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Theoretical Study Based on the Numerical Simulation of the Steady State Behavior of a Corona Discharge in Pure Air

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Abstract: Plasmas generated by electrical discharges at atmospheric pressure have lately been tested as new tools for acting on flows. Experimental results confirm that this type of electroaerodynamic triggers can effectively contribute to the modification of moving fluid properties. The operating modes of electrical discharges as well as the phenomena which contribute to such a result are poorly understood though. Large discrepancies are seen according to the type of discharge which is used, suggesting that the mechanisms of action are not yet identified. The present research is a theoretical study based on the numerical simulation of the steady state behavior of a corona discharge in pure air at atmospheric pressure. The mathematical model is composed of the laminar flow equations (mass and momentum conservation) and the Poisson equation for the computation of the electrical potential. The influence of the electrical field on the flow is taken into account by the addition of the electrical force term in the Navier Stokes equations. The validation of the model is based on experimental observations. The variation of dynamic, geometrical and electrical parameters is also studied. Fluent 6.3 software is used to perform numerical computations.

Key words: Electro hydrodynamics, corona discharge, flow control, EHD, plasma

INTRODUCTION

Aerodynamic movements induced by of-equilibrium discharges at atmospheric pressure can be used for active control of applied flows (aeronautics, automotive…), particularly in near wall regions.

Despite the fact that this phenomenon is known since a long time, it has become a subject of great interest only in the last decade (Moreau, 2007). This is due to its potential application to the applied flows optimization and the subsequent possibilities of energy consumption reduction. Easily observable, the phenomenon is not fully understood though. This is particularly true since it depends on important number of parameters and on the different discharge types (Moreau, 2007; Boeuf and Pitchford, 2005; Pons *et al*., 2005).

Experimental study of such systems is not simple either. Plasmas generated by off-equilibrium electrical discharges at atmospheric pressure are often unsteady, weakly luminous and of small dimensions (Dong *et al*., 2006). Numerical approach can therefore, be of great help in bringing about new elements for physical understanding of the subject.

The goal of the investigations which are propose is to better understand the role of the plasma generated by the discharge and to analyze its interaction with the flow depending on the velocity of the latter and on the discharge conditions. This should allow the optimization of the ionized medium properties and to efficiently increase the effects of the induced modifications on the flow depending on its characteristics.

This technique of active control is still the subject of ongoing research but offers numerous possibilities of application. The present study is a contribution to these efforts and aims at simulating the behavior of an experimentally observed flow with a simple model and to obtain information on the order of magnitude of the forces which are exerted on the flow by the discharge.

MODELLING

As a preliminary step, it is attempted to reproduce the observations made on the experimental set up shown in Fig. 1 with a simple model. The set up is made of a flat plate with a rounded leading edge which is equipped with two wire electrodes on its top surface. The two

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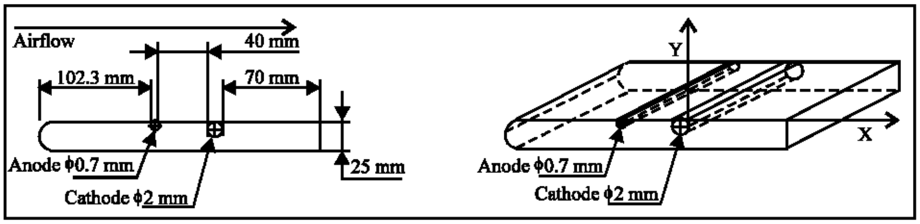

Fig. 1: Schematic view of experimental setup

electrodes are connected to a high voltage power supply that allows the generation of a crown discharge on the top surface of the plate. The plate itself is placed in air flow. A 2D unstructured grid computational domain with 398002 grid points is associated to the set up.

A number of simplifications and reasonable assumptions are necessary in order to model the observed process. This is particularly valid since the goal is not to model ions and molecules interactions at the molecular scale but rather to show the global effect of an electrical field on the fluid flow.

The model is based on the Navier Stokes equations for a laminar air flow which include a term for the electrical forces caused by an electrical field. The electrical field itself derives from an electrical potential ϕ which is computed through the resolution of Poisson's equation. The set of equations which describe the electro-hydrodynamic flow is as follows:

- Poisson's equation for the electrical potential ϕ:

$$\nabla^2 \phi = -\frac{\rho_C}{\varepsilon_0} \quad (1)$$

Where ρ_C is the charge density and ε_0 is the permittivity (dielectric constant) in vacuum.

