

# PIV Measurements of the Influence of Seeding Particles Concentration on the Velocity of an EHD Flow

Michel Daaboul, Christophe Louste, and Hubert Romat

Laboratoire d'Etudes Aérodynamiques (LEA) – Université de Poitiers, ENSMA, CNRS

SP2MI – Téléport 2, Boulevard Marie et Pierre Curie – BP 30179

86962 Futuroscope Chasseneuil Cedex, France

**Abstract**— The two major electrical phenomena used to induce a fluid motion in an isothermal dielectric liquid are bulk conduction and ion injection. Several techniques are utilized in order to measure the velocity of these flows. A well known technique in fluid mechanics is the Particle Image Velocimetry (PIV). This method is very useful to obtain large scale velocity fields but requires seeding the flow with small tracer particles. As a consequence, it is important to prove that these particles are not significantly intrusive. In this paper, the choice and the concentration of seeding particles are discussed. The influence of the seeding particles concentration on the velocity is measured. Experiments were investigated on a typical two-dimensional charged plume flow produced between a blade and a flat plate under negative and positive DC voltages.

**Index Terms**— Blade-plane geometry, charged plume, dielectric liquid, electrohydrodynamics, Particle Image Velocimetry

## I. INTRODUCTION

WHEN an electric field is applied on an isothermal dielectric liquid, electrohydrodynamical forces are generated into the liquid [1-3]. These forces can be used to produce, modify, and control a flow [4-6].

In order to improve the performance of electroconvective devices, the velocity of the flow must be recorded as accurately and precisely as possible. The Laser Doppler Velocimetry (LDV) method is the most commonly used technique in electrohydrodynamics (EHD). But it is difficult to obtain a global map of the velocity field with LDV because it

only gives one measurement at one single point in space at the same time. A solution to obtain a global map of velocity field consists in the use of the Particle Image Velocimetry (PIV) method.

This paper is a second part of a study that aims to adapt the PIV method, which was originally developed in the field of experimental fluid mechanics, on electroconvective flow measurements. In the first part [7] the effect of seeding particles on the injection current was studied. It has been proved that the choice of seeding particles is essential. Moreover the particles concentration must not exceed a threshold value of 150 mg/l to have no noticeable influence on the current. Beyond this value, the electric current is affected.

This paper focuses on the influence of the seeding particles concentration on the measured velocity. Experiments are performed on the same blade-plane geometry device. A DC voltage is applied between the two electrodes. Negative and positive polarities are investigated. The evolution of the charge injection is examined while increasing the seeding concentration in the liquid.

## II. EXPERIMENTAL SETUP

### A. Electrical Device

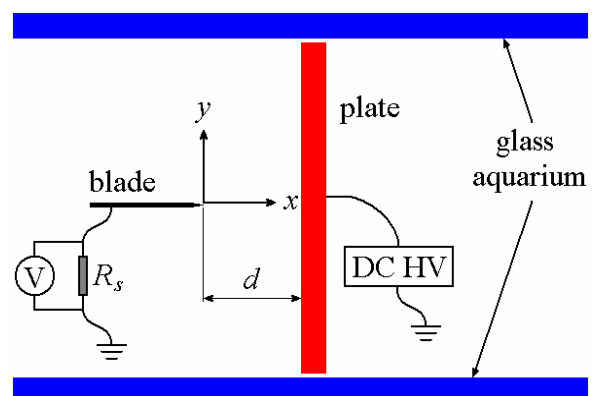


Fig. 1. Experimental apparatus.

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Michel Daaboul is with the Electrofluidodynamic Unit at the Laboratory of Aerodynamical Studies and a PhD student at the University of Poitiers, France (corresponding author; phone: +33549496941; fax: +33549496968; e-mail: 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 (e-mail: christophe.louste@lea.univ-poitiers.fr).

Hubert Romat is with the Electrofluidodynamic Unit at the Laboratory of Aerodynamical Studies and a professor at the University of Poitiers, France (e-mail: hubert.romat@lea.univ-poitiers.fr).

