Electroconvective cavity flows produced by a cylinder/plane electrode geometry

S. Modh [(1)], C. Gouriou[(1)], R. Sosa[(2)], M.Daaboul[(3)], P. Traore[(1)], C. Louste[(1)]
(1) P' institute, electrohydrodynamic Team
CNRS - Université de Poitiers - ISAE-ENSMA
(2) Laboratorio de Fluidodinamica
University of Buenos Aires Conicet
(3) Dept. of Mechanical Engineering
University of Balamand
phone: (+33) 549-496-931
e-mail: christophe.louste@univ-poitiers.fr

***Abstract*— The presented work is an experimental study on electroconvective cavity flows produced by a cylinder- plane electrode geometry. Flows are recorded by the used of the well-known particle image velocimetry technique. The main objective of this work is to develop flow control methods in order to enhance the heat transfer and the mixing efficiency in fluidic and microfluidic systems. In this study, the electrohydrodynamic flow is obtained by applying a dc voltage to a set of electrodes immersed in a working liquid. It is shown that the produced velocity fields strongly depend on apply voltage. An analysis of the velocity field is then realized to display electric forces. The current is also measured with an oscilloscope using a shunt resistor connected to the ground electrode. Introduction**

Theoretically, three electric volume forces may be created by applying a high electric on a dielectric liquid [1]. The most famous one is the Coulomb force which acting on free ions. The two others are the electrostictive force and the dielectrophoretic force. These two body forces arise from the interaction of an electric field with either induced or permanent dipoles.

In practice, the electrostictive force is weak in incompressible liquids and the dielectrophoretic force is produced only when a permittivity gradient exist. Moreover, the Coulomb forces is stronger than the two others. Then, in most of electrohydrodynamic applications, the Coulomb force is used to set liquid in motion. In many studies this electric force is used to produce electrohydrodynamic pumps [2] and electroconvective flows as jets, wall jets and impinging jets [3][4][5].

The Coulomb force acts both on positive and negative ions. Then a net body force is locally generated only if an imbalance between positive and negative electric charges can be created. Two phenomena are quoted in the literature to obtain such an imbalance in liquids. The first one is the conduction pumping effect [6]. It is based on the dissociation/recombination phenomenon and generated heterocharge layers on the surface of the electrodes. The second one is the injection phenomenon [7][8]. It produces homocharge layer at the electrode vicinities. The two phenomena are well described in literature and it is generally assumed in most of papers that one dominates and then the other one can be neglected. The conduction phenomenon is assumed to be predominant at low voltage. At the opposite, the injection start when a threshold voltage is reached. In practice, these two phenomena can exist together when a strong electric field is applied on a liquid. The creation of the charge layers and then of the force magnitude depends on local parameters as electrode assemblies, working liquids, usable conditions (temperatures, impurities etc.).

In this work an experimental study is performed on a cylinder/plane electrode geometry in a cavity. The produced flow are analyzed in order to determine how electric forces act on the dielectric liquid. A special attention is given to the electrode polarity.

I. Experimental Setup

The schematic diagram of the setup is shown Fig. 1. It is mainly composed of two stainless steel electrodes (1) and (2). The first electrode (2) is a 5mm diameter and 45 mm long cylinder. It is connected to a high voltage power supply. The second one (1) is a 70x45x3 mm plate. This second electrode is grounded. These two electrodes are placed in a cavity cell 80x60x40 cm in PMMA (3). In order to avoid edge effect, the electrode edges are embedded in two wall sides (4) and (5) in PMMA. The cell is filled by the used of two holes (6) (7) placed on the upper face of the cell. The leak tightness is achieved by two sealing strips (8) placed in the two sidewalls. The cavity is filled with HFE 7600.

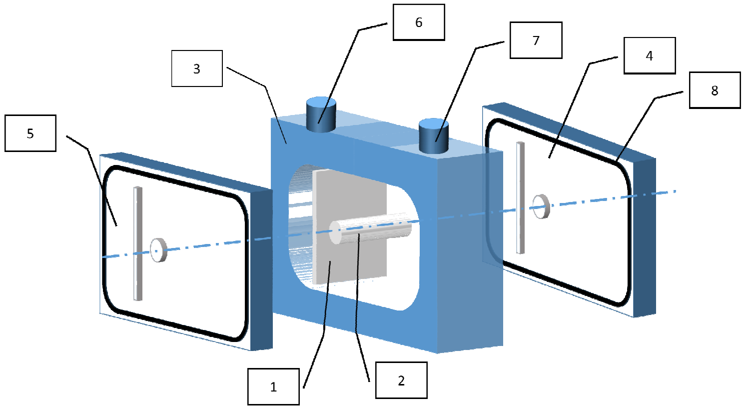

Fig. 1 schematic of the experimental cell

This liquid is a weakly conductive dielectric liquid. Typical characteristics of this dielectric liquid at a temperature of 20 °C are presented in table 1.

