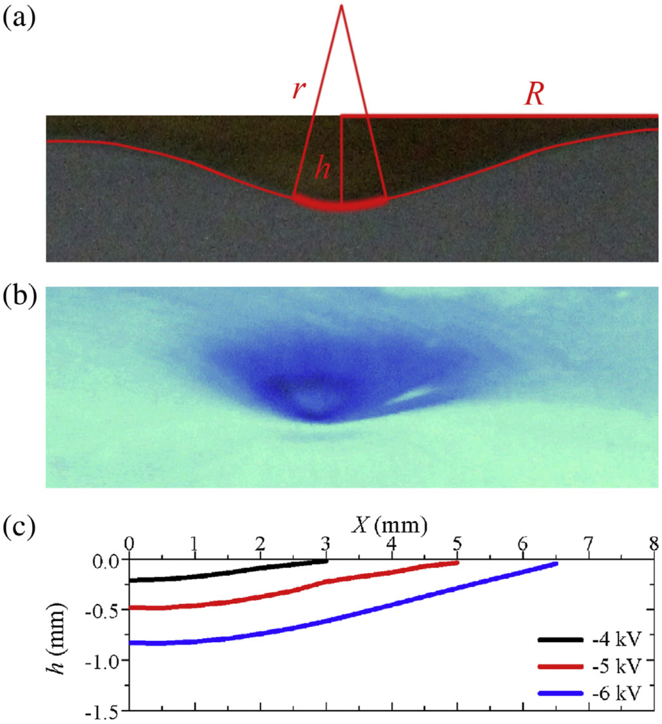

Fig. 2. Images of the water deformation for $d = 2$ mm, $U = -5$ kV, (a) recorded at horizontal position, (b) recorded at 30° inclined view, and (c) the fitting curves at different voltages.

$$P_{\text{wind}} = P - P_0 = \rho g|h| + \frac{2\alpha}{r} \tag{2}$$

where the mass density of water is $\rho = 1 \times 10^3$ kg/m^3 and the tension coefficient of water is $\alpha = 7.2 \times 10^{-2}$ N/m.

3. Results

3.1. Current–voltage characteristics

The current–voltage characteristics are presented in Fig. 3 for negative DC corona discharge with water anode. The needle cathode has tip radius of $\sigma = 50$ μm. The curves are obtained by increasing the voltage and changing the gap spacing from 2 to 5 mm.

It is seen that the corona occurs at onset voltage U_c, which are −3.2, −3.5, −3.7 and −4.3 kV for gap spacing from 2 to 5 mm, respectively. Then, the discharge current increase with the applied voltage until the spark appears. The breakdown voltage for spark is $U_{br} = -6.2$, −8.2 and −9.7 kV for $d = 2$, 3 and 4 mm, respectively. The plot of I is almost a quadratic function of U and accords well with the classical Townsend's relation, or $I = kU(U - U_c)$ [15], where k is a constant determined by the discharge conditions. The current–voltage characteristics demonstrate that the discharge in this configuration is a typical corona in atmosphere.

3.2. The distribution of wind pressure

The values of r and h are determined according to the method in Section 2.2 and the distribution of wind pressure is calculated by Equation (2). Fig. 4 shows an example for $d = 2$ mm and tip radius