Experimental and Numerical Analysis of the Flow Induced by Electric Injection in Blade-Plane Geometry

M. Daaboul

Laboratoire d'Etudes Aérodynamiques
Boulevard Pierre et Marie Curie, BP 30179,
86962 Futuroscope-Chasseneuil, France

Ch Louste

Laboratoire d'Etudes Aérodynamiques
Boulevard Pierre et Marie Curie, BP 30179,
86962 Futuroscope-Chasseneuil, France

Ph. Traoré

Laboratoire d'Etudes Aérodynamiques
Boulevard Pierre et Marie Curie, BP 30179,
86962 Futuroscope-Chasseneuil, France

Abstract— **This paper deals with two-dimensional electro-hydrodynamic plumes that arise when a sharp metallic contours submerged in non conducting liquids supports high electrostatic potential resulting in charge injection. Experiments by PIV measurements and numerical simulations have been conducted in order to confront the both approaches. A very good agreement has been found through velocity profiles and velocity field which testifies the relevance of our numerical model. Some captions of the temporal evolution of the charge density which is not accessible from experiment is given thanks to the numerical simulation.**

Index Terms— **Electrohydrodynamic plumes, PIV experiment, numerical simulation, charge injection**

Manuscript received May 18, 2009.

Michel Daaboul is with the Electrofluidodynamic Unit at the Laboratory of Aerodynamical Studies and a PhD student at the University of Poitiers, France (email: michel.daaboul@lea.univ-poitiers.fr).

Christophe Louste is with the Electrofluidodynamic Unit at the Laboratory of Aerodynamical Studies and an associate professor at the University of Poitiers, France (email: christophe.louste@lea.univ-poitiers.fr).

Philippe Traoré is with the Electrofluidodynamic Unit at the Laboratory of Aerodynamical Studies and an associate professor at the University of Poitiers, France (corresponding author; phone: +33549496941; fax: +33549496968; email: philippe.traore@lea.univ-poitiers.fr).

1. INTRODUCTION

PERFORMANCE of industrial systems using liquids could be improved by using flow control devices. Electrohydrodynamic (EHD) devices could provide an efficient solution to control a liquid flow. In fact EHD apparatus have many advantages such as: low power consumption, short response time, and good reliability.

Two main phenomena can be used for that purpose. The first one is the conduction phenomenon [1-3]. It is currently proposed in electrostatics pumping and devices using a thin film of liquid as in cooling applications [4]. The second one, which is studied in this article, is the injection of ions from a wire or a blade in a dielectric liquid under the influence of an applied electric field [5,6]. In such condition, convective motion in form of a jet arises. These particular flows have been referred to as EHD plumes and are present in most of industrial devices exploiting electric forces.

In previous works it has been shown that a blade-plane geometry device generates an impinging jet which can reach a velocity of 1 m/s [7,8].

The adaptation of the Particle Image Velocimetry (PIV) technique to electrohydrodynamic flows [9] has permitted to obtain large velocity maps of jets and Dielectric Barrier Injection flows [10-11]. Characteristics of such flows have been studied as well as in transient or in stationary regimes [9,11]. Although the last improvements of the PIV measurement technique some data remain non-measurable.

The analogy of EHD plumes with thermal ones has conducted many authors [12, 13, 14, 15] to analyze EHD plumes by the mean of self-similar analysis or integral model. Under some simplifying assumptions the governing EHD equations are made tractable and the mathematical model is closed to the one of thermal plumes for $Pr \to \infty$ (where $Pr = \nu / k$ is the Prandtl number ν is the kinematic viscosity of the fluid and k its thermal diffusivity).

Another way to obtain information on data which are not accessible experimentally, for instance the electric charge density in the device as well as the electric field at each point of space, is to require to numerical simulations.

Several attempts to model numerically the development of EHD flows and especially electro-convective flows have been made in the past. But most of the authors started their computations from an assumed velocity field and not from a real resolution of the Navier-Stokes equations [16]. In [17] the appropriate electrodynamics equations coupled with the full Navier-Stokes equations are solved numerically using an efficient finite volume method to study the flow structure of EDH plumes.

In this paper, detailed comparisons between experimental results obtained from PIV measurements and numerical predictions are presented in the case of an EHD plumes induced par charge injection from a blade.