TABLE 1
TYPICAL CHARACTERISTICS HFE 7600AT 20 °C

Mass density	ρ (kg/m^3)	1540
Kinematic viscosity	ν (m^2/s)	1.1 10^{-6}
Electrical conductivity	σ (S/m)	3.3 10^{-9}
Dielectric Strength	2.54 mm gap [kV]	31
Relative permittivity	ε_r	6.4

In this study an asymmetric electrode configuration is used. The main advantage of the cylinder plane device is to produce a strong electric field only at the cylinder vicinity. The electric field strength is ten times stronger on the cylinder surface than on the plate surface Fig2.

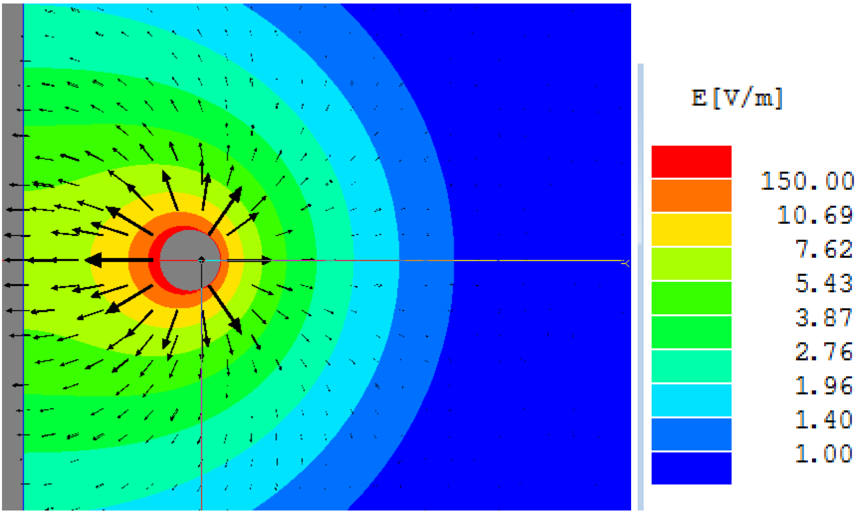

Fig. 2: Numerical calculation of the electric field calculated with 1 volt on the cylinder and 0 volt on the plate

In this study, velocity flow fields are recorded by the use of the Particle Image Velocimetry. The PIV method is a velocity flow measurement technique which is used to obtain the time dependent full field velocity distributions of single and multi-phase flows. This technique requires seeding the flow with small tracer particles. The choice of these seeding particles is a major difficulty despite the wide variety of seeding particles types.

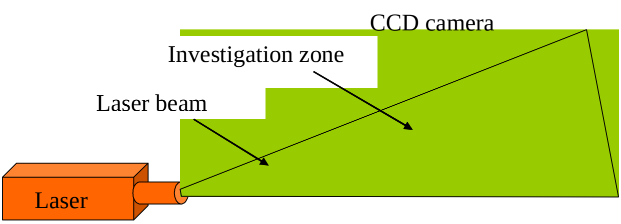

Fig. 3 : PIV measurement apparatus

The PIV apparatus is presented in Fig 3. In order to record the positions of the particles the tracer particles are illuminated with a sheet of light from a pulsed laser. Two successive laser shots light the studied scene and the particles positions is recorded by a camera. From the two successive images, a specific software using correlation algorithm determines the change in particle positions. The time delay between two consecutive shots allows to calculate the velocity vectors field. The PIV device used here is a LaVision acquisition system (LaVision GmbH, Göttingen, Germany). Images are acquired with a CCD digital camera. The frames are analyzed with Davis software. A number 1000 of frames per series of measurements is used to reach a statically converged time-averaged result.