- The electrical field E is given by:

$$E = -\nabla\phi \quad (2)$$

- The current density J is given by:

$$J = -D\nabla\rho_C + \rho_C\left(\mu_E E + U\right) \quad (3)$$

Where μ_E is the mobility of air ions in an electrical field, U is the air flow velocity and D the diffusivity of ions.

The equation of charge conservation (electrical neutrality) is added to these equations:

- The continuity equation for current density is given by:

$$\nabla \cdot J = 0 \quad (4)$$

The air flow is described by the Navier Stokes and the continuity equations:

- Navier-Stokes equations for a laminar incompressible flow under electrical forces:

$$\nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \alpha\vec{E} \quad (5)$$

- Continuity equation:

$$\nabla \cdot (\rho\vec{v}) = 0 \quad (6)$$

Where, ρ is the air density, v is the air velocity, p is the pressure, τ is the stress tensor and α is an adjustable constant.

Substituting the expression of the current density given by (3) in Eq. 4 and taking into account the expression of the electrical potential (2) and the continuity Eq. 6, the transport equation for the electrical charge can be given as following:

$$\nabla \cdot \left(-D\nabla\rho_C - \mu_E\rho_C\nabla\phi\right) + U \cdot \nabla\rho_C = 0 \quad (7)$$

In general, the conduction term is dominant in Eq. (3) compared to the convection and diffusion terms in the case of an air flow in a crown discharge. Therefore, these terms are often neglected in the numerical simulation literature. As a first approximation, the first and the third terms in Eq. 7 are neglected. This leads to the following simplified equation:

$$\nabla.\left(\mu_E \nabla\phi\, \rho_C\right) = 0 \quad (8)$$

Thus, the electro-hydrodynamic flow is described by the set of Eq. 1, 5, 6 and 8 along with the associated boundary conditions.

Most of the numerical studies have been performed for the optimization of electrostatic precipitators. The flow velocities for such cases are of the order of 1-5 m s^{-1}. The drift velocity of ions is approximately in the range of 100-150 m s^{-1}. The assumption of neglecting the convective term in the equation of charge conservation can be justified in such cases due to the difference in the order of magnitude of the two velocities. In the case of the present study, flow visualization does not allow observing any effect of the flow on the discharge for flow velocities of 0.5-2 m s^{-1}. Neglecting the convective term allows then to decouple the discharge equation from the flow equations and the electrostatic forces can be evaluated independently from the flow. This assumption is admitted in most of the publications and notably those of Soldati (1998). In the case of coupled approaches, drastic assumptions are made in order to simplify the flow equations.

NUMERICAL COMPUTATION

A two dimensional laminar flow on a flat plate (Fig. 2) with consideration of electrical forces is computed. The computational domain is divided in two zones. The zone between the electrodes is modeled as a parallelogram whose leading edge favors the flow (Fig. 3). This zone is 4 cm long, with a variable height h. Several values of h are considered in order to study its effect on the flow. This zone is called domain 2, the rest of the computational domain is called domain 1.

Taking into account all the simplifying assumptions, notably that of a constant charge density, leads to the following mathematical model for domain 2 (Fig. 3):

$$\begin{aligned} &\nabla \cdot (\rho \vec{v}) = 0 \\ &\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \alpha \vec{E} \\ &\Delta \phi = 0 \\ &\vec{E} = -\nabla \phi \end{aligned} \tag{9}$$

The mathematical model for domain 1 is given by the following equations:

$$\begin{aligned} &\nabla \cdot (\rho \vec{v}) = 0 \\ &\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) \\ &\Delta \phi = 0 \end{aligned} \tag{10}$$

Computations are performed using the commercial software Fluent® version 6.3. There is no integrated standard function allowing for the solution of the electrical equations in Fluent. It is possible, though, to include a user defined function which can be dynamically loaded with Fluent in order to take into account for electrical forces.

