Evaluation of the time-resolved EHD force produced by a plasma actuator by particle image velocimetry – a parametric study

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Abstract. Surface plasma discharges, and more specifically dielectric barrier discharge, find several applications in aerodynamic due to their capability to produce a local flow at the dielectric wall. The present study proposes a numerical method to estimate the EHD force by using experimental velocity information. Here, this method is used in a parametric study and the obtained results are compared with force balance measurements. It is shown that the EHD volume force increases in space and in amplitude for increasing voltage and increasing AC frequency. Furthermore the force distribution expands in an homothetic manner.

1. Introduction

Non-thermal surface plasma discharges have gained an increasing interest over the last decade due to their capability for manipulating flows at low speed flow conditions. A variety of actuators have been designed over the years [1] and all of them have demonstrated their own merits in terms of aerodynamic performance increase [2]. These surface actuators produce a tangential wall jet limited to maximal velocity of about 7 m/s, but the control mechanism is most of the time related to excitation or damping of the natural flow instabilities suggesting that the induced mean flow velocity is not necessarily the main actor for an effective control. The studies performed over the years have confirmed that the optimization of these discharges in terms of efficiency and electromechanical conversion is definitively a harsh challenge. Despite significant effort from the community, several technical obstacles remain and have to be tackled. Among them, the experimental characterization of the electrohydrodynamic (EHD) body force (in space and in time) produced by such a discharge is a key point because no optimization can be conducted without a fine understanding of the body force production mechanisms and also because experimental data could be of great help for an accurate numerical modeling of the electro-mechanical transfer occurring in a non-thermal plasma.

Here, by inversion of the Navier-Stokes equations [3,4,5], the spatial distribution of the mean EHD force is evaluated based on the mean velocity field. Velocity measurements are conducted for different voltages and frequencies. Then, the spatial distribution of the EHD force and its integrated value can be compared for an increasing applied voltage and an increasing frequency.
2. Experimental set-up
The DBD actuator consists of two aluminum electrodes asymmetrically mounted on a 3-mm thick dielectric plate made of PMMA. All its dimensions are indicated in figure 1. A signal amplifier (Trek, model 30/40 mA) is used to apply a gain of 3,000 V/V to the input voltage provided by a function generator. The input signal is a sine waveform applied to the top electrode while the bottom electrode is grounded and encapsulated.

The mean velocity produced at the center of the actuator (z=0) is measured by a PIV acquisition system composed of dual-head Nd–YAG laser (Evergreen Big Sky, Quantel), a CCD camera with 4920×3280 px² resolution (LX 16M, Lavision), a trigger unit and a multi-core PC running Davis 8 PIV software. The camera is equipped with a 105 mm to record a field of view of 40×14 mm (spatial resolution of 8.1 μm). The flow is seeded with droplets of dielectric oil (Ondina 919). The velocity fields are obtained by a cross correlation algorithm with adaptive multi-pass (resolution of one vector every 65 μm). The time-averaged velocity field is obtained by recording 6000 images for each configuration.

Figure 1. Schematic illustration of the surface DBD plasma actuator.

Figure 2. Illustration of the local flow produced by a surface plasma actuator operated at different voltages

3. Results and Discussion

3.1. Estimation of the EHD body force
The mean flow produced by the discharge obeys the incompressible 2D flow momentum equations. At each data point of the measured velocity field, the mean EHD volume force \( f \) can be expressed as:

\[
\mathbf{F} - \mathbf{V}_p = \rho \mathbf{U} \cdot \nabla \mathbf{U} - \mu \nabla^2 \mathbf{U}
\]  

where \( p \) is the pressure field, \( \mathbf{U} \) is the mean velocity field while \( \rho \) and \( \mu \) are the gas density and gas dynamic viscosity, respectively. The right hand side of equation (1) can be evaluated at each measurement location from the velocity measurements as the two cases shown in Figure 2. It is considered here that the pressure contribution is minor regarding the volume force produced by the discharge. Subsequently, the left hand side of equation (1) approximates the EHD volume force. A fortran code (F90) is developed to discretize and then solve equation (1) by finite difference method with second order spatial schemes.

The distribution of the volume force is illustrated in figure 3 for an applied voltage of 20 kV and AC frequency of 1000 Hz. The force is high on the edge of the top electrode, but it also spreads above the dielectric surface. The total volume force is mainly due to \( f_z \), the influence of \( f_x \) being restricted to the region above the top electrode. Here, the total force propagates in the first 7-10 mm where the density of the charged species under the influence of the electric field is high.

The EHD body force can be computed as the integral surface of the volume force. The definition of the integration surface needs a careful attention in order to limit the contribution of background noise. Here, the body force is evaluated by integrating the volume force over a control surface that starts from a fixed point located 3.5 mm upstream of the top electrode edge and that propagates gradually in the x and y directions following a rectangular surface (n×2n where n increases by steps of 65 μm). A
convergence plot such as the one presented in figure 4 is finally obtained. The force magnitude for which a further increase in the spatial domain does not change the EHD force by more than 1% is retained as final converged value of the EHD body force.

![Figure 3](image1.png) ![Figure 4](image2.png)

**Figure 3.** Spatial distribution of the horizontal (a) and vertical (b) components of the evaluated EHD volume force. Force in N/m³.

**Figure 4.** Illustration of the control surface evolution and typical convergence plot for the evaluation of the mean EHD body force.

3.2. Influence of the voltage amplitude and AC frequency

Some illustrations of the volume mean force distribution are proposed in figure 5. These plots indicate an increase in space and in amplitude of the volume force when higher voltage amplitude and frequency are applied. By increasing the voltage and the AC frequency, the density of the ionized species is promoted. This is accompanied by an increase of the produced force in space and amplitude as shown here. However, the topology of the volume force is not dependent on the amplitude and the frequency of the applied high voltage but the body force distribution seems to enlarge by an homothetic manner.

In order to fully validate the evaluation of the EHD body force by experimental measurements coupled to numerical approaches, the results of the present investigation are compared to those reported in [6] where the mean EHD body force was experimentally measured by a precision force balance. In most of the cases, the EHD body force is slightly overestimated when it is evaluated by velocity derivation probably because force balance measurements suffers for parasitic drag penalizing the thrust produced by the discharge. However, the evolution of the EHD body force for an increasing voltage, frequency or consumed power are in agreement with the ones obtained by a precision balance (figure 6). The EHD body force increase as a power of 2 with the applied voltage amplitude while the increase is linear for an increasing AC frequency [1] [2]. Here the saturation regime is not reached, and then the produced EHD body force varies linearly with the electrical consumed power.

4. Conclusion

The spatial distribution of the volume force as well as the EHD body force have been evaluated from the velocity fields produced by a surface DBD plasma actuator. Measurements for different voltage amplitudes and frequencies have been conducted. The evaluation method has been validated by comparison with direct experimental measurements by a force balance. The present study gives useful information regarding the spatial distribution of the mean EHD force and the obtained spatial distribution of the EHD volume force can be used in computational fluid dynamic codes as a realistic source that models plasma actuator.
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Figure 5. Influence on the EHD volume force of the voltage amplitude while AC frequency is 1000 Hz (a) and applied AC frequency while the voltage amplitude is 20 kV (b). Force expressed in N/m³.

Figure 6. Influence on the EHD body force of the voltage amplitude, AC frequency and consumed electrical power.

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