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Electroconvective flow induced by dielectric barrier injection in silicone oil

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ABSTRACT

It has been demonstrated that dielectric barrier actuators can be used to induce electrohydrodynamics flows in air as well as in gas. These actuators are often called surface non-thermal plasma actuators in gas applications. Plasma actuators have proved their efficiency for aerodynamics flow control in air. However dielectric barrier devices don't generate plasma in liquids. Electroconvective flows are induced by charge injection at the surface electrode tip. These dielectric barrier injectors (DBI) are particularly well adapted for wall jet production vortex, shedding, and mixing layer applications in dielectric liquids. Dielectric barrier actuators have proved their efficiency on various dielectric liquids. In this study, a dielectric barrier device is tested on silicon oil. Instead of the typical wall jet, a reverse flow is observed in specific configurations. Particle Image Velocimetry and Shlieren measurements are achieved to characterize the unusual electroconvective flow.

1. Introduction

Dielectric barrier devices are mainly composed of two electrodes separated by a dielectric material. Electrodes are excited with an AC signal in a frequency range from a few hertz to several kilo hertz. Dielectric barrier devices are very interesting because they allow reaching very high electric field (which means strong electric force) while preventing the occurrence of electric sparks.

First experiments on dielectric barrier actuators have been performed by J R Roth in 1992. He worked with the NASA Langley Research Center, US on surface decontamination and he created a new device for surface plasma production in gas. After some experiments he founds that his device base on dielectric barrier geometry could induce an airflow of several ms^{-1} [1–3]. This first dielectric barrier discharge (DBD) actuators, called One Atmosphere Uniform Glow Discharge Plasma is protected by a US patent since 1995 [4]. DBD actuators have had a great influence on airflow control researches because of their simplicity and efficiency. Since more than ten years, dielectric barrier discharge actuators also called surface non-thermal plasma actuators have proved their efficiency for aerodynamics flow control applications. A wide review on dielectric barrier discharge and their use for flow control has been recently published by Moreau (2007) [5]. At that time, more than one hundred papers have been published on DBD actuators and on their airflow control applications.

Surprisingly, only few studies have been conducted on liquids. Some experiments and measurements have been performed on electroconvective flows in dielectric liquids but with blade-planes or grid/grid geometries. First velocity measurements have been made by Priol [6] by Laser Doppler Velocimetry and a first description of the flow induced by dielectric barrier device in liquid was proposed by Louste [7,8].

Unlike in gas, no plasma is created by a charge injection using a dielectric barrier device in liquid. Previous works have proved that such DBI device could be used as electrohydrodynamic (EHD) actuator when it is immersed in a dielectric liquid. This method has been successfully used to generate an electrical wall jet which could lead to many engineering applications especially in cooling systems or for flow control applications.

Recently, velocimetry techniques have been adapted to EHD flows. It has been demonstrated that by suitably choosing the seeding particles, velocimetry techniques can be used for EHD flow measurements. Particle Image Velocimetry (PIV) method can be used to record the position and time dependent velocity values in entire EHD flow field. Phase analysis of the flow velocity has shown that at low frequency the DBI actuator mainly acts as

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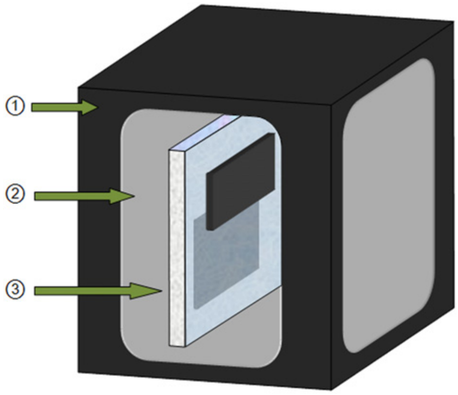

Fig. 1. Schematic view of the test cell.

a vortex generator. On the contrary, at high frequency, no coherent structures are detected and the flow is similar to a classical turbulent wall jet. Moreover, the results obtained demonstrate that DBI actuators are able to generate a jet velocity of more than 0.25 m/s.

In this study, a DBI actuator is immersed in silicone oil and the liquid flow induced in the surface vicinity is measured by Particle Image Velocimetry (PIV). The structure of the wall jet is described and analyzed for both signal polarities. On the contrary of other experiments the electroconvective flow has been maintained for hours under DC signal. Moreover, an unusual behavior of the fluid has been observed when a negative voltage is applied to the electrode. The work presented in this article is devoted to the description and the understanding of these phenomena.

