Explaining the electrohydrodynamic force and ionic wind spatiotemporal distribution in surface AC dielectric barrier discharge actuators

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Abstract

We show that the spatio-temporal ElectroHydroDynamic (EHD) force production in surface AC-Dielectric Barrier Discharge (AC-DBD) actuators is dictated by both the streamer regime during the positive phase and the micro-discharge regime during the negative phase. We demonstrate that the ionic wind spatial distribution can only be explained by the positive contribution of the streamer regime. The negative sub-cycle contributes also to positive x-directed force production while a strong negative force region exists near the exposed electrode, linked to the micro-discharge and cathode sheath layer formation. The extension of the EHD force leads to a maximum of the ionic wind velocity profiles located in several millimeters from the exposed electrode.

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1 Introduction

ElectroHydroDynamic (EHD) flows induced by surface Alternative Current Dielectric Barrier Discharge (AC-DBD) actuators have found use in a variety of applications mainly as means of aerodynamic flow control. Separation delay and flow re-attachment, turbulent enhancement and laminar-to-turbulent transition control, vortex generation, turbine blades aerodynamic enhancement are a few of such applications. Despite the numerous studies, the spatio-temporal distribution of the induced EHD flow or ionic wind is yet to be fully understood. Experiments have demonstrated that the plasma discharge nature is very different in both half-phases [2]. In the positive going cycle, high current streamer discharges form above the dielectric layer while in the negative going cycle, lower current but higher frequency micro-discharges are present. The contribution of each phase to the EHD force production and consequent ionic wind profiles is a controversial subject. Concerning temporal aspects, push-push and push-pull scenarios have been proposed and supported by experiments and simulations. Concerning spatial aspects, experimental studies have been used retrieve the force distribution [1, 9, 8, 11, 12]. These studies are mostly based on strong assumptions (pressure gradients, local acceleration, turbulent fluctuations) and an inverse NS procedure that render the results ambiguous as they do not correlate with velocity measurements. Numerical and theoretical studies on the ionic wind profiles show in general good agreement with experiments in terms of overall thrust production but fail to capture the maximum position of the induced wall-jet. Most of these numerical studies suffer from low accuracy due to the numerical schemes used and insufficient spatial discretization while limited information on the spatial distribution of the EHD force has been provided (e.g. Ref. [4], see also references in Ref. [10]).

In this work, based on the detailed numerical simulations of our recently submitted work in Ref. [10], we answer two important questions on the spatio-temporal incertitude of EHD force and ionic wind produced by surface AC-DBD discharges: Why the ionic wind spatial profile present maxima at a distance of several millimeters from the exposed electrode? How does each phase of the AC cycle contribute to the induced flow (magnitude and direction)? To do so, we elaborate on the results of Ref. [10], demonstrate the time-averaged spatio-temporal EHD force and ionic wind produced by an AC-DBD actuator and propose an illustrative explanation of the complex
plasma-flow interaction.

\section{On the plasma evolution over a full AC cycle}

A self-consistent modeling approach has been followed in order to obtain the full cycle characteristics of the surface AC-DBD operation. Details on the numerical and physical models used can be found in Ref. \cite{7,10}. In Ref. \cite{10}, we show that the AC-DBD operation can be decomposed in two phases which are nevertheless strongly inter-connected in agreement with several experimental studies \cite{13,2}. In summary our findings demonstrate that: In the positive phase, a positive corona-like discharge forms at the active electrode interrupted by a high current surface streamer discharge. The streamer propagates detached from the dielectric surface acting as a virtual anode. When its propagation is stopped, it slowly relaxes and positive ions from its body charge the dielectric surface contributing to an elongated zone of positive potential and consequent high electric field at a distance of several millimeters from the active electrode. In the negative phase, volumetric charge separation leads to the initiation of repetitive microdischarges which attach to the active electrode (cathode in this phase) forming a thin cathode layer. Each microdischarge terminates with the propagation of a thin plasma layer attached to the dielectric surface. The positively charged portion of the dielectric which persists from the positive/streamer phase, pulls this layer further and further until it is quenched due to electrons and negative ions which drift towards the dielectric. In the relaxation phase between consecutive microdischarges, positive ions are repelled outwards from the dielectric surface and the thin ion layer attached to the dielectric consists of mainly negative ions.