The generalized form of the transport equation for an arbitrary scalar quantity Φ_j that can be solved by Fluent is given by:

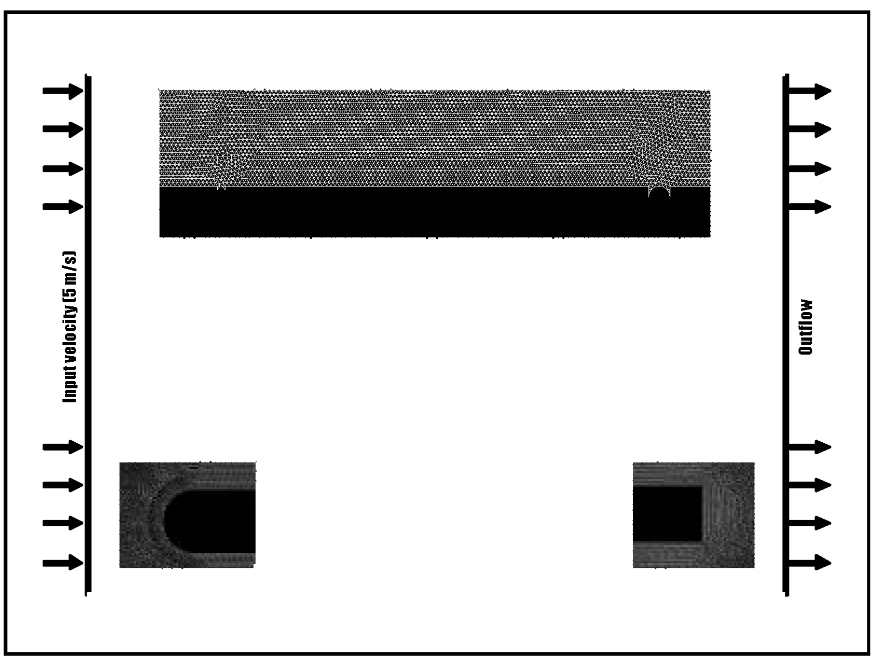

Fig. 2: Computational domain and boundary conditions

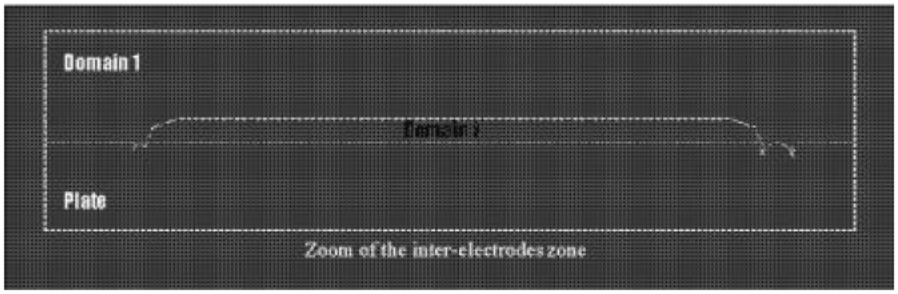

Fig. 3: Discharge zone

$$\frac{\partial \rho \Phi_j}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho \overline{u_i}\,\Phi_j - \Gamma_j \frac{\partial \Phi_j}{\partial x_i}\right) = S_{\Phi_j};\, j = 1,2,........N \qquad (11)$$

Where Γ_j and $S_{\Phi j}$ are the diffusion coefficient and the source term provided by the user for each equation.

In order to transform Eq. (11) in the form of Eq. (12) the variables are defined as follows:

$$\Phi_1 = \phi;\ \Gamma_1 = \sigma;\ S_1 = 0;\ u_1 = 0 \qquad (12)$$

In addition, the transport equation must be solved in its equilibrium state form.

The effect of the electrical field on the flow are taken into account through the addition of the electrical force term in the Navier-Stokes equations: $\vec{F}_e = \alpha\,\vec{E}$, α being a constant which must be determined.

The approach which is considered in the present study, although simplified, allows for the computation of values for the constant α which can be compared to that obtained with more sophisticated models taking into account the very nature of the discharges. These values are found to be proportional to the electrically charged species density and to their mobility. The present approach does not effectively consider the presence of a discharge in the flow since it does not explicitly account for the presence of electrically charged in the computation of the electrical field. The effects of the entrance velocity as well as that of the voltage at the electrodes are also studied. The boundary conditions are the no slip condition at the plate surface, a known free stream velocity U_0 and a tangent velocity at the upper limit of the domain (Fig. 2).