2. Experimental facility

The apparatus consists of a 30 cm × 30 cm × 30 cm plastic tank ①, full of silicone oil (Fig. 1). Four windows ② have been installed on the four faces of the cube for PIV measurements.

The dielectric barrier actuator ③ was disposed vertically in the tank. It is composed of two electrodes separated by a dielectric plate ④ Fig. 2. The first electrode (emitter electrode ⑤) is a metallic strip 20 mm wide and 100 μm thick and with a 5 μm tip radius. It is placed on the upper plate surface of the dielectric plate. The second electrode ⑥ is glued on the opposite surface and is embedded into an epoxy resin layer ⑦. The dielectric plate is in glass (length $L = 80$ mm, width $l = 90$ mm, thickness $H = 3$ mm). The emitter electrode is connected to a HV Spellman SL1200 DC power supply and the second electrode is grounded.

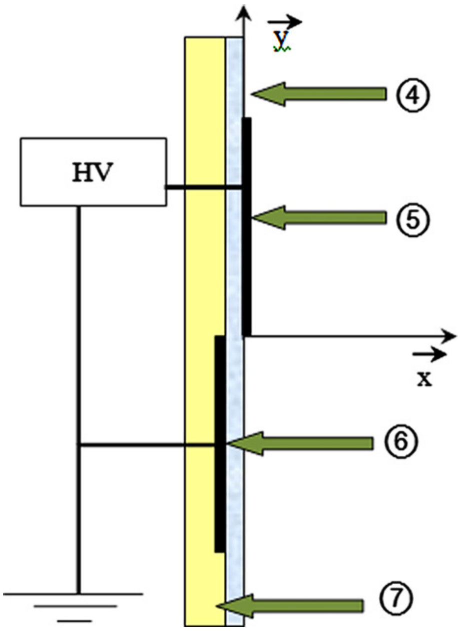

Fig. 2. Dielectric barrier actuator.

Table 1
Typical characteristics of the dielectric oil at 20 °C.

Conductivity	$\sigma = 1 \times 10^{-13}$	$(\Omega\ \mathrm{m})^{-1}$
Density	$\rho = 910$	kg m^{-3}
Relative permittivity	$\varepsilon_r = 2.59$	
Dielectric strength	14	kV mm^{-2}
Kinematic viscosity	$\upsilon = 5 \times 10^{-6}$	$\mathrm{m}^2\ \mathrm{s}^{-1}$

The dielectric liquid used in these experiments is silicon oil. Properties are given in Table 1.

3. Results

The liquid has been seeded by SiO_2 particles of 0.5 μm diameter 0.01 g/L concentration for PIV measurements. Particles are illuminated by a green laser sheet. The motion of these seeding particles was acquired with a CCD digital camera. It has been proved by [9] that particles must respect electrical and mechanical properties in order to have no major influence on the fluid flow and to obtain accurate PIV measurements.

All criterions have been scrupulously respected in this work.

The PIV measurements frequency is 4 Hz. Images are acquired at a spatial resolution of 2048 × 2048 pixels. Each couple of images is collected with a time spacing allowing an average particle displacement of 8 pixels in the flow region. The frames are analyzed with Davis 7.0 software. An interrogation window size of 32 × 32 pixels has been used in order to have at least 10 particles per window. In these conditions, the measurement accuracy for the instantaneous velocity magnitude could be estimated to 1%. The confidence interval to have 95% of precision for the average velocity $\overline{U}$ in our experiments for $n = 200$ repeats is calculated by the use of the following formula:

$$\overline{U} \pm \frac{2\sigma}{\sqrt{n-1}}$$

where σ is the standard deviation and n is the number of sample.

In this condition the measurement accuracy of the average value could be estimated within ±3% with a 95 percent confidence interval.

