The effect of DC voltage polarity on ionic wind in ambient air for cooling purposes

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Abstract

Gas flows can be induced by gas discharges like DC coronas because neutral molecules gain momentum by ion-neutral collisions. This can be used for active cooling and has advantages over mechanical fans. We investigate ionic wind by a DC corona discharge under different conditions with an emphasis on the effects of voltage polarity and the transition between different discharge regimes. We also consider the gas temperature of a DC corona which is important when it is to be used for cooling purposes. Although DC coronas are usually characterized as low temperature plasmas, gas heating can have a significant impact on flow generation, especially at higher operating voltages. In this paper, a 5-20 kV DC voltage of positive and negative polarity is applied to a needle-cylinder electrode. The ionic wind velocity at the exit of the cylinder electrode is measured by hot wire anemometry and the emission spectrum is used to study the gas temperature. It is found that the flow velocity induced by positive coronas is higher than that by negative coronas for voltages above 10-15 kV, which is also demonstrated by a phenomenological EHD force model. Furthermore, a heated column is observed by Schlieren technique for both voltage polarities. An improved self-consistent ionic wind model considering heat transfer is built to study the temperature distribution. The simulation results indicate that the gas flow velocity is lower on the symmetry axis when the temperature gradient is taken into account, something which is usually ignored in ionic wind simulations.

Keywords: corona, streamer, ionic wind, DC voltage, heat transfer

1. Introduction

It is known for many years that cold atmospheric discharges like coronas and dielectric barrier discharges (DBD) can induce gas flows. The earliest reports on this phenomena date back to 1709 [1]. In corona discharges this effect is generally called corona wind but more generalized it is known as ionic wind or electric wind. It occurs when charged particles are accelerated in an electric field while constantly transferring their gained momentum
to the neutral molecules (or atoms). The momentum transferred from charged particles to neutral molecules generates an electrohydrodynamic (EHD) force. Boeuf and Pitchford [2] established a simple analytical expression of the EHD force. In a non-neutral region, the force is a result of the charged particle density gradients and the electric field terms. There are two non-neutral regions in a bulk-gas discharge: the ionization region and the ion drift region, which usually dominates the force generation.

A promising application of ionic wind is the cooling of electronic devices like LED-lighting systems [3–5]. Even very efficient light sources still produce a significant amount of heat while the junction temperature should remain below a certain value (around 120°C). In all cases, passive cooling of the components by natural convection of ambient air is preferable above any other method because it does not consume any power and has an almost unlimited lifetime. However, for higher powers and small packages complete passive cooling becomes impossible. Presently this is mostly solved by using active cooling through mechanical fans. However, this has a few disadvantages, most notably the generation of noise and vibration and limitations on lifetime. Ionic wind cooling devices do not need any mechanical moving parts, which makes them easy to be miniaturized and can greatly reduce noise. Meanwhile, the reported efficiency of this method is still on the low side. This is partly caused by different definitions of efficiency as was recently shown by June et al. [6], but improvements in efficiency are still required. The ionic wind may also be potentially applied in portable electronic devices. For example, Apple describes a system in which the direction of ionized air moving through a computing device is deflected by either an electric or a magnetic field [7].

Many researchers have conducted experiments of characterizing ionic wind under different conditions [8,9]. The polarity of the applied voltage is an important parameter which influences the discharge and flow characteristics. Kim et al. [10] designed an ionic wind generator consisting of a wire and a semi-cylindrical contour-shaped electrode. The experimental results show that negative DC coronas produce higher flow velocities than positive DC coronas when the voltage amplitudes are the same. However, no further comparison of velocities was made for the same value of the current or input power. The current density determines the EHD force and the average current is found to be nearly proportional to the square of the maximum velocity [11]. Moreau and Touchard [12] measured the distribution of flow velocities 2 mm downstream from the outlet in a needle-mesh electrode geometry. The velocity profiles of positive and negative corona are similar at the same average current of 12 µA, except at the center of the exit, where a higher velocity is found for positive coronas. The flow rate and efficiency of negative coronas are slightly smaller than those of positive coronas. The ionic wind profiles for both polarities in a needle-ring electrode are compared in [13]. The flow velocity is larger when it is generated by a positive corona instead of a negative corona at the same voltage, while in the latter case the flow is distributed more homogeneously. It should also be noted that the maximum withstand voltage of the gap is usually higher under negative polarity than positive polarity. So the maximum attainable flow velocity might be higher for negative coronas at a given electrode geometry [14].

There is only limited discussion about the mechanism of how voltage polarity influences the flow generation by DC corona. One of the major differences between negative and positive DC corona is the
discharge mode. The positive corona is characterized by its branching behavior while a luminous glow around the sharp electrode is observed for negative corona. Apart from the contribution of the ion drift region to flow generation, some researchers argue that propagating streamers can also induce gas flow. This is due to the high electric field and space charge density in the thin curved sheath of the streamer head which can generate a large EHD force. The “over-velocity” of gas flow in [12] is possibly explained by the presence of streamers.