RESULTS

Figure 4 shows a fairly good agreement between experimental and numerical results for air flow velocity profiles. Without a discharge, the profile is that of a typical laminar boundary layer. With a discharge, the profile undergoes acceleration in the parietal zone between the electrodes. This indicates that the introduction of the electrical forces term in the flow equations correctly approaches the experimental observations. Figure 4a shows a shift between experimental and numerical results. This discrepancy is much smaller in the case with discharge (Fig. 4b). This

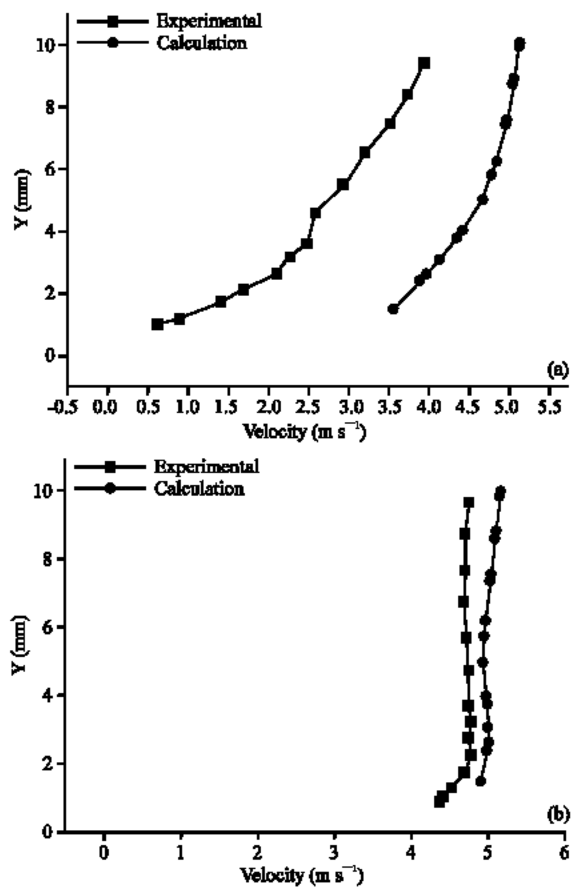

Fig. 4: Velocity profile at 1 cm downstream of the cathode. (a) without discharge; (b) with discharge [U_0 = 5 m s^{-1}, ϕ_{anode} = +22 kV, $\phi_{cathode}$= - 10 kV, $\alpha = 0.5*10^{-3}$]

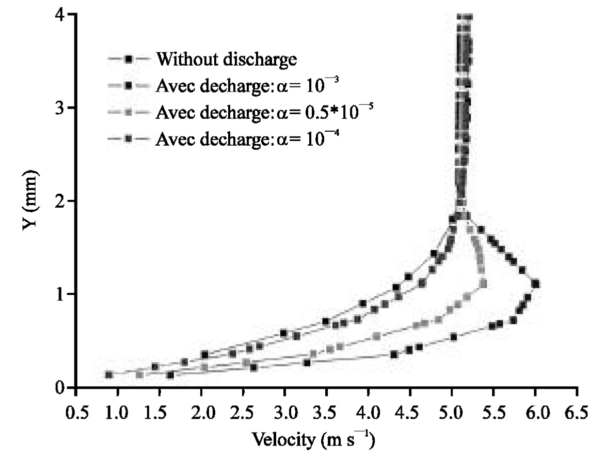

Fig. 5: Flow velocity profile at 1cm downstream of the cathode for different values of α ($U_0 = 5$ m s^{-1})