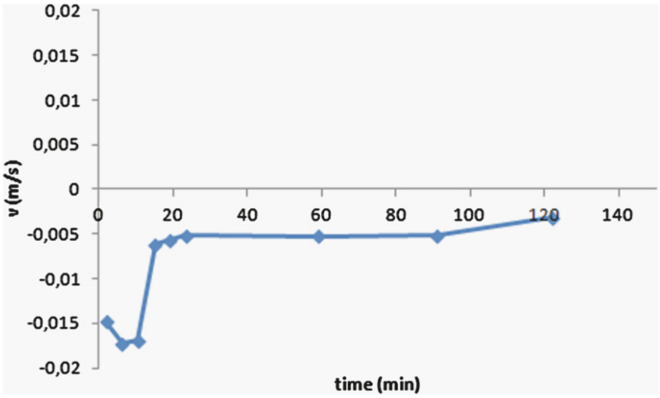

Fig. 3. Positive polarity–time history of the vertical component of velocity v at position $x = 1$ mm, $y = -5$ mm 2 h duration.

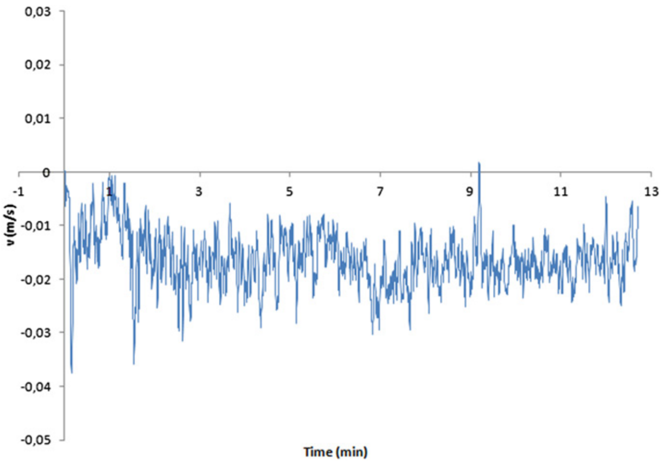

Fig. 4. First 10 min in positive polarity time history of the vertical component of velocity v at position $x = 1$ mm, $y = -5$ mm.

3.1. Positive polarity

In first experiments, a positive DC voltage has been applied to the emitter electrode.

It is well known that when a high positive potential is applied to the blade electrode an electroconvective flow is generated. This stream is similar to a wall jet which is a typical flow in fluid mechanics. It originates at the electrode tip and flows down along the dielectric plate surface. Such electrical wall jets have already been observed with dielectric barrier devices in diesel oil using an AC signal. Because of the charge accumulation on the dielectric surface, long-term experiments cannot be performed in diesel oil in DC voltage with these devices.

However, contrary to the behavior observed in diesel oil, an EHD jet can be maintained for hours with a dielectric barrier device in silicon oil even with a DC voltage. However, significant change of velocity was observed in long-term experiments. An example of these variations is presented Fig. 3. It can be noticed that during the first 15 min the time average velocity is about 2 cm/s at position $x = 1$ mm and $y = -5$ mm but it suddenly decreases into 5 mm/s at $t = 18$ min.

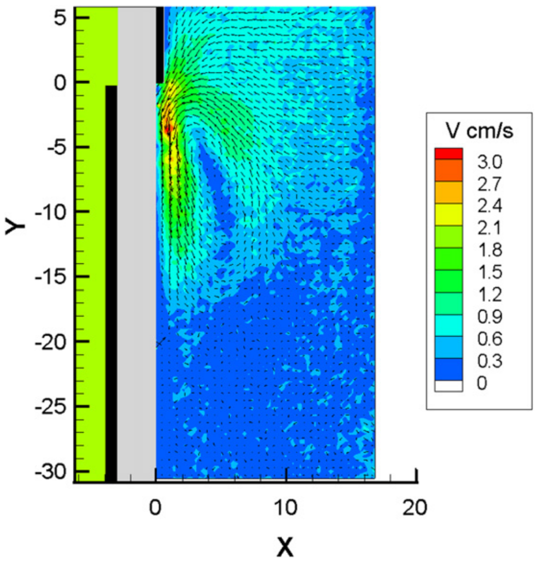

Fig. 6. PIV velocity field at $t = 4$ min.

The jet is also unsteady. A lot of high frequency fluctuations of the liquid velocity can be observed (Fig. 4). Nevertheless, no particular frequencies seem to be accentuated or subdued.

A hole is also visible at $t = 1$ min in Fig. 4.This hole in the velocity versus time history curve corresponds to a variation in the flow regime.

During the first minute, the wall jet is thin and remains stuck at the surface (Fig. 5). The center line velocity reaches 3 cm/s and seems to be homogenous along the flow (Fig. 6).