A concern about cooling with ionic wind is the gas temperature of the plasma itself, which is seldom mentioned in previous studies. Although a corona discharge is known as a low temperature plasma, the gas temperature near a sharp high voltage electrode can still reach several hundreds of Kelvin [15], and even above 1000 K under pulsed positive voltages[16]. Staack et al. [17] measured the gas temperature in atmospheric pressure dc glow discharges by emission spectroscopy using the second positive system (SPS) of N2. The time-averaged gas temperatures in the entire discharge region are 700 K and 1550 K for a 0.4 mA and 10 mA discharge, respectively. The gas heating is partly due to the transfer of energy gained by ions from the electric field. In addition, the electron energy deposited into exited states of gas molecules is also thought to heat the gas [18,19]. Local high temperatures should be avoided in cooling applications and the temperature should not be much greater than the ambient temperature. Hence it is worth comparing the gas temperatures by positive and negative DC coronas.

On the other side, the influence of gas heating on flow generation by a DC corona discharge is seldom discussed. Spyrou et al. [20] measured the temperature distribution by using emission spectroscopy in a secondary streamer discharge in a point-plane gap. A high gas temperature of 800 K was measured in the vicinity of the point, and the temperature decreases to about 450 K for greater distances. So, the investigation of gas temperature also will help to better explain the gas flow generation by a corona discharge.

The aim of the present work is to investigate effect of the DC voltage polarity on ionic wind generation for cooling purposes. We firstly present experimental results of current and gas flow velocity under positive and negative DC voltages. The gas temperature is determined from the spectrum emitted by the discharge by means of the SPS of N2. Then a numerical model coupling continuity equations of charged particles and Navier-Stokes equations is employed to simulate the ionic wind including the heat transfer in the discharge. Insight in the influence of gas temperature on flow generation is thus obtained. Finally, the effect of the streamer discharge mode on the flow velocity is discussed with a phenomenological model.

2. Experimental set-up and method

In our experiment, the ionic wind is induced in a needle-cylinder electrode configuration. The corona discharge is produced on a sharp needle electrode with a length of 15 mm and a diameter of 1.8 mm. The tip radius is about 190 μm and tip angle is 30 degrees. The collector electrode is a cylinder with an inner diameter of 34 mm and a height of 30 mm. The distance between the needle and the cylinder is 20 mm. The whole experimental set-up is schematically presented in Figure 1(a). The discharge current to the ground is measured by using a 50 Ω shunt resistor connecting the cylinder and the ground. A hot wire anemometer probe (Testo 405i) is placed
10 mm downstream the exit of cylinder to measure the flow velocity. An ICCD camera (Stanford Computer Optics 4 Picos) is used to observe the discharge morphology. To achieve better visualization of streamer branching structures, the greyscale photographs are transformed to pseudo-color images according to a preset relationship between the gray intensity and RGB value. Color images of the corona discharges are taken with a CMOS photo camera (SONY, Model: DSC-R1).

The emitted light by the discharge is collimated by a positive lens into an optical fiber connected to a spectrometer (Ocean Optics Maya 2000) equipped with a holographic grating of 1800 lines/mm and a 25 μm wide slit. This is used to study the emission spectrum from the SPS of N₂ in the experiment. The gas temperature in the corona region is assumed to be equal to the rotational temperature of N₂ molecules. Due to the small energy separation between the rotational levels, the population of the rotational states will correspond closely to the translational temperature [20]. The rotational structure of the nitrogen C-B (0-2) band (368-381 nm) is used to determine the rotational temperature by fitting the spectrum with Specair [21]. This method is also used to measure gas temperature in plasma jet, DBD and spark discharges [22–24]. In Specair, the slit function is a trapezoid of base 0.3 nm and the spectral step is 0.01 nm.

Schlieren method is usually employed in flow measurements. It shows the variance of the refractive index, which is related to the gas density and, according to the ideal gas law, the temperature and pressure. A typical Schlieren system is able to reveal 2% density change which corresponds to a Mach number of 0.2 by way of elementary isentropic gas-dynamic theory [25]. In actual experiments, Schlieren technique have been used to visualize low velocity gas flows (< 1 m/s) produced by SDBD actuators [26,27]. In these cases, the temperature gradients as well as flow-induced density gradients are both significant. The Z-type Schlieren setup that has been used is shown in Figure 1(b). The light from an LED torch travels through a condenser lens to focus it on a slit. The slit is placed in the focal point of the first parabolic mirror (Φ = 150 mm and f = 900 mm), which makes a parallel beam in the test area. The second mirror re-focuses the light beam and projects it on a camera (Nikon D3100). A knife edge is placed in the focal point of the second mirror and blocks the image of the light.

![Figure 1. Experimental set-up of ionic wind diagnostics.](image-url)
source. The knife edge is parallel to the symmetry axis of the needle-cylinder gap (the $z$-direction in Figure 1) so that the Schlieren diagnostic can record density gradients perpendicular to it (the $r$-direction in Figure 1). When an object is placed inside the test area, gradients in refractive index bend the light rays leading to differences in intensity on the camera sensor. This illustrates that how the phase difference is converted into an amplitude difference [25].