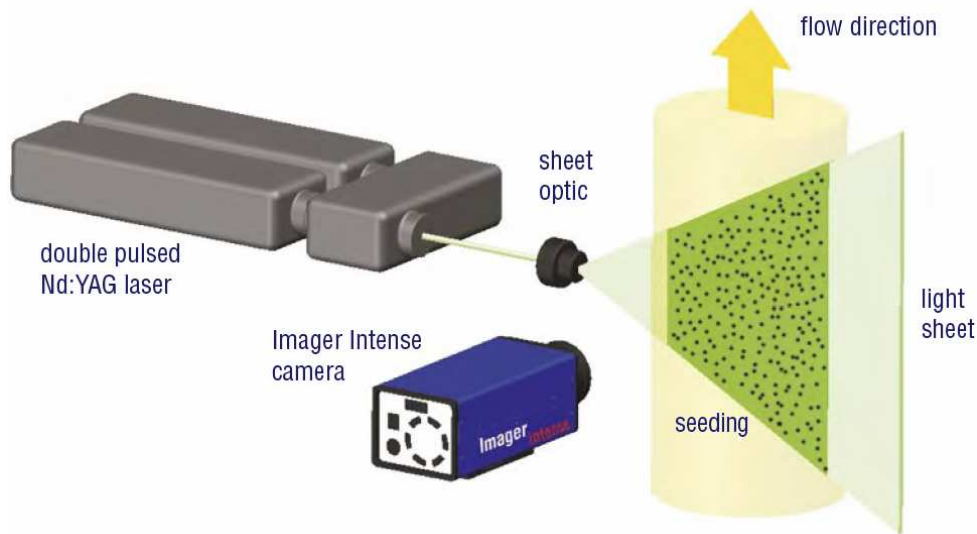


Fig. 2. Particle Image Velocimetry measurement system (© LaVision GmbH, Germany, <http://www.lavision.de>).

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  $7 \pm 2 \mu\text{m}$ .

A variable difference of potential (0–60 kV) is supplied by a Spellman SL1200 DC power supply. A Meterman 37XR multimeter ( $\pm 0.1 \text{ V} - \pm 0.01 \mu\text{A}$ ) was used to measure the voltage across a shunt resistance  $R_s = 99.3 \text{ k}\Omega$ .

The tests are carried out when the blade has a relative negative voltage to the plate as well as when it has a relative positive one. The experimental results are therefore examined for “Negative Injection” and “Positive Injection”. The term of “Negative Injection” is used to represent a unipolar injection of negative charges from the blade tip.

The liquid used in the experiments is dielectric oil with slight electrical conductivity. The characteristics of this dielectric liquid at a temperature of 20 °C are presented in Table I.

TABLE I  
TYPICAL CHARACTERISTICS OF THE DIELECTRIC OIL AT 20 °C

Mass density	$\rho \text{ (kg/m}^3\text{)}$	850
Kinematic viscosity	$\nu \text{ (m}^2\text{/s)}$	$4.3 \cdot 10^{-6}$
Electrical conductivity	$\sigma \text{ (S/m)}$	$1.15 \cdot 10^{-9}$
Relative permittivity	$\epsilon_r$	2.2

### B. Particle Image Velocimetry Method

The Particle Image Velocimetry method is a common technique used in experimental fluid dynamics. It consists of seeding a flow with small tracer particles and tracking these particles to determine the velocity map of the test zone. A double pulsed laser sheet illuminates the investigation scene and a CCD camera takes 2 successive photos in order to determine the successive positions of the seeding particles (Fig. 2). A special software using correlation algorithm gives the velocity map knowing the time delay between the 2 successive images.

This work was realized with a LaVision acquisition system (LaVision GmbH, Göttingen, Germany.) The images were acquired with a CCD digital camera at a spatial resolution of 1376×1040 pixels. The frames were analyzed with Davis 7.1 software. The choice of seeding particles held on SiO<sub>2</sub> particles of 0.5  $\mu\text{m}$  of diameter.

## III. EXPERIMENTAL RESULTS

### A. Q-Q Plot Method

In this part, the influence of seeding particles on the behavior of the correlation system is examined. The purpose is to verify that the statistical distribution of PIV measurements still follow a normal law even with the presence of high concentrations of particles.