Velocity profiles and vector fields are correlated and the charge field in the device is extracted from the numerical results.

2. Experimental Apparatus and Techniques

A schematic diagram of the system is shown in Fig. 1. The test cell is composed of a 30 cm × 15 cm × 15 cm glass aquarium filled with the dielectric liquid. The electrical device is totally immersed in the liquid and fixed in a confined zone of 10 cm × 8 cm × 6 cm with flat glass surfaces in order to be able to realize PIV measurements without Laser reflections. An 8 cm long and 0.5 mm thick stainless steel blade is placed in front of a duralumin flat plane electrode. The distance *d* between the blade tip and the counter-electrode is set to 20 mm and the radius of curvature of the blade tip is about 7 ± 2 Mm.

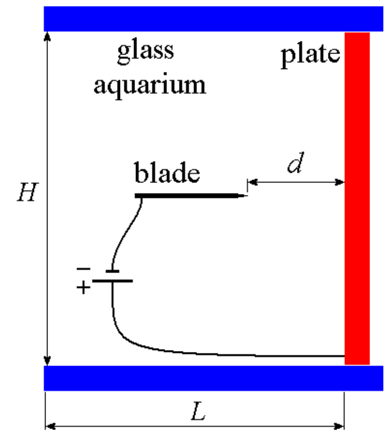


Figure 1. Experimental apparatus

A variable difference of potential (0–60 kV) is supplied by a Spellman SL1200 DC power supply. A Meterman 37XR multimeter (±0.1 V – ±0.01 mA) was used to measure the voltage across a shunt resistance Rs = 99.3 kΩ.

3. Numerical Method

The problem is formulated considering the usual hypotheses of a Newtonian and incompressible fluid of dynamic viscosity μ and density ρ. The Navier-Stokes equations (mass and momentum conservation) are coupled with EHD equations and give rise to the following partial differential equations system.

$$\nabla . \vec{U} = 0 \quad (1)$$

$$\rho\left(\frac{\partial \vec{U}}{\partial t} + (\vec{U}.\nabla)\vec{U}\right) = -\nabla P + \mu \Delta \vec{U} + q\vec{E} \quad (2)$$

$$\frac{\partial q}{\partial t} + \nabla . \left(q(\vec{U} + K\vec{E})\right) = 0 \quad (3)$$

$$\Delta V = -\frac{q}{\varepsilon} \quad (4)$$

$$\vec{E} = -\nabla V \quad (5)$$

$\vec{U}$ is the fluid velocity, P the pressure, q the charge density, V the potential and $\vec{E}$ the electric field. K is the ionic mobility and ε is the dielectric constant. We have depicted the computational domain and the boundary conditions in figure 2. q_0 and V_0 are respectively the charge density and potential applied on the blade.

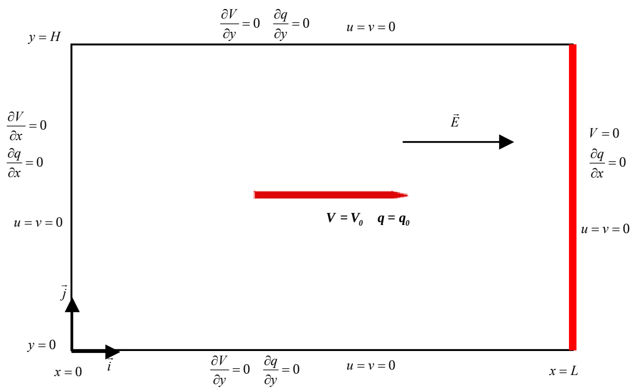


Figure 2. Computational domain and boundary conditions

The numerical procedure is based on the integration of the whole system of equations by a finite volume method using a staggered grid and a semi-implicit second order in time a space accurate schemes [18]. All details of the present numerical method can be found in [17].