II. Results

A. Positive Voltage

A first set of experiments is performed with a negative voltage applied to the cylindrical electrode. The second electrode is grounded. 1000 instantaneous flow fields are recorded by the use of the PIV method and the time averaged flow field is computed. A typical result of flow field is presented Fig. 3. The two electrodes are represented in grey. Black arrows are used to indicate the flow direction and the background color map shows the velocity amplitudes. As the laser is placed above the setup, a shaded zone appears under the cylinder. In this region the tracer particles don't shine and it is not possible to estimate the velocity field. This shaded area is visible as a blue region under the cylindrical electrode.

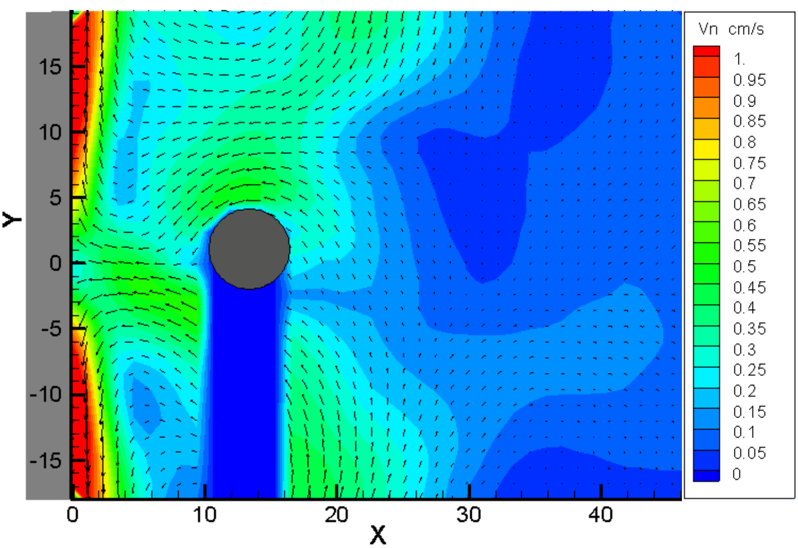

Fig.4 Time averaged velocity field with colored map of velocity modulus (cm/s) for –2 kV.

Two typical time-averaged velocity fields are shown in Fig. 4 and Fig. 5 for an applied voltage of respectively -2kV and -15 kV. An electroconvective liquid flow is created by the electric forces. Between the cylinder and the plate a flow starts from the cylindrical electrode and moves towards the plate. Before arriving to the flat plate, the flow splits into two wall jets which move along the plate. This phenomenon is commonly observed on typical impinging jet. Such behavior on impinging jets and wall jets have already be observed by Daaboul [3] Yan **Erreur ! Source du renvoi introuvable.** and Wu [10] on an electrohydrodynamic wall jet produced by a blade plane electrode geometry.

The flow seems to be repelled from the cylindrical electrode. It is reasonable to think that an unipolar charge injection occurs on the cylindrical electrode surface. An homo-charge layer is created and then the liquid is pushed by the volume Coulomb force towards the plane. The maximum liquid velocity is observed on the plane surface and the two wall jets seems to remains close to the surface. The wall jet detachment looks slower than the one observed on typical mechanical wall jet. This phenomenon must be confirmed by new experiments but it could be due to a conduction phenomenon on the plate surface which attract the flow and limit the detachment. It has also be observed that the flow velocity increases with the voltage but the global velocity field pattern remains the same.

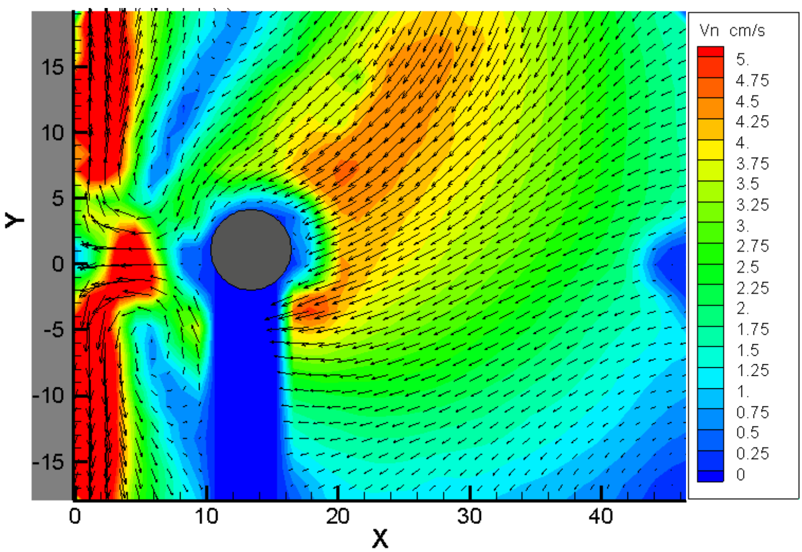

Fig.5> Time averaged velocity field with colored map of velocity modulus (cm/s) for –15 kV.