The experimental results are obtained with a specific software which correlates the images taken in PIV measurements. The software permits to export the velocity maps and have the velocity value of every point in the studied area. A series of 1000 images is set to have a statistically convergent result. The correlation software can also calculate the average value of the 1000 acquisitions. This average value has no signification unless the statistical distribution follows a normal law.

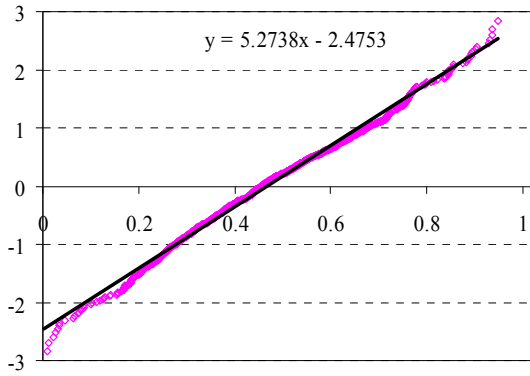


Fig. 3. Q-Q plot distribution for a tested sample.

Measurements accuracy was investigated using the Quantile-Quantile (Q-Q) Plot method. This technique is used to test the convergence of the results and the error obtained on the average value. It compares the distribution of the experimental measurements to the one of a normal statistical law. Afterwards, a straight line should be obtained. From the equation of this straight line ( $y = ax + b$ ) the average value can be obtained ( $-b/a$ ) as well as the standard deviation ( $-1/a$ ).

A locally developed algorithm is used to extract the 1000 velocity values at a same point of space. These values are then investigated with the help of the Q-Q Plot method. An example is given in Fig. 3 below.

We plotted the order statistics (velocity values in m/s) of the sample (1000 points at  $x = 10$  mm,  $y = 0$  mm for a seeding concentration of 400 mg/l) on the horizontal axis and the quantiles of the normal distribution on the vertical axis. We obtained a straight line. That means that the distribution follows a normal statistical law.

The mean value (which intersects with the  $x$ -axis) is equal to:

$$V = \frac{2.4753}{5.2738} = 0.469 \text{ m/s}$$

The standard deviation is calculated as the inverse of the slope:

$$\sigma = \frac{1}{5.2738} = 0.189 \text{ m/s}$$

The confidence interval to have 99.7% of precision for the average velocity value in our experiments for  $n = 1000$  repeats is calculated by the use of the following formula:

$$V \pm \frac{3\sigma}{\sqrt{n}} = 0.469 \pm 0.018 \text{ m/s}$$

The measurement accuracy for the average value could be estimated to 4% to have 99.7% of confidence.

This accuracy test was done for all measurements and similar results were obtained. A precision range going from 1% to 10%, with a confidence of 99.7% on the average value, was obtained for the different measured cases. The seeding concentration does not affect the normality of the statistical distribution of the sample and the accuracy of measurements. As a consequence, the average values presented in this paper are obtained with this method. The precision of the experimental results does not depend on the seeding concentration.

*B. Global Velocity Map*

In this section, the influence of the seeding concentration on the global velocity map is examined. The vector fields are nondimensionalized in order to underline the global shape of the impinging jet.

When the blade is set to a high voltage, an impinging jet is induced from the blade tip and is directed to the plate [8]. In Figs. 4 and 5 we can see the dimensionless velocity vector fields for a negative and a positive 40 kV injection and for 2 different seeding concentrations. In the background the velocity modulus contour is presented. The zone with no data corresponds to a masked area due to the shade of the blade when illuminated by the laser sheet.

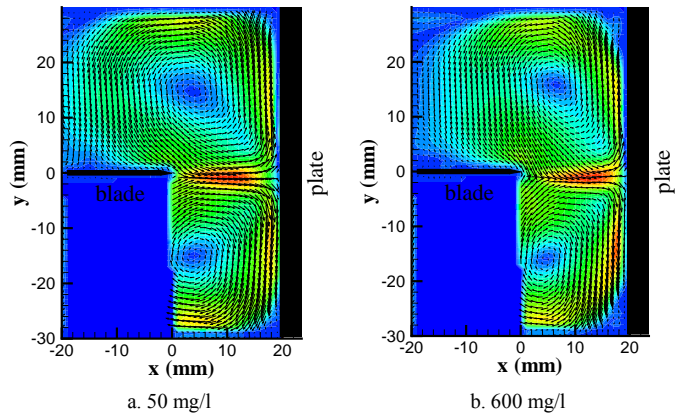


Fig. 4. Dimensionless velocity vectors for a 40 kV negative injection.