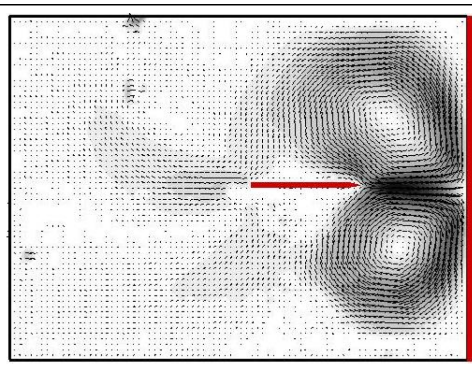
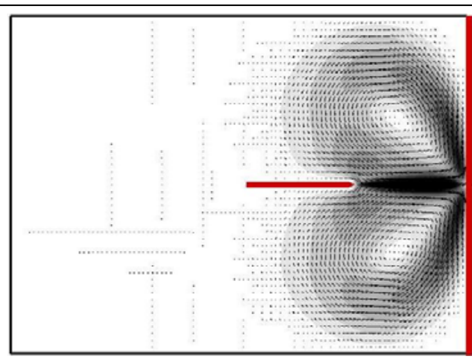
	-5kV
experiment	
numeric	

Figure 3. Snapshots of stationary velocity field for an applied voltage of -5kV.

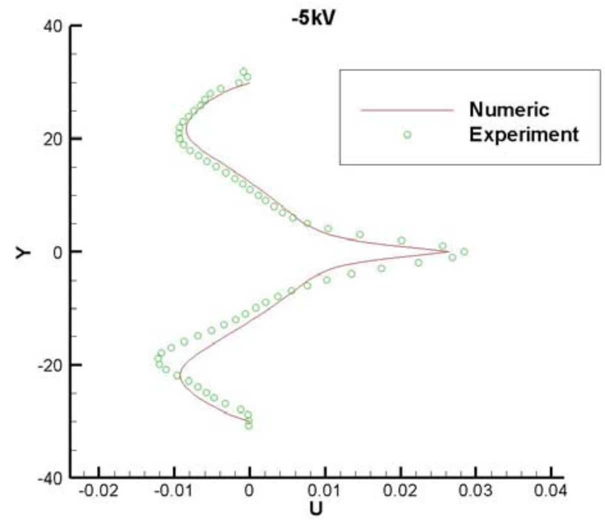


Figure 4. Comparisons of the longitudinal velocity profiles in the x middle plane field for the same applied voltage.

4. Results and Discussion

We are interested in the stationary laminar regime obtained for an applied voltage of 5kV. The structure of the flow is made of two stationary main vortices on either side of the plumes which are easily identified on the figure 3. The comparison between experimental and numerical results shows a very good agreement.

In figure 4 we have plotted the longitudinal velocity field in x middle plane for the both case experimental and numeric. Here again the curves depicted for this value of the applied voltage match quietly good. The little discrepancy of the profiles around y=-20mm must be ascribed to a slight dissymmetry of the experimental apparatus that we noticed at the end of our campaign of measurements.

One of the most interesting features of numerical simulation is that it allows computing some quantities which are note available by measurements. The charge density is a good example of such inaccessible variable by measurement means.

In figure 5 we have depicted the time evolution of the charge density in the computational domain. It is interesting to notice that the charge density is confined in a thin layer which arises from the blade until it reaches the counter electrode. The iso-values of this charge density are quite low in accordance with the relatively moderate applied voltage.