Between 1 min and 15 min, the jet is limited to an area close to the emitter tip. The flow is a typical EHD wall jet as describe by Ref. [8]. A unipolar injection occurs at the blade tip. Due to the strong electric field generated, the injected electric charges move from the blade toward the dielectric surface, which produces an electroconvective flow. Velocity decreases rapidly as the jet widens. Injected electric charges are rapidly dispersed in the bulk by the flow.

Beyond 20 min, the stationary regime is reached (Fig. 7) but high frequency fluctuations are still visible on instantaneous velocity

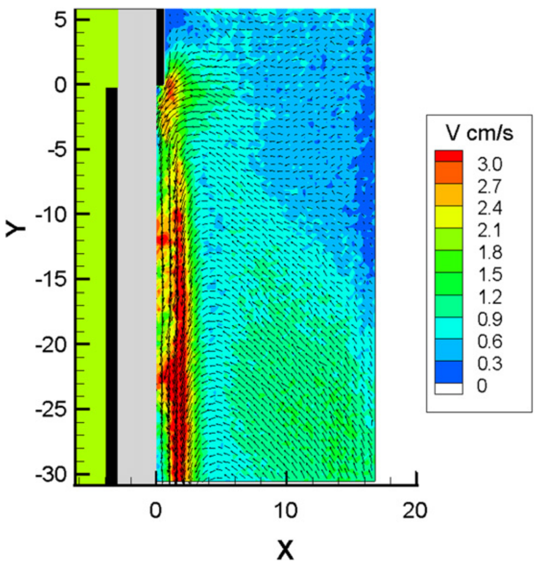

Fig. 5. PIV velocity field at $t = 0.5$ min.

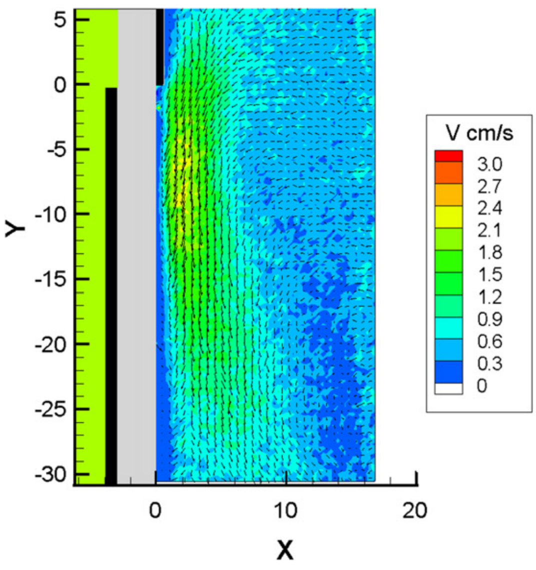

Fig. 7. PIV velocity field at $t = 20$ min.

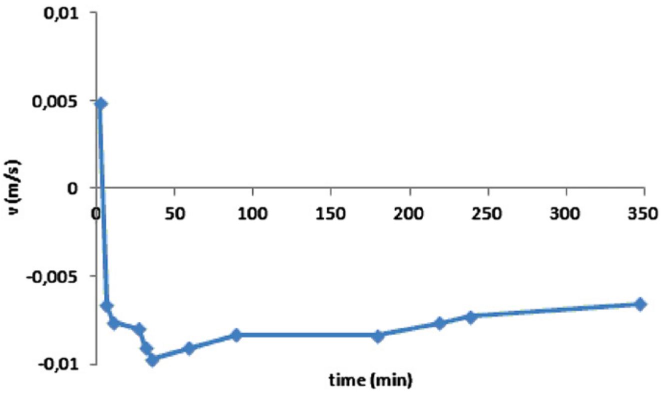

Fig. 8. Negative polarity–time history of the vertical component of velocity v at position $x = 1$ mm, $y = -5$ mm 2 h duration.

measurements. The flow remains clearly unstable and the electroconvective flow forms a wide wall jet. The jet thickness is larger than the one observed on EHD jet in diesel oil. These instabilities are probably due to an irregular charge injection. Some temporary local accumulations of charge density may disrupt the injection process.

After several hours of operation, the velocity decreases slowly. The decay is similar to a capacitive load. We assume that the charge injection will stop when the experimental tank will be fully charged. Experiment has been stopped at $t = 300$ min. Velocity was 0.5 cm/s. At this time, the emitter electrode was grounded and the discharge current was recorded. 10 h is required for fully discharging the tank.