Since experiments were performed in ambient air, the relative humidity variations are due to weather conditions outside. Every time before and after a measurement, the temperature, pressure and humidity in the laboratory room were recorded. During the experiments, the temperature is 20-22 °C, the air pressure is 101.9-102.2 kPa, and the relative humidity (RH) is 40-60%.

3. Experimental results

Experimental results including corona modes, voltage-current characteristics, voltage-flow velocity characteristics, emission spectra and Schlieren results are shown in detail in this section. The average current, flow velocity and gas temperature are compared for positive and negative DC corona.

3.1. Corona modes

As firstly summarized by Giao and Jordan [28] in 1968, there are different discharge modes regarding the positive and negative DC corona. These discharge modes may influence the gas flow generated by a DC corona. We will firstly show what the differences of these corona modes are from ICCD photographs and current waveforms.

3.1.1. Positive DC corona

Figure 2 shows three typical current waveforms when the DC voltages are 5.0 kV, 12 kV and 20 kV, where three modes of a positive DC corona are clearly seen. When the voltage is just above the corona inception voltage (~5 kV), there are a few current pulses in the current waveform in Figure 2(a). The current baseline is nearly zero. The discharge morphology is shown in Figure 3(a). A single streamer channel can be clearly seen in the ICCD photograph with an exposure time of 100 μs. Since streamers appear randomly from the needle tip, hundreds of photographs were taken in order to capture one streamer channel. From a time-integrated photograph by the CMOS camera we can also see a faint channel with a purple color. This mode is called the onset streamer stage. When increasing the voltage, the current also increases and the current pulses are rarely seen in Figure 2(b). There is a small luminous spot around the needle tip in both the ICCD and CMOS photographs in Figure 3(b). This mode is called the glow stage. When the voltage increases above a certain voltage, the current pulses appear again, which is shown in Figure 2(c). The amplitudes of the current pulses are rather high and reaches tens of milli-amperes when the voltage is 20 kV, while the baseline of the current is around tens of micro-amperes. Meanwhile, the current pulses appear rather regularly with a frequency of 3.7 kHz. From a statistics analysis of a total of 30 current pulses from Figure 2(c) we found a positive pulse amplitude of 33.1±5.2 mA. The rise time and full width at half maximum (FWHM) of the positive pulses are
99±11 ns and 154±34 ns, respectively, which are both larger than those of Trichel pulses in negative coronas [29].

The time-integrated CMOS photographs show that there are many streamers emerging from the tip. There is a bright thin channel extending from the tip and then the illuminating region is like a cone shape. Later we use the ICCD camera to better observe the discharge morphology. Since these current pulses coincide with streamers, the exposure time is set to 100 μs to capture the emission during a single current pulse. The ICCD photograph in Figure 3(c) shows that there is a glow region around the tip and branching streamers emerge from this glow. Actually, there are two types of discharges at this voltage i.e. the glow and the streamer, which accordingly correspond to the baseline and pulse components of the current.

![Figure 2](image1.png)

Figure 2. Typical current waveforms of positive DC coronas: (a) onset positive streamer; (b) glow; (c) glow and burst streamer.

![Figure 3](image2.png)

Figure 3. The time-integrated photographs of positive DC corona by the CMOS and ICCD cameras: (a) Onset streamer, +5.0 kV; (b) glow, +12 kV; (c) glow and burst streamer, +20 kV. The exposure time is 10 s for normal images (upper row) and 100 μs for the ICCD images (lower row).

3.1.2. Negative DC corona

The negative DC corona modes are quite different from the positive corona. When the voltage is slightly above the corona inception voltage (~4.8 kV), a few large current pulses are also seen in the current waveform in Figure 4(a). The amplitudes of these current pulses are less than those of the positive corona. For this onset negative corona stage, a streamer-like discharge morphology can neither be seen in the long-time integrated CMOS or short exposure ICCD photographs in Figure 5(a). When the voltage is increased, the discharge current
is composed of current pulses with a higher frequency (a few megahertz) and a lower amplitude (hundreds of micro-amperes). This mode of the negative DC corona, which is the well-known Trichel pulse, was firstly reported in [30]. The steady component of the total current is usually tens of micro-amperes, while the amplitudes of the current pulses are hundreds of micro-amperes. The frequency and amplitude of current pulses both increase with the voltage. Figure 5(b) shows that there is a small glow region around the tip, which is similar to the glow mode of the positive corona. As the voltage further increases, the current pulses disappear and the discharge changes to a new mode of corona - a pulseless glow [28]. This can be seen in Figure 4(c) for $U = -20$ kV. The negative corona in this mode is a bright conical glow around the needle tip, which can be seen in Figure 5(c). The size of the glow region also increases with the voltage.