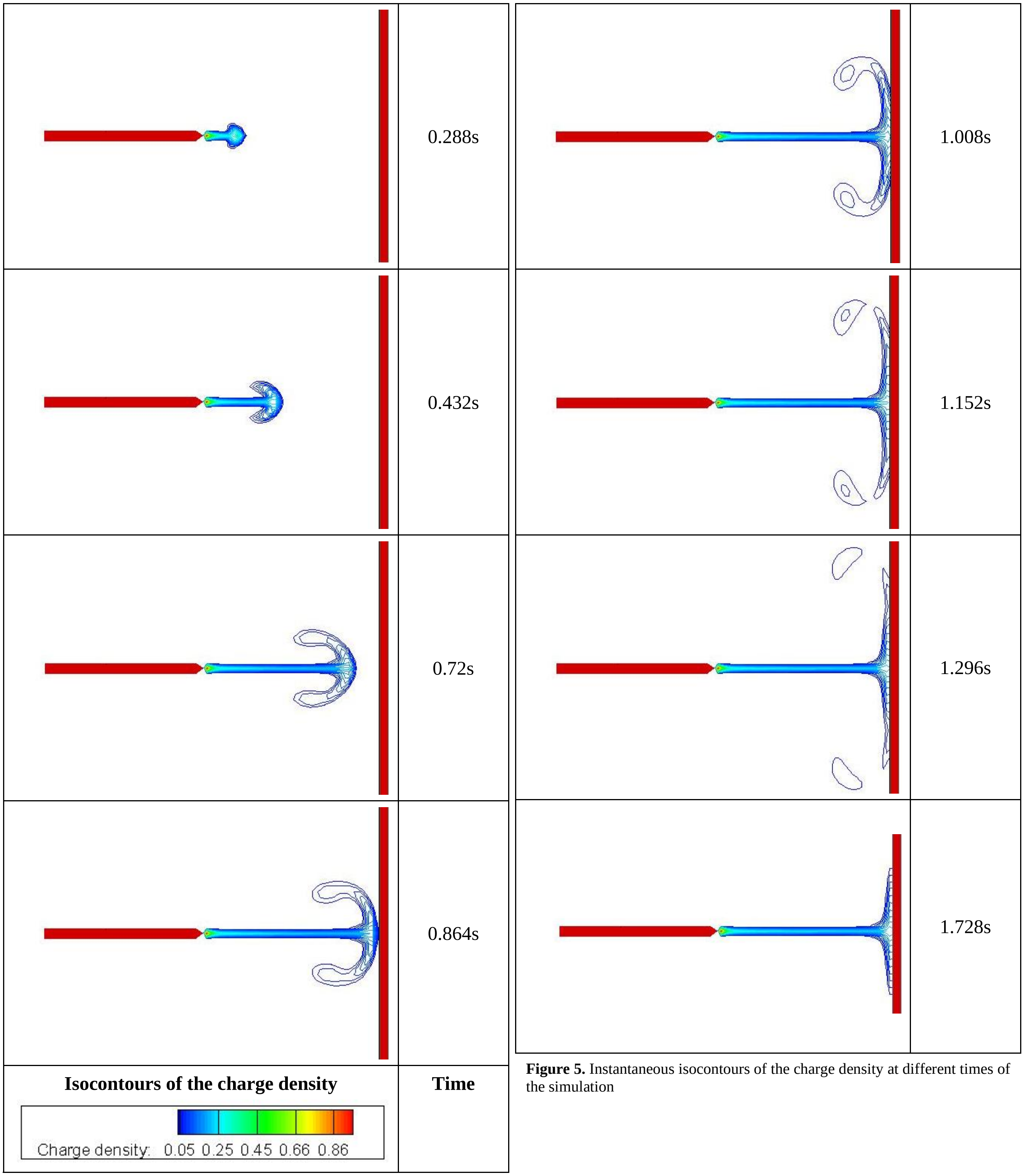


Figure 5. Instantaneous isocontours of the charge density at different times of the simulation

5. CONCLUSION

Experimental measurements and numerical simulations have been conducted to analyze EHD plumes arising from ions injection between a blade and a plane in a dielectric liquid under the influence of an applied voltage. Comparisons between longitudinal velocity profile in the x middle plane, as well as the velocity field for different applied voltage show a perfect agreement which testify of the validity of our numerical model. The real effect of the PIV particles of the flow through their charge catching must be more precisely investigated and determined.

REFERENCES

[1] P. Atten and J. Seyed-Yagoobi, “Electrohydrodynamically induced dielectric liquid flow through pure conduction in point/plane geometry”, IEEE Trans. Dielectr. Electr. Insul, Vol. 10, pp. 27-36, 2003.

[2] J. Seyed-Yagoobi, “Electrohydrodynamic pumping of dielectric liquids”, J. Electrostatics, Vol. 63, pp. 861-869, 2005.

[3] Y. Feng and J. Seyed-Yagoobi, “Understanding of electrohydrodynamic conduction pumping phenomenon”, Phys. Fluids, Vol. 16, pp. 2432-2441, 2004

[4] M. A. W. Siddiqui and J. Seyed-Yagoobi, “Experimental study of pumping of liquid film with electric conduction phenomenon”, IEEE Trans. Indust. Appl., Vol. 45, Issue 1, pp. 3-9, 2009.

[5] P. Atten and A. Castellanos, “Injection induced electrohydrodynamic flows”, Handbook of Electrostatic Processes, Ed. New York: Dekker, pp. 121-146, 1985.