The instantaneous EHD force per unit volume is given by \cite{5}:

\begin{equation}
\vec{F}_{EHD} = q(n_+ - n_- - n_e)\vec{E}
\end{equation}

where $q$ is the elementary charge, $n_+, n_-$ and $n_e$ are the positive, negative ions and electrons density respectively and $\vec{E}$ is the electric field vector. It is clear that the EHD force is generated in regions with high electric fields, without charge neutrality and high unipolar charge concentration.
3 Results on EHD force profiles

The space-integrated EHD force (x and y component) versus time extracted from the detailed simulations of Ref [10], is shown in Fig. 1. The effects of both the streamer and micro-discharges are quite remarkable: The x-force is strongly negative during each micro-discharge formation while it becomes positive in the relaxation phase (thin layer propagation) during the negative going cycle. In the positive going cycle the x-force is always positive and the streamer produces a pulse of positive force. The streamer discharge seems to have a very important influence on the y-force: While the y-force remains a lot weaker that its x-component, each streamer produces a significant negative y-force.

![Figure 1: Space integrated EHD force (x and y components) [N/m] vs Time [µs]](image)

This suggests that the definition of the EHD forcing as a push-push or push-pull action is misleading. Both phases contribute positively to the EHD x-directed force but strong negative parts exists during the negative phase too. As we will see below at the spatial distribution and resulting ionic wind profiles, the negative parts can form zones of strong negative flow. Thus, the temporal forcing or velocity profiles extracted from experiments should strongly take into account the measurement location. Moreover, the
y-directed forcing is negative throughout the AC cycle.

As the fluid response takes place in much longer time-scales than these two phases and the AC frequency of operation, the time-averaged EHD-force provides a good representation of the continuous EHD forcing and resulting flow. The time-averaged force has been calculated during an AC period (third period of Ref. [10]) and its spatial distribution (magnitude, x and y components) is plotted in Fig. 2. The EHD force occupies a volume of approx. 4-5 mm in x-direction and 1.5-2 mm in y-direction. It is very high in a small volume near the exposed electrode where its mainly negative-directed (both in x and y directions).

The X-directed EHD force is positive and important inside three regions. The first is linked to the initiation of the streamer discharge - the zone at a distance of approx. 0.5 mm where strong ionization occurs. The second is a zone very close to the dielectric layer where negative ions exist during the negative phase. The third is the zone in front of the streamer final elongation length linked to its propagation and dielectric charging during the positive phase. It is thus obvious that the positive going cycle (streamer regime) has important implications to the EHD force production and especially to its spatial distribution in both phases. The negative x-directed EHD force zone near the exposed electrode is linked to the cathode layer formation during the negative phase. This zone is also very important and simplified models often neglect it. The negative y-directed EHD force is located mainly close to the active electrode and a layer attached to the dielectric. This zone is due to both phases (positive charges accelerated into the streamer sheath during the positive phase and negative ion charging drifting towards the dielectric as the thin layer moves downstream during the negative phase). The reader should refer to Ref. [10] for more details on the discharge evolution in each AC subcycle which support all of the above.

The total elongation of the EHD force is approx. 3.5 mm. To our knowledge this is the first time that such a result has been obtained - one that links the EHD force distribution with the streamer regime and demonstrates the experimentally observed elongation of the EHD forcing (see Ref. [3] for example). We also note that a longer streamer elongation (due to photoionization effects or streamer pulse repetition during the positive phase under lower actuation frequency) should reproduce similar effects and elongate the
EHD force localization even more. As streamers have been experimentally observed to propagate at distances in the order of 10 mm, our results should translate to such cases too.