![Figure 4](image.png)

Figure 4. Typical current waveforms of negative DC corona: (a) negative onset corona; (b) Trichel pulse; (c) stable glow.

![Figure 5](image.png)

Figure 5. The time-integrated photographs of positive DC corona by the CMOS and ICCD cameras: (a) negative onset corona, -4.8 kV; (b) Trichel pulse, -12 kV; (c) pulseless glow, -20 kV. The exposure time is 10 s for normal images (upper row) and 100 μs for ICCD images (lower row).

### 3.2. Current-voltage characteristics

The mean current as function of the mean voltage for both voltage polarities is plotted in Figure 6 for three different relative humidity levels. We firstly compare the current for both voltage polarities at a given relative humidity of 43%, see Figure 6(a). The current of negative coronas is greater than that of positive coronas for voltage magnitudes below 18 kV. When the voltage magnitude is further increased, the current of positive coronas starts to surpass negative coronas. The same trend is found at the other two humidity levels shown in Figure 6(b) and (c). As we mentioned in the corona modes section, the current of positive coronas is composed
of a baseline with pulses. Figure 6 also shows the baseline value of the mean current with a circle marker. The mean current of this baseline for positive coronas is lower than that of negative coronas. Ferreira et al. [31] measured the current-voltage characteristics thoroughly in a point-plane gap for both positive and negative coronas for gap distances between 1.5 cm and 6 cm. Their measurements were carried out in the regular Trichel pulse regime for negative coronas and in the glow regime for positive coronas. They found that the mean current of negative polarity is greater than the positive polarity for the same absolute voltage value in this region, which agrees with our experimental results. This difference may be due to a higher mobility of negative ions in air. However, they did not show results of the streamer mode regime of positive coronas. So, they did not find that the current is larger for positive coronas in the streamer mode.

As we increase the voltage magnitude, the curve of the baseline starts to deviate from the total mean current curve, which indicates that the current pulses appear. The current jump can be seen at the voltages of 14 kV, 17 kV and 13 kV for relative humidities of 43%, 48% and 54%, respectively. The current jump appears when the voltage is above a voltage level which corresponds to the corona mode transition. This phenomenon is especially obvious in Figure 6(b). The total current of positive coronas is 9 μA greater than its baseline at 17 kV, which is 31% of the baseline current. At the deviation points, the increment value of the current are 3.8 μA and 0.5 μA in Figure 6(a) and (c). This current jump is seldom mentioned in literature, for it is not that easy to be noticed when current pulses appear at a relative low voltage. This jump in the current indicates a glow-to-streamer discharge mode transition for positive coronas. Its transition voltages are not constant for different humidity levels. Besides, most researchers used to use a Townsend relation to describe the current-voltage characteristics. But this relation may not be appropriate in the streamer mode, as suggested in Figure 6(b).

![Figure 6. Current-voltage characteristics for positive and negative DC corona discharge at different relative humidity levels: (a) 43%; (b) 48%; (c) 54%.](image)

3.3. Flow visualization and velocity-voltage characteristics

In this section, we focus on the flow characteristics of the ionic wind by our DC corona. The average flow velocities at the exit of the cylinder electrode are compared for positive and negative DC coronas. The hot wire probe measures a very weak flow after the corona inception. Figure 7 shows the average flow velocity as function of voltage. With the voltage magnitude increasing from 5 kV to 20 kV, the average velocity increases nearly linearly with the voltage and it reaches values above 4 m/s. At the highest applied voltage of 20 kV, the velocity does not seem to be saturated. However, the highest flow velocity is limited by the breakdown voltage
of the gap. At all three humidity levels, the velocities for both polarities are similar at lower voltages. At higher voltages the flow velocity by positive coronas is a little higher than that by negative coronas. For example, at 20 kV the velocities by positive coronas are 11.1%, 5.5% and 15.1% higher than those by negative coronas. In Figure 7(a), when the voltage magnitude reaches 14 kV, the flow velocity by positive coronas exceeds the velocity by negative coronas. It is interesting to see that at this voltage level the positive discharge mode transits to the streamer type. This coincidence is also seen at the humidity of 54% in Figure 7(c). However, when the discharge mode changes no velocity jump is observed in Figure 7(b) at the voltage of 17 kV. We repeated this experiment at a similar humidity of 47%. The results show that the current jump appears at a lower voltage of 15 kV, which indicates that the discharge mode changes at random voltage levels. And it shows a similar trend like RH = 43% and RH = 54% that the flow velocity of positive coronas becomes greater than negative coronas at the same voltage of the current jump. Therefore, we can tentatively conclude that the greater flow velocities of positive coronas at higher voltages are due to the discharge mode transition. In other words, the occurrence of streamers may lead to an increase of the flow velocity. This will be discussed in more detail in section 4.2.

Figure 7. Velocity-voltage characteristics for positive and negative DC corona discharge under different relative humidity: (a) 43%; (b) 48%; (c) 54%.