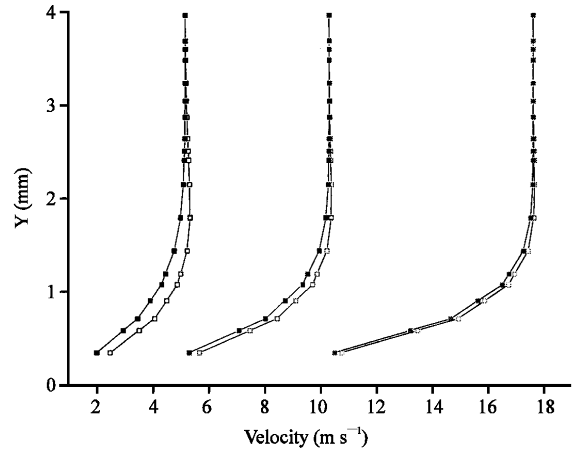

Fig. 7: Axial velocity profile at 1cm downstream of the cathode without discharge (-□-) and with discharge (-■-) for $U_0 = 5$, 10 and 17 m s^{-1} and $\alpha = 0.5*10^{-3}$

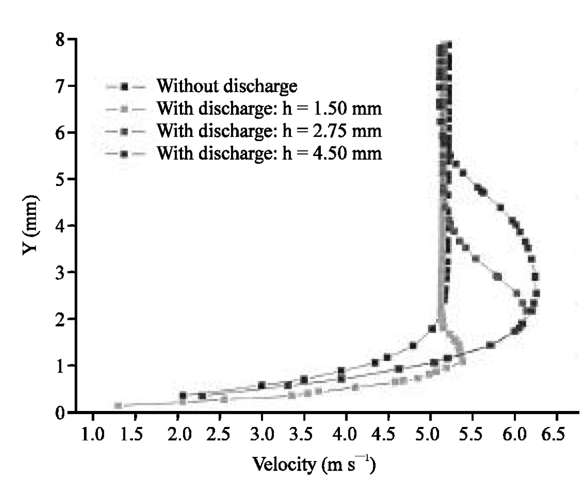

Fig. 6: Axial velocity profile at 1cm downstream of the cathode for different values of h ($U_0 = 5$ m s^{-1} and $\alpha = 0.5*10^{-3}$)

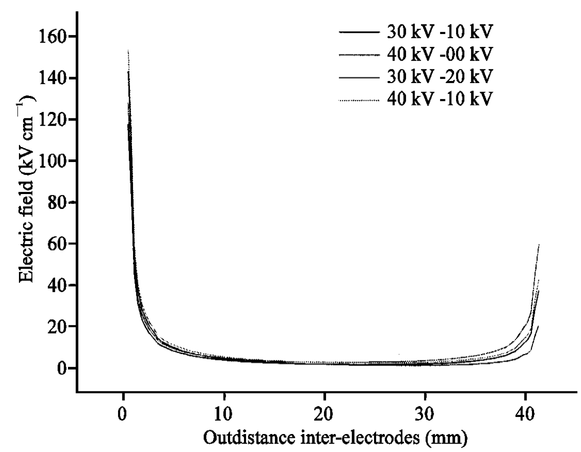

Fig. 8: Variation of the electrical field in the inter electrode region for several discharge voltages

can be explained by the fact that experimental measurements are performed with a Pitot tube which captivates the axial velocity. In the case of the presence of a discharge, it is this component of the velocity which is accelerated and becomes dominant, leading to a better agreement between experimental and numerical results in this case.

Moreau *et al*. (2005) has shown the difficulty of generating a stable discharge between two surface electrodes immersed in an air flow at atmospheric pressure as well as the complex nature of the ionic wind phenomenon. An important number of parameters affect the electrical discharge. The voltage, the electrodes shape, their positioning on or in a dielectric, air humidity or the presence of a flow are parameters that act on the very type of discharge which is observed. Modeling all these parameters becomes a formidable task. A parametric study of the effect of part of these parameters can contribute to this goal.

Effect of the value of α: Figure 5 shows the flow velocity profiles for different values of α. The constant α is directly proportional to the electrical charge i.e. to the number of electrical charge carriers (electrically charged species bulk density). This explains the increasing difference with the no charge case as α increases owing to an increased effect of ionic wind.