B. Positive Voltage

In the second set of experiments a positive is voltage applied to the cylindrical electrode. The second electrode remains grounded.

It can be observed in Fig. 6 and Fig. 7 that the flow is in the opposite direction of the one observed with the negative voltage. At 2kV Fig. 6, the liquid situated between the plate and the cylinder move from the plate toward the cylinder. In the electrode gap, two vortices are visible close to the cylinder surface. They show that the liquid is attracted by the cylinder rather than repelled by the plate. Then the flow get around the cylinder and move to the right. This phenomenon could be explained by a conduction phenomenon. An heterocharge layer is probably created on the cylinder surface. Due to the strong electric field, a Coulomb force is exerted on this layer. Then the liquid is as directed toward the cylinder.

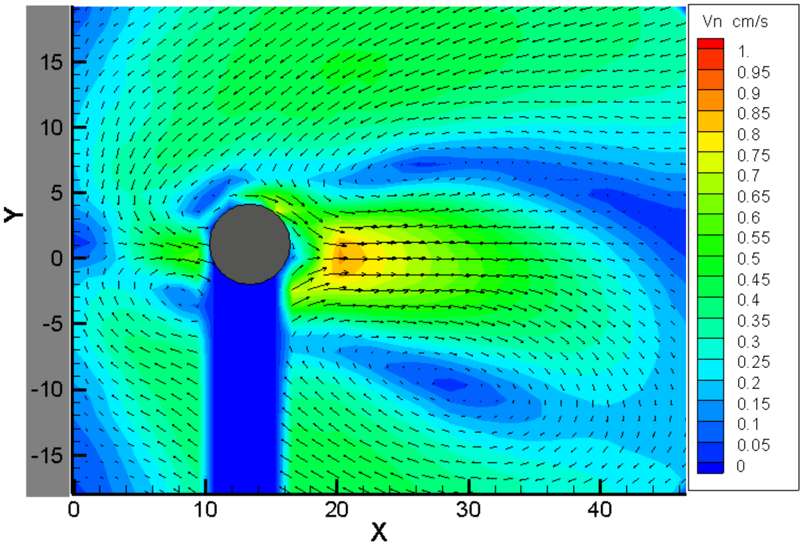

Fig.6 Time averaged velocity field with colored map of velocity modulus (cm/s) for +2 kV.

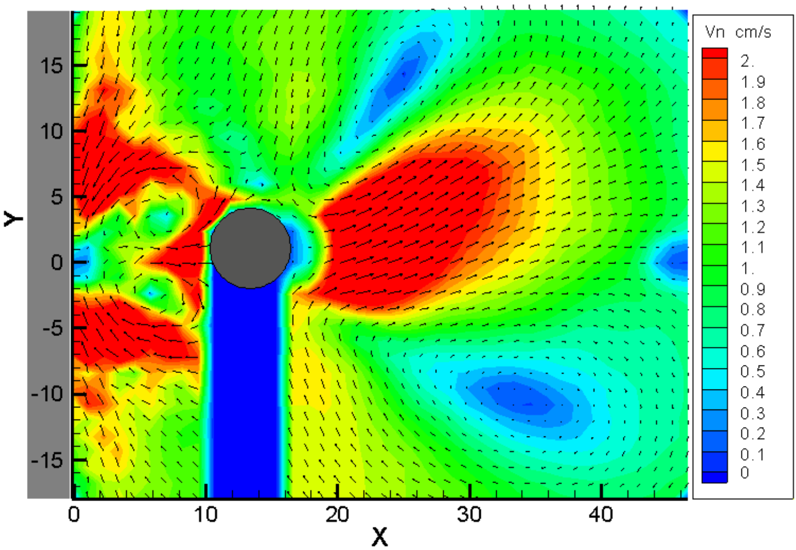

Fig.7 Time averaged velocity field with colored map of velocity modulus (cm/s) for +15 kV.