3.4. Gas temperatures and Schlieren results

Time-averaged gas temperatures are calculated from the spectroscopic measurements of the N\textsubscript{2} C–B transition. The lens is aimed at the region below the needle tip and mainly collects the light from the visible corona region. Hence, the temperature measurements are spatially averaged. Besides, it should be noted that there may be light from positive streamers entering the spectrometer.

Specair is used to model the spectra from these transitions [32]. A least square fit between the experimental spectra and the modelled spectra is obtained using the rotational temperature $T_{\text{rot}}$ as the fitting parameter. The error in rotational temperature is less than 100 K [17]. It is further assumed that the gas temperatures $T_{g}$ is equal to the rotational temperature at atmospheric pressure [17,33].

Figure 8 is a plot of the measured and fitted spectra at $U = +20$ kV. The best-fit spectrum gives a rotational temperature of 650 K in the corona region. The gas temperatures as function of voltage for both polarities are shown in Figure 9. It was not possible to calculate the gas temperature for voltages below 11 kV, because the intensity of the emitted spectra was too weak compared to the background noise. The gas temperatures in the corona region increases with voltage since there is a corresponding increase in the discharge power input. There
is not much difference in gas temperatures between the two polarities, both are in the range of 350-700 K for the voltage magnitude range of 11-20 kV.

![Figure 8](image1.png)

Figure 8. Measured spectra and curve fit using Specair. The dotted line is the calculation at $T_{rot} = 650$ K, and the solid line is the normalized measured spectrum at $U = +20$ kV.

![Figure 9](image2.png)

Figure 9. Gas temperature of corona region near the tip for different polarities at a humidity of 54%.

![Figure 10](image3.png)

Figure 10. Schlieren measurement results. Positive voltage: (a) 6 kV, (b) 12 kV, (c) 20 kV; Negative voltage: (d) -6 kV, (e) -12 kV, (f) -20 kV. The exposure time is 1/4000 s.

The spectroscopic measurements cannot give us two-dimensional information on the gas temperature, while the Schlieren technique can be employed to see the gas temperature distribution qualitatively for low flow velocities. In Figure 10 Schlieren images with an exposure time of 1/4000 s for positive and negative corona
are shown. No significant density gradients can be found in Figure 10(a) at +6 kV. When the voltage is increased to +12 kV, there is a vague thin channel visible around the central axis in Figure 10(b). This channel becomes more clearly defined at the voltage of +20 kV in Figure 10(c). This channel reveals the existence of a column of different gas density and thus indicates a local temperature gradient. This heating channel coincides with the discharge channel in Figure 3(c), so this temperature increase is likely attributed to the repetitive streamers from the tip. However, this heating channel is also seen in the negative corona discharge. When increasing the voltage magnitude, this channel can be observed clearly in Figure 3(f) at -20 kV, very similarly to the +20 kV results from Figure 3(c). However, the negative corona does not have any streamer discharges and does not show a discharge channel in the camera observations from Figure 5(c).

Kurimoto and Farish [34] found the existence of a similar thin ‘jet’ in the axis of a point-plane electrode with a negative voltage applied to the point. Their high-speed Schlieren records different stages of the pre-breakdown corona. As the voltage was increased, a long narrow column becomes dominant. They showed that this column corresponds with a temperature rise by direct measurements of the gas density using interferometry. The gas heating is associated with both the Trichel and glow coronas. It is interesting to see in our experiment that the heating channels appear for both polarities. We will calculate the temperature distribution by corona discharge simulation and show how the heating channels are generated in section 4.1.

4. Discussion and modelling

4.1. Influence of gas heating on flow velocity

It was found from the Schlieren results that a DC corona can generate a thin heated column in the needle-cylinder electrode, even for the negative corona without streamer discharges. Therefore, it is worth simulating the temperature distribution of the negative DC corona. Besides, the spectroscopic study shows that the temperature around the needle reaches 700 K. We can also investigate the influence of gas heating on flow velocity through ionic wind simulation. A self-consistent ionic wind model was demonstrated in [35]. Here, the model is improved by considering the energy conservation and thus the temperature distribution is obtained.

The number densities of the charged species are calculated by solving the following set of continuity equations (1)-(3) coupled with a Poisson equation (5).

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot (-\mu_e \vec{E} - D_e \nabla n_e) = \alpha n_i \mu_i \vec{E} - \eta \mu \vec{E} k_e n_e n_p
\]  
(1)

\[
\frac{\partial n_p}{\partial t} + \nabla \cdot (\mu_p \vec{E} - D_p \nabla n_p) = \alpha n_i \mu_i \vec{E} - k_e n_e n_p
\]  
(2)

\[
\frac{\partial n_n}{\partial t} + \nabla \cdot (-\mu_n \vec{E} - D_n \nabla n_n) = \eta n_i \mu \vec{E} - k_e n_e n_p
\]  
(3)

\[
\vec{E} = -\nabla \phi
\]  
(4)
\[ \nabla^2 \phi = -\frac{e(n_p - n_e - n_n)}{\varepsilon} \]  

(5)

where \(n_e\), \(n_p\) and \(n_n\) are the electron, positive and negative ion number densities; \(\mu_e\), \(\mu_p\), \(\mu_n\), \(D_e\), \(D_p\), and \(D_n\) the mobility and diffusion coefficients for electrons, positive and negative ions respectively; \(\alpha\) the Townsend ionization coefficient, \(\eta\) the attachment coefficient and \(k_{ep}\) and \(k_{np}\) the recombination coefficients of positive ions with electrons and negative ions, respectively. \(E\) is the electric field, \(\phi\) the electric potential, \(\varepsilon\) the permittivity of air and \(e\) the electron charge.