![Figure 2: Time-integrated (over 1 AC period) EHD force distribution - Force magnitude [N/m³, log-scale - scaled to min of 10 N/m³] and Fx, Fy components [N/m³, scaled to min of -100 kN/m³ and max of 100 kN/m³ for visualization purposes] (min and max values are also indicated on the top-left corner of each figure)](image)

In order to provide an explanation in a more illustrative way and based on the work of Ref. [10], in Fig. 3 and Fig. 4 we present schematically the EHD force production zones in the positive and negative phase respectively. We note that dimensions are not in scale and the representation is illustrative: not all ion cloud zones are presented but only the most important for the EHD force production. The instantaneous EHD force vectors presented in Fig. 4, 10 and 17 of Ref. [10] along with the detailed operational description
During the positive phase, the EHD force is located inside 3 main regions: First, the positive ion cloud expanding over the dielectric. Second, the streamer head and the streamer sheath region between its body and the dielectric surface during its short-term propagation. Third, an important part of the EHD force is located in the zone ahead of the streamer maximum elongation length during the relaxation phase. The latter is due to the conductive nature of the streamer and the positive dielectric charging during the (long-term) relaxation phase of the streamer discharge. Both of these factors lead to a zone of enhanced electric field just downstream the streamer body, promoting ionization, positive-ion production which along with the diffusion of the latter from the streamer body contribute to a positive x-directed EHD forcing, as the positive voltage phase persists. The x-directed component is positive in all three regions while a negative region of y-directed force exists in the sheath region between the streamer body and the dielectric. Phase C as illustrated in Fig. 3 contributes the most to the EHD force as it lasts several 100s of ns.

During the negative phase, the EHD force is located inside two main regions: First, the negative ion cloud as a remnant of the positive phase streamer with an important x-directed positive component inside a region near the dielectric and between the charged dielectric portions. Second, inside the cathode sheath layer formed due to each micro-discharge generation. The force there is strongly negative and mainly x-directed as positive ions dominate. Third, during the relaxation phase between each microdischarge inside the thin negative ion layer attached to the dielectric. This layer expands further and further after each microdischarge pulse as the electric field between the surface charged regions progresses along. By the end of the negative phase, the region once covered by the streamer discharge is now covered by ion clouds and the thin negative layer near the dielectric which is now negatively charged all along. In all phases, dielectric charging plays an important role in both the discharge behavior as well as the electric field enhancement in critical regions for EHD force production. The reader may find additional details in the captions of the illustrative Fig. 3 and Fig. 4.
Figure 3: Illustration of the positive phase EHD force production zones: A) Initially the positive ion cloud expands over the dielectric surface until space charge effects initiate the quasi-neutral streamer. A positive space charge and high electric field region exists at the head of the streamer. B) The streamer propagates quickly parallel to the dielectric surface. In addition to the space charge at its head, a zone of high electric field populated by diffused positive ions exist as a sheath between the streamer body and the dielectric. C) At the relaxation phase, the streamer relaxes and charges the dielectric positively. The virtual anode formation due to the streamer (after-burn) and dielectric charging (relaxation) enhances the electric field at a distance of several millimeters and leads to an elongated zone of EHD force production.
Figure 4: Illustration of the negative phase EHD force production zones: A) Electrons produced near the active electrode drift towards the dielectric charging it negatively. Positive ions near the cathode contribute to a negative EHD force. The negative ion cloud region near the dielectric (remnant from the positive phase) produces positive EHD force under the influence of the electric field due to the potential difference between the negative and positive charged portions of the dielectric surface. B) A quasi-neutral micro-discharge forms and rapidly attaches to the exposed electrode forming a cathode layer. The cathode layer holds very high electric fields, positively dominated space charge and a negative EHD forcing zone appears. Positive ions are generated in the near surface region due to the previously mentioned electric field. C) Once the micro-discharge relaxes and the plasma layer propagates on the dielectric surface, positive ions are repelled from the dielectric leaving a negative ion layer behind. The EHD force is there positive and dominant due to the time-scale of the relaxation phase between each microdischarge. D) The surface ion layer expands after each microdischarge until it reaches the end of the positively charged portion of the dielectric (linked to the streamer elongation during the positive phase).
4 Results on ionic wind profiles