3.2. Negative polarity

In this second experiment, a negative voltage is applied to the emitter electrode. The second electrode remains grounded. As in the positive case, important velocity variations are visible on the first 10 min (Fig. 8). Beyond 20 min, the flow mean velocity reaches a quasi steady state value and decreases slowly. After 6 h of operation the velocity is about 0.6 cm/s. Once again, this decrease is assumed to be mainly due to the charge accumulation in the tank.

Analysis of the first 10 min (Fig. 9) shows three flow regimes. The first regime lasts until 3 min. It is characterized by a positive velocity. The second one is between 3 and 6 min. Velocity at position $X = 1$ mm and $Y = -5$ mm is about 0. The last regime starts after 6 min of operation and can persist for many hours.

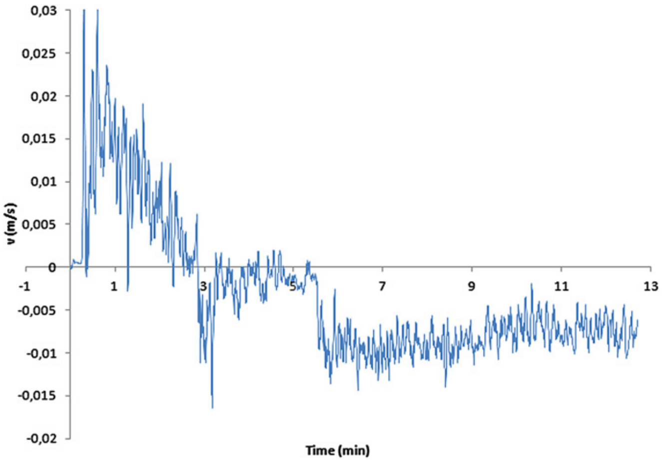

Fig. 9. First 10 min in positive polarity time history of the vertical component of velocity v at position $x = 1$ mm, $y = -5$ mm.

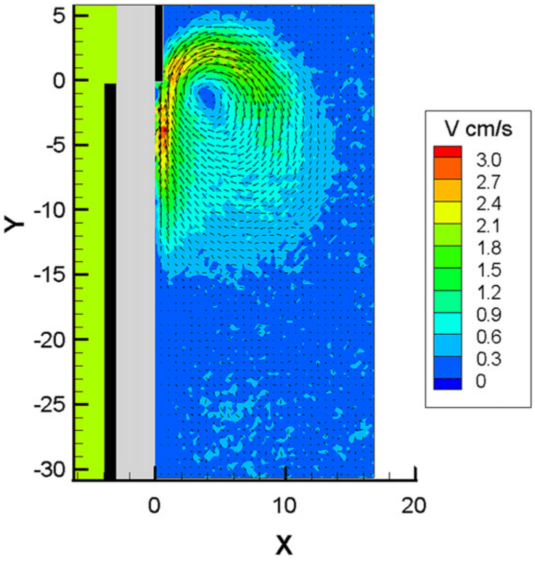

Fig. 10. PIV velocity field at $t = 0.5$ min.

During the first 3 min the flow is reversed (Fig. 10). This behavior has never been described before. The flowing liquid in contact with the dielectric plane is attracted by the emitter electrode. An upward wall jet is induced. This jet turns at the electrode tip and create a vortex. This upward flow decreases rapidly. After 3 min, the vortex has disappeared.

Between 3 and 6 min the main stream is again directed downward but the jet is detached from the plate body (Fig. 11). This detachment is due to a vertically upward flow on plate surface. The jet velocity is weak and the jet is wide.

In the last regime (Fig. 12), the liquid flows as a classical EHD wall jet. The liquid accelerate over a distance of 1 cm. It remains attached to the dielectric plate and the maximum velocity of 3.8 cm/s is reached.