The obtained electric field and charged particles density are regarded as input to the Navier-Stokes equations. A weakly compressible flow model (6)-(7) is coupled with the heat transfer equation (8).

\[
\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \vec{u}) = 0
\]  

(6)

\[
\rho_g \left( \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = \nabla \cdot \left[ -p \mathbf{I} + \mu_e (\nabla \vec{u} + (\nabla \vec{u})^T) - \frac{2}{3} \mu_v (\nabla \cdot \vec{u}) \right] + f_{ehd}
\]  

(7)

\[
\rho_g C_p \frac{\partial T}{\partial t} + \rho_g C_p \vec{u} \cdot \nabla T - \nabla \cdot (k_T \nabla T) = P_{heat}
\]  

(8)

where \(\vec{u}\) is the flow velocity, \(\rho_g\) the air density; \(p\) the static pressure, \(\mu_e\) the air dynamic viscosity, \(\mathbf{I}\) is the unit tensor; \(T\) the gas temperature, \(C_p\) the fluid heat capacity at constant pressure, \(k_T\) the thermal conductivity and \(f_{ehd}\) the EHD force.

A simplified model of the energy transfer [36,37] is used in this paper. Firstly, the energy released through collisions between ions and neutrals is assumed to be totally transferred into gas heating. Secondly, over a wide range of the reduced electric field, a fraction of the electron energy is expended on the excitation of the electronic degrees of freedom of \(N_2\) molecules and instantaneously released into gas heating [18].

\[ f_{ehd} = e(n_p - n_e - n_n)E \]  

(9)

\[ P_{heat} = (j_p - j_n) \cdot \vec{E} - \xi_{ex} j_e \cdot \vec{E} \]  

(10)

The EHD force \(f_{ehd}\) in (9) is responsible for the momentum transfer from charged particles to neutrals. The energy deposition in gas is due to the heating source \(P_{heat}\) is defined in equation (10). \(j_e\), \(j_p\) and \(j_n\) are the current densities by electron, positive and negative ion; for discharges in air \(\xi_{ex} = 28\%\) is the total fraction of electron power deposited into gas heating [38].

This ionic wind model including heat transfer is implemented in COMSOL Multiphysics 5.2. The discharge equations (1)-(5) are solved by the “transport of diluted species” and “electrostatics” modules, and the gas dynamics equations (6)-(8) are solved by the “Laminar flow” and “Heat Transfer in fluids” modules. The corona model is unidirectionally coupled to the non-isothermal flow model, and the former one provides the EHD force.
and heat source to the latter. The impacts of the gas flow and temperature on the discharge are ignored.

The simulation is performed in an axisymmetric geometry. The initial and boundary conditions for \( n_p, n_e, n_n, p \) and \( u \) can be found in reference [35]. The initial temperature \( T \) is 293 K. At the needle the temperature is set as a homogeneous Neumann boundary condition, and at other boundaries the temperature is set to 293 K. A DC voltage of \(-16 \text{ kV}\) is applied to the needle electrode. A non-uniform triangular mesh is used with a maximum element size of 1.25 \( \mu \text{m} \) near the needle tip. The element size increases to 1 mm in the area far away from the needle. In total around 80000 triangular elements are used. The time step size is automatically determined with a maximum step of \(10^{-8}\) s. The minimum time step can go down to \(10^{-13}\) s.

A fully-coupled model has such a high computational cost that it is impossible to achieve a steady solution in a reasonable amount of time. Therefore, we break the simulation into a two-step process. Firstly, the corona discharge model is simulated. The total simulation duration is 120 \( \mu\text{s} \) which takes about 140 hours to complete on a standard PC. Secondly, the time scale of gas dynamics is several orders of magnitude slower than that of the corona discharge. In order to calculate the steady-state velocity distribution, the gas dynamic model is decoupled from the plasma model and instead the time-averaged EHD force and heating power density are used as input to calculate the flow behavior during 1 s, which is long enough for the temperature to reach a stable state. This process takes about 4 hours to complete. Thus, the steady-state velocity and temperature distribution are obtained.