[6] F. J. Huigera, "Electrohydrodynamic flow of a dielectric liquid around a blade electrode", *Phys. Fluids* , Vol 12 (11), 2000, pp. 2732-2742

[7] P. Baudel, C. Louste and H. Romat, “LDV Measurements of Dielectric Liquid Motion Induced by Charge Injection in a Needle to Plane Configuration,” International symposium on Electrohydrodynamics ISEHD/IEEE, pp.149-152, December 2006, Argentina.

[8] M. Daaboul, C. Louste, and H. Romat, “Transient velocity induced by electric injection in blade-plane geometry”, J. Electrostatics, Vol. 67, pp. 359–364, 2009.

[9] M. Daaboul, C. Louste, and H. Romat, “PIV measurements on charged plumes – Influence of SiO2 seeding particles on the electrical behavior”, IEEE Trans. Dielectr. Electr. Insul., Vol. 16, Issue 2, pp. 335-342, 2009.

[10] L. Priol, C. Louste and H. Romat, “Experimental Study of a Dielectric Barrier Injection in Diesel Oil. Measurements of Liquid Velocity by LDV,” ESA/IEEE joint conference of electrostatics, pp.95-102, June 2006.

[11] C. Louste, M. Daaboul, H. Romat, “A study of vortex shedding induced by dielectric barrier injection”, J. Electrostatics, Vol. 67, pp. 348–353, 2009.

[12] P.A. Vazquez, A.T.Perez, A. Castellanos, P. Atten, "Dynamics of electrohydrodynamic laminar plumes: Scaling analysis and integral model", Phys. Fluids , Vol 12 (11), 2000, pp. 2809-2818.

[13] P.A. Vazquez, A.T.Perez, A. Castellanos, "Thermal and electrohydrodynamic plumes. A comparative study", *Phys. Fluids , Vol 8 (8), 1996, pp. 2091-2096.*

[14] P.A. Vazquez, A. Castellanos, A.T.Perez, R. Chicon, "Numerical modelling of EHD flows due to injectors of finite size", *Conference on Electrical Insulation and Dielectric Phenomena, 2000, pp. 101-104.*

[15] P.A. Vazquez, A.T.Perez, A. Castellanos, "Steady and Transcient Electrohydrodynamic Plumes ", *Conference on Electrical Insulation and Dielectric Phenomena, 1996 IEEE Annual Report*.

[16] R.Chicon., A. Castellanos, E. Martin, "Numerical modelling of Coulomb-driven convection in insulating liquids", *J Fluid Mechanics*, 344, 43-66, 1997.

[17] A.T.Perez, P.Traoré, D. Koulova-Nenova, H. Romat. "Numerical study of an ElectroHydrodynamic plume between a blade injector and a flat plate", 16th IEEE International Conference on Dielectric Liquids, ICDL2008, France.

[18] Patankar, "Numerical Heat Transfer and Fluid Flow", *Stockholm, Washington, DC, 1980*.

Michel Daaboul was born in Lebanon in 1982. He received the Engineering Diploma from the Lebanese University in 2005 and the M.Sc. degree from the University of Poitiers, France in 2006. He is preparing for the Ph.D. degree at the University of Poitiers, France. He is mainly working on electrohydrodynamic flows of dielectric liquids at the Laboratoire d’Etudes Aerodynamiques LEA, Poitiers, France.

Christophe Louste was born in France in 1971. He received the Ph.D. degree from the University of Montpellier II, France in 1998. He is working as an associate professor at the University of Poitiers, France. He is working on electrohydrodynamic flows of dielectric liquids at the Laboratoire d’Etudes Aerodynamiques LEA, Poitiers, France.

Philippe Traoré was born in Grenoble (France) in September 1963. He was graduated from the Superior National Engineering School of Aeronautical Constructions of Toulouse (France) in 1987 and received, from the University of Toulouse, his PhD degree in fluid mechanics in 1996. He holds an associate professor position in the mechanical department of the University of Poitiers (France) where he teaches fluid mechanics and scientific computation. His research interests, at the Laboratoire d’Etudes Aerodynamiques LEA, Poitiers, focus on numerical simulations in fluid mechanics, two-phase flows and granular flows as well as on electrohydrodynamic flows of liquids subjected to charge injection.