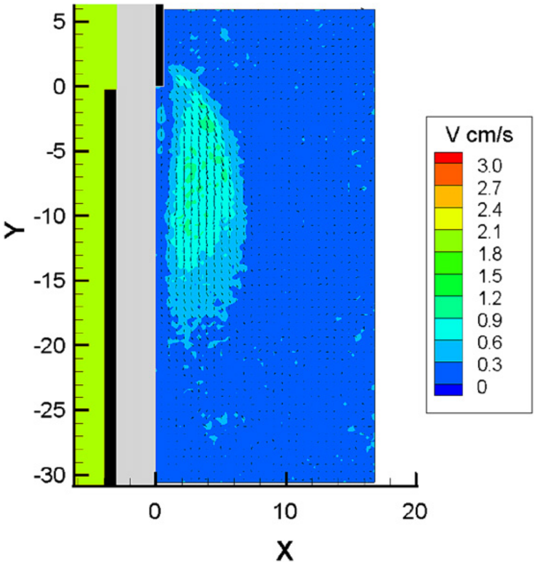

Fig. 11. PIV velocity field at $t = 4$ min.

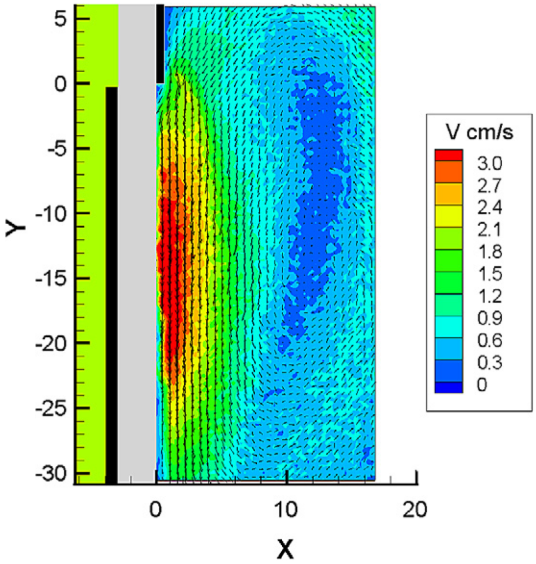

Fig. 12. PIV velocity field at $t = 20$ min.

4. Conclusion and discussion

It has been proved that the electroconvective flow produced by a dielectric barrier actuator is induced by a charge injection. The use of a solid dielectric barrier allowed obtaining a very strong electric field at the upper electrode surface. As a consequence a significant charge injection occurs at the upper electrodes tip and a homocharge layer is created at the electrode vicinity. This layer is set into motion by the Coulomb force and a net flow is generated.

In previous studies conducted in diesel oil it has been demonstrated that the flow stops in less than 10 s when a DC signal was applied to the electrodes. This phenomenon can be explained by the accumulation of electric charges on the dielectric upper surface. Ions produced by the charge injection move toward the grounded electrode. They are stopped by the dielectric plate and accumulate on the dielectric surface. Then the electric field at the electrode tip decreases gradually as the potential of the dielectric surface increases. The charge injection stops when the electric field drops below the threshold value, then the flow slowdown. It is necessary to reverse the signal polarity to obtain a new injection. Then flow is maintained if the emitter electrode is excited by an AC signal.

In this study an EHD jet has been analyzed for more than 6 h under DC signal independently of the signal polarity. In case of silicon oil electric charges do not accumulate on the upper surface. They are mainly convected far away from the emitter electrode by the flow. This phenomenon is probably due to the very low conductivity of silicon oil.

The experimental work presented in this article is based on velocity fields obtained by PIV measurements. This study focuses on the flow induced by a dielectric barrier actuator on silicon oil.

Six regimes can be observed (three per signal polarity). During the first 2 min an original flow is produced independently of the polarity.

After few minutes typical EHD wall jets comparable to those in diesel oil are observed. They are created by the ion drag force. A transient regime can be observed between these two regimes. Transient regimes last only few minutes. They are described in details above.

We assume that the original behavior of the first 2 min can be explained by the presence of a positive charge layer on the dielectric plane surface. This layer is mainly composed of free charge and is set in motion when the device is switched on.

So when a positive voltage is applied, the positive layer suddenly repels and the liquid flows rapidly at the plane vicinity and an attached wall jet is generated. Under negative polarity, the surface charges are attracted by the electrode and a reverse flow is induced.

In few seconds the most important part of the layer is dispersed and the flow changes. During the next few minutes the remaining charges maintain a local flow at the electrode vicinity (downward in the positive case and upward in the negative case). Classical wall jets form as soon as the layer is fully dispersed.

The positive layer is probably the diffusive part of a double layer which develops at the dielectric liquid solid interface. This assumption should be tested in new experiments and compared to numerical models.

The combined use of the double layer and the charge injection should expect to develop reversible actuators which may be very interesting for flow control applications.

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