When the voltage is increased until +15kV (Fig.7), the two small vortices situated between the plate and the cylinder remains visible but two other vortices appears on the right part (in blue on Fig.7). The red regions in the electrode gap indicate that the liquid is attracted by the cylinder but also by the plate. We may conclude that an heterocharge layer is also produced on the plane surface.

In the right part a jet seems to be created from the cylinder to the right (red on Fig. 7). This jet looks like the one created by a charge injection and presented part A. However, the electric field on the right part of the cylinder is weak and a charge injection is unlikely to occur. An analysis of the velocity flow field shows that the global flow is 3D. Then it is probably due to a 3D effect.

C. From conduction to injection

The conduction/ injection models proposed in the literature assume that transition between conduction and injection phenomenon occurs at a threshold electric field. The threshold value depends mainly on the liquid properties but also on parameter like temperature. The conduction phenomenon occurring when the electric field is below the threshold value. At the opposite the charge injection process dominates when the electric field exceeds the threshold value.

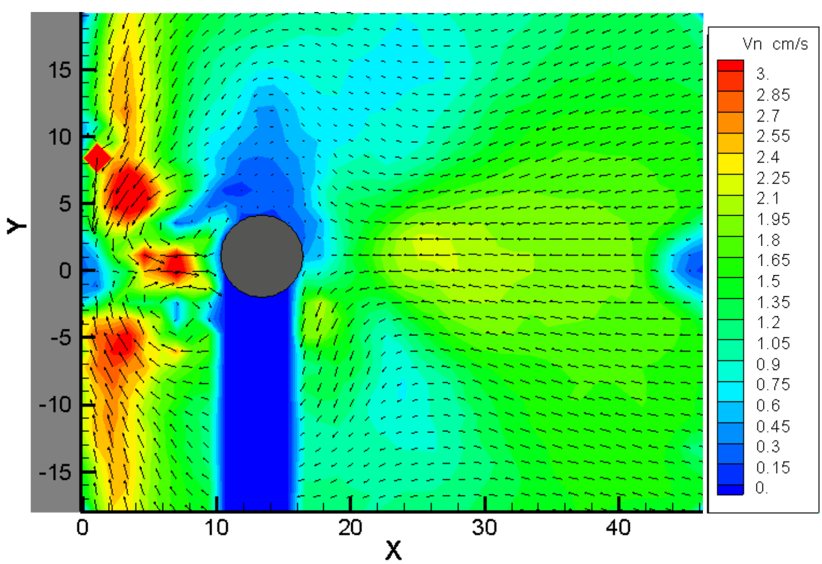

Fig.8 Time averaged velocity field with colored map of velocity modulus (cm/s) for +15 kV.

In order to determine the threshold value of the HFE liquid the voltage has been increased until 22kV (Fig 8). Unfortunately, no major change is detected on the flow pattern into the electrode gap. Observed flow remains characteristic of a conduction phenomenon. But a strange behavior occurs on the right part of the cavity. In this region, the flow direction change at 21kV. Below 21kV, in the right part, the flow looks like a jet which originates from the cylinder and moves toward the right. At 22kV the flow suddenly reverses. It comes from the right and moves toward the cylinder and the liquid is at rest on the bottom and top of the cylinder. This strange phenomenon is probably due to a global flow which takes place in the all cavity.

D. Acknowledgements

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III. CONCLUSION

In order to investigate the transition between the conduction and injection phenomena, Particule Image Velocimetry measurements have been performed on an electrohydrodynamic cavity flow. A dielectric liquid has been set in motion by a cylinder/plane electrode geometry. Two different flows have been generated. The first one is an impinging jet. It is characteristic of a charge injection phenomenon. The second one is characterized by a flow motion toward the cylindrical electrode and it is associated to the conduction phenomenon. These two flows has been related to the cylindrical electrode polarity. A negative voltage induces a charge injection while a positive one provokes a conduction phenomenon. Unfortunately, the electric field threshold predicted in the literature has not been detected. More experiments will be realized with this device and a more detailed analysis will be performed on the flow field in order to confirm these preliminary results. Finally, the setup will be modified in order to increase the electric field and to reach the threshold value.

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