Figure 11 shows the gas temperature distribution at the end of the simulation. The 2D distribution of the gas temperature is demonstrated in Figure 11(a). A very thin heated channel can be seen, which is very similar to the Schlieren results. The highest temperature reaches 1200 K near the needle tip. The temperature quickly decreases to 608 K at \( z = -0.0001 \text{ m} \) in the symmetrical axis and to 417 K at \( z = -0.001 \text{ m} \). The measured gas temperature is about 600 K, which is close to the simulated result. It is should be noted that the measured gas temperature is spatially averaged in the vicinity of the tip. We also show 1D temperature distributions at five lines perpendicular to the symmetry axis in Figure 11(b). The temperature reaches the highest value at the symmetry axis and then decreases rapidly outwards. Furthermore, the highest temperature on the symmetry axis decreases from 608 K to 300 K when moving away from 0.1 mm to 20 mm from the tip.
Figure 11. Gas temperature distribution after 1 s in a needle-cylinder DC corona set-up with -16 kV applied voltage.

Figure 12. Calculated axial flow velocities by the ionic wind model with and without consideration of heat transfer. The DC voltage is – 16 kV. (a) 2D velocity $v_z$ distribution without heat transfer; (b) 2D velocity $v_z$ distribution with heat transfer; (c) axial flow distribution on the symmetry axis; (d) axial flow velocity distribution as function of radial position at the exit surface of the grounded cylinder electrode.

Next, the influence of gas heating on flow velocity is studied. Figure 12(a) and (b) present the axial flow velocity $v_z$ obtained by the ionic wind model with and without consideration of heat transfer. There are two velocity regions: the gas in the vicinity of the needle flows upwards while the gas at most area below the needle flows downwards. This phenomenon was also shown in [35]. The results with heat transfer differ from those without it close to the lower boundary where the velocity is lower for the improved model. This is more clearly shown by plotting the velocity profiles on the symmetry axis in Figure 12(c). The velocity calculated by the improved model reaches a higher maximum value near the tip, while it becomes lower as the axial distance increases. Figure 12(d) compares the axial velocity distribution at the exit surface of the grounded cylinder electrode as function of the radial position. A measured velocity profile at a relative humidity of 54% is also plotted in this figure. At the cylinder center the simulation gives higher velocities than the experimental value.
of 2.7 m/s. For \( r > 0.005 \) m the simulated velocities agree well with the experimental velocities. Several reasons might be responsible for the discrepancy around the axis. Firstly, the output of the discharge model at \( t = 120 \) \( \mu \)s is used in the gas flow model. The distribution of the EHD force and heat source would be different if the corona model would be performed for longer simulation times. Secondly, the measurement position is 10 mm lower than the simulation sampling point which will lead to lower velocities. Thirdly, the measuring area of the probe is much larger than the sampling point in the simulation which decreases the measured maximum temperature.

When the heat transfer is considered in the model, the flow velocity near the symmetry axis is decreased from 9.0 m/s to 6.9 m/s, while at larger distance \( r \) the velocity is hardly affected by this change. The simulation results indicate that the high temperatures near the tip create a region with a low gas density. This will have an opposite effect on the gas flow downwards on the symmetry axis, which is driven by the momentum transfer of charged particles. This also indicates that it would be sensible to couple the results of gas density back to the discharge model, because a reduced gas density can have a large effect on the discharge parameters. So, it is suggested that the heat transfer should be considered in ionic wind modelling by a DC corona discharge, especially at higher voltages.

### 4.2. Influence of repetitive streamers on flow velocity

The experimental results show that the ionic wind created by positive DC coronas is slightly larger than that by negative coronas, but only at higher voltages. At lower voltages the flow velocities are nearly identical. Meanwhile, when increasing the voltage, the discharge mode of positive coronas changes from a glow to a glow-with-streamers regime. It is worthy of discussion whether these repetitive streamers have influence on the flow generation. Since the streamer channels emerge from the tip randomly and have three-dimensional trajectories, it is difficult to simulate them and their effects on gas flow generation directly. Nevertheless, we can still make estimations of the flow velocity when a single streamer propagates towards the cathode based on a simplified model. Firstly, the EHD force in the streamer head has to be calculated. Equation (9) shows that the EHD force is proportional to the net charge density and electric field. A ‘Gaussian charge ball’ was used to simulate the flow generation, which assumes a positive charge density sphere with Gaussian radial and axial distribution [39]. However, this assumption contradicts numerical simulation that streamers are extending ionized fingers and the space charge layer is strongly curved [40]. So, simulation results of the net charge density \( \rho \) and electric field \( |E| \) from a 2D fluid streamer model, which are shown in Figure 13(a) and (b), are used as input to our gas flow model [41]. During the development of this “artificial” streamer i.e. the curved shell of positive charges, the time-dependent EHD force in this region can be written as:

\[
 f_{\text{str}}(r, z, t) = \rho(r, z - v_{\text{str}}t)E(r, z - v_{\text{str}}t)
\]

where \( r \) and \( z \) are the radial and axial coordinates, respectively. \( v_{\text{str}} = -2 \times 10^5 \) m/s is assumed to be the typical average streamer propagation velocity [42,43] and the negative sign means that the streamer propagates downwards. Figure 13(c) and (d) show the 2D distribution of the EHD forces in \( r \) and \( z \) direction.
s while the streamer diameter also remains
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s by, the velocity increases to
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ly
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s by streamers
but the flow velocity by the positive corona is 0.5 m/s higher than that by the negative corona. The calculated
U
growth due to repetitive streamers is
The velocities gradually increase
the initial 100 ns of each period, and then decrease for the rest of time since no EHD force is exerted on the gas.
for
0.
starts to flow due to the EHD force by the streamer. As the first streamer passe
0.25
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m/s. In