The time-averaged EHD body force term has been incorporated into a CFD solver (openFOAM [16]) in order to calculate the flow field resulting from the AC-DBD actuators (Fig. 5). We note here that the total time-averaged space-integrated x-directed force is 64 mN/m while the total y-directed force is -45 mN/m. Laminar flow is assumed (the effect of turbulence is left for a future study but preliminary results using the k-ω SST turbulent model show that only the boundary layer thickness is affected by the model). Fig. 6 presents the steady-state velocity contours and profiles at a distance of 3 mm, 1, 2 and 3 cm from the exposed electrode edge. The wall jet flow reaches maximum speeds at a height of approx. 0.5 mm (for 2 and 3 cm) from the dielectric surface in good agreement to experimentally obtained velocity profiles (see Ref. [13] and references therein). The thickness of the boundary layer wall jet ranges from 1-2 mm. The maximum velocity occurs at a distance of approx. 3.5 mm from the exposed electrode. To our knowledge, this result is also novel: Not only it clearly demonstrates the importance of the streamer propagation and subsequent dielectric charging (in both phases as described in Ref. [10]) to the ionic wind spatial profile but it also explains the experimental profiles in a physical manner linked to the plasma formation and not purely to fluid dynamics. The maximum elongation length of the EHD force and the resulting ionic wind maximum at a distance of 3.5 mm coincide with the maximum elongation length of the streamer discharge, showcasing its influence on the ionic wind spatial distribution. We note here that Ref. [14], Ref. [6] and Ref. [15] point out towards this direction too. We also note that the maximum elongation distance of the streamer discharge is subject to various parameters (AC frequency, applied voltage, dielectric constant and thickness) and thus the maximum of the ionic wind can be found quite further for different test cases. In addition, a negative flow region is observed initiated near the exposed electrode - quite weaker than the positive flow. This jet flow, induced by strongly negative zone near the electrode as we have seen, might indicate that opposing flows are present in DBD actuators - another aspect that needs further investigation and might have been ignored so far. We note finally that the high velocities obtained (compared to the experimental results) are linked to the high AC frequency used in the simulations. The reader is referred to Ref. [10] for a detailed analysis of each phase along with charge evolution, electric field and surface charging distributions at different time instants.
Figure 5: Steady state flow field - Velocity magnitude contours [m/s] and zoom near the HV electrode zone. Min value is 0 m/s, Max value is 14 m/s

Figure 6: Velocity profiles at 3 mm, 1 cm, 2 cm and 3 cm from the HV electrode
5 Conclusion

In conclusion, we provided an explanation for the ionic wind spatio-temporal profiles induced by surface AC-DBD actuators. Based on a detailed numerical study of the surface AC-DBD actuator (presented in Ref. [10]), we demonstrated that the elongation of the EHD force and local maxima of the ionic wind are mainly due to the streamer regime of the positive phase but also the presence of a thin negative ion layer during the negative phase attached to the dielectric. A strong negative force region also exists near the exposed electrode linked mostly to the negative phase (micro-discharge formation). Therefore, a push-push or pull-pull scenario strongly depends on the localization of the measurements. We have proposed a detailed explanation behind the EHD production zones and backed up our claims with numerically extracted profiles of the EHD force and the ionic wind. Our results indicate that streamers can be used to enhance the EHD force and/or create localized distributions. Apart of the obvious implications to aerodynamic flow control, several domains can leverage such findings to improve EHD flows or create novel devices. Improved actuators can be designed based on repetitive streamer production and subsequent charge drift. The influence of streamers to EHD force production is under study in simplified configurations such as point-to-plane discharges. Such optimized devices could also be used for in-atmosphere propulsion systems replacing typical corona based ion propulsion systems. Lastly, it is worth mentioning that ns-DBDs do not create any significant ionic wind as the streamer production is terminated by the nanosecond pulse and no strong positive electrostatic field exists after its termination to enhance positive ion drift. Superposition of DC fields over the nanosecond pulse could lead to enhanced forcing towards an optimized and efficient actuator system.

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