Effect of the height of domain 2: Figure 6 shows the flow velocity profiles at 1 cm downstream of the cathode

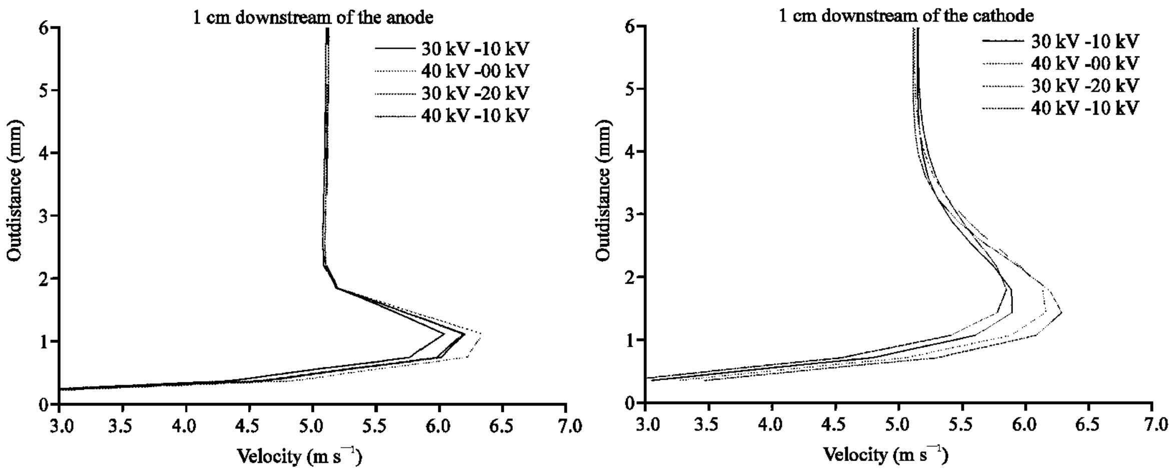

Fig. 9: Flow velocity profile for several discharge voltages (U_0 = 5 m s^{-1} and $\alpha = 0.5*10^{-3}$)

without discharge and with discharge for different values of h. It shows that the viscous effects remain dominant in the near wall region in all cases. The height h representing the application domain of the discharge, the figure also shows that we must go to values of h greater then 1,5 mm in order to extend the effect of the discharge beyond the viscous zone and make it observable. For such values of h, an acceleration zone extending approximately to a distance h from the wall is established at the boundary layer edge. In this zone, the effect of ionic wind is predominant in the discharge region before going back to the free stream value of the velocity. These results confirms the possibility of modelling the ionic win phenomenon in a DC discharge as a drift of electrically charged species created in the active zone of the computational domain.

Effect of free stream velocity u_0: Figure 7 shows the flow velocity profiles at 1 cm downstream of the cathode without discharge and with discharge for a free stream velocity of 5, 10 and 17m s^{-1}. We can see that the effect of the discharge decreases as the free stream velocity increases due to increasingly dominant effect of inertial forces compared to electrical forces in the boundary layer edge zone. The same observation is reported by Moreau (2007).

Effect of the voltage at the electrodes: Figure 8 shows the variation of the electrical field in the inter electrode region (domain 2) for several discharge voltages.

Peak values correspond to the anode and cathode positions and vary with the applied voltage. In other positions, no noticeable difference can be observed. Figure 9 shows the flow velocity profile for the same voltages. The results show that flow acceleration can be favoured in the inter electrode zone or more down stream rather by changing the distribution of the electrical energy.

CONCLUSION

The goal of the present research is to study the electro-hydrodynamic effects caused by plasma on a flow. These effects offer the possibility of using electrical discharges as triggers for active boundary layer control as revealed by an experimental study. This experiment is modeled through a simple 2D laminar hydrodynamic model where the effect of electrical forces is taken into account allowing for a study of the interaction between the plasma generated by the discharge and the flow. The simplifying assumptions which are considered allow for the decoupling of the electrical field computations from the flow computations. The electrical forces term depends on a constant α representing electrically charged species bulk density. Comparison of the numerical results with experimental measurements shows that a good agreement is obtained for a value of α of the order of 10^9 cm^{-3}.

The results show that the model does not allow for an exact quantification of the effects of an electrical discharge on a flow but does give a good description of such effects, regarding the order of magnitude and the position, as well as the trends caused by the change of different controlling parameters. This descriptive nature of the present approach can be considered as satisfactory in predicting trends when parameters such as the size of the discharge zone, applied voltage or free stream velocity are varied but cannot give an exact quantification or be extended to different geometrical configurations. A more comprehensive model is then needed to describe the discharge; the hydrodynamic model can also be improved to take into account the parietal nature of the flow.

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