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-0.30
-0.25
-0.20
-0.15
-0.10
-0.05
0.00
z (mm)
r (mm)
(a) Simulation results of net charge density \( \rho \); (b) Simulation results of electric field \(|E|\); (c) Input of EHD force in \( z \) direction; (d) Input of EHD force in \( r \) direction.

Secondly, the flow velocity is calculated from this EHD force generated by the “artificial” streamer front. It
must be emphasized that this non-self-consistent model can only estimate the influence of streamers on the flow velocity. As the experimental results shown in section 3.1, repetitive streamers propagate from the tip with a frequency of 3.7 kHz at \( U = 20 \text{ kV} \). This means that the EHD force is also periodical with the same frequency. In our simulation, the streamer is assumed to propagate along the symmetry axis in the first 100 ns of each period, and to stop at \( z = -20 \text{ mm} \). The rest of the time, the EHD force is zero. The total simulation time is chosen to be 8.1 ms to show the velocity variance in the first thirty cycles. Again, Comsol Multiphysics is used to perform simulations.

Figure 14 shows the axial velocity \( v_z \) along the symmetry axis during the first 100 ns. It shows that the gas starts to flow due to the EHD force by the streamer. As the first streamer passes by, the velocity increases to 0.034 m/s. In Figure 15, we show how flow velocities at certain points on the symmetry axis change over time for longer time-scales. The flow velocities at the three positions show a similar trend. They firstly increase at the initial 100 ns of each period, and then decrease for the rest of time since no EHD force is exerted on the gas. The velocities gradually increase at a slower rate and finally become saturated. In this case, the flow velocity growth due to repetitive streamers is 0.25 m/s which is around 6.6% of the average flow velocity of 3.8 m/s at \( U = +20 \text{ kV} \) in the experiments. The averaged current for the positive corona and negative corona are the same, but the flow velocity by the positive corona is 0.5 m/s higher than that by the negative corona. The calculated velocity gain by streamers is less than that of the experimental result. Since we assume the electric fields in the streamer front region do not decrease as the streamer propagates while the streamer diameter also remains constant, the EHD force by the streamer is exaggerated in the simulation. This means that the influence of a single streamer on gas flow generation is relatively small compared to the influence of the ion drift region.
However, there are several streamer branches, which will all contribute to the gas flow generation. It explains why the velocity gain by the simulation is lower. Therefore, the actual velocity increase by repetitive multiple streamers in the whole domain should be further investigated by a 3D self-consistent model in the future.

Figure 14. The calculated velocity $v_z$ due to a single streamer along the symmetry axis at different times of the initial 100 ns.

Figure 15. The calculated time-dependent velocity $v_z$ due to repetitive streamers at three positions on the symmetry axis as function of time.

5. Conclusions

We have shown a detailed experimental study of ionic wind by a DC corona discharge in a needle-cylinder electrode arrangement. For a given voltage magnitude, the current of negative coronas is usually higher than of positive coronas. It is interesting to see that the positive corona current suddenly jumps up tens of percent when the discharge mode changes from glow to glow-plus-streamer. At a relative humidity of 48%, the total current of positive coronas becomes 31% greater than its baseline at 17 kV. On the other hand, the gas flow velocity for negative coronas is higher than for positive coronas at low voltages, while this reverses for higher voltages where streamers appear at positive polarity. However, the flow velocity does not seem to increase as sharp as the current at this transition. At 20 kV the velocities by positive coronas are 11.1 %, 5.5% and 15.1% higher than those by negative coronas. A spectroscopic study shows that the gas temperature reaches as high as 700 K at 20 kV. This was further proven by measurements with the Schlieren technique. A heated channel near the symmetry axis is found for both polarities.

An improved ionic wind model that considers the heat transfer from ions and electrons to neutrals is built to investigate the gas temperature distribution. Its results show a similar column with high temperatures on the
symmetry axis. This heating also influences the gas flow velocity, which near the symmetry axis is lower than in the results from the model without heating. This indicates that the temperature gradient should be taken into account when simulating the gas flow at higher voltages. Furthermore, the influence of repetitive positive streamers on flow velocities is studied by a phenomenological model, in which the EHD force is generated by a moving artificial streamer front. The flow velocity is increased by about 0.25 m/s due to repetitive streamers at 20 kV which accounts for 6.6% of the total average flow velocity of 3.8 m/s in the experiments. It is suggested that the positive corona will produce a higher flow velocity because of streamers at higher voltages.

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