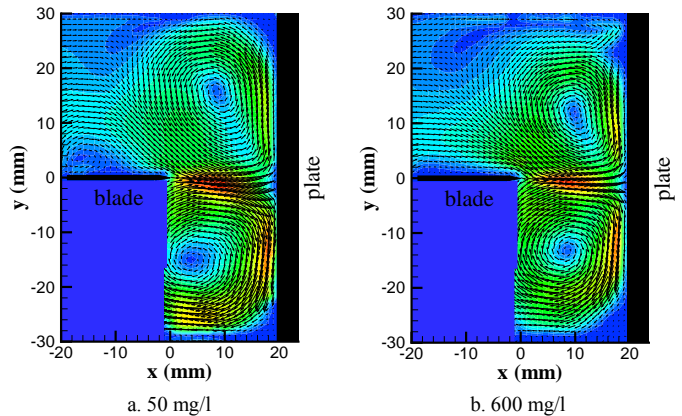


Fig. 5. Dimensionless velocity vectors for a 40 kV positive injection.

In all cases we have a central flow directed from the blade tip to the plate. This flow type is known as the charged plume. Before arriving to the plate the flow splits into 2 flows which form 2 vortices up and down the blade axis. The shape of the flow remains similar for different concentrations of the seeding particles in the negative injection case (Fig. 4a and 4b). In the positive one, the vortices centers seem moving towards the central axis of the jet when the seeding concentration increases (Fig. 5a and 5b).

The influence of the seeding concentration seems to be low on the global shape of the jet. In the following section, the influence on the charged plume is investigated.

### C. Velocity Measurements

The measurements presented in the following curves correspond to the mean value of 1000 instantaneous vector fields.

In Fig. 6 the velocity on the axis of the charged plume is presented for various seeding concentrations. It can be noticed that the profiles is structured in 2 main parts. The first one ( $x$  going from 0 to 10 mm) corresponds to an acceleration due to the charge injection from the blade tip. The second one is a deceleration phase provoked by the presence of the plate. The velocity is equal to zero at the impinging point ( $x = 20$  mm). It reaches a local maximum around  $x = 10$  mm. The evolution of this maximum velocity with concentration is presented in Fig. 7.

As seen in Figs. 6 and 7, the seeding concentration has no remarkable effect on the liquid velocity below a value of 100 mg/l. Another observation in Fig. 6 is that the acceleration next to the blade tip ( $x$  going from 0 to 2 mm) decreases while increasing the seeding concentration. This effect visibly corresponds to a lower Coulomb force, moreover to less electric charges and lower injection indeed. This consequence could be explained by an electric field reduction on the blade tip which is probably due to the fact that the seeding particles accumulate some electric charges.

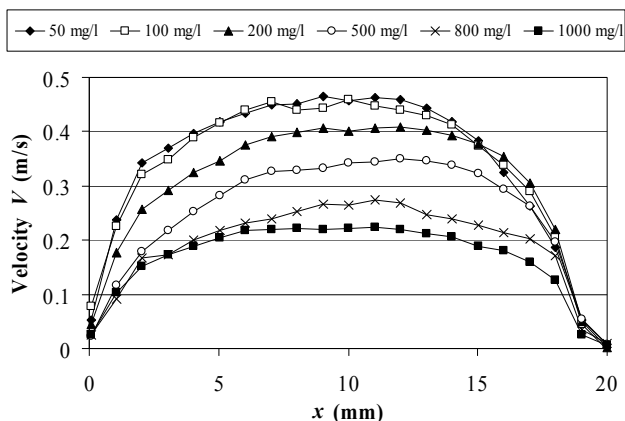


Fig. 6. Evolution of the maximum velocity in the core of the charged plume ( $y = 0$  mm) between the blade tip and the plate for various seeding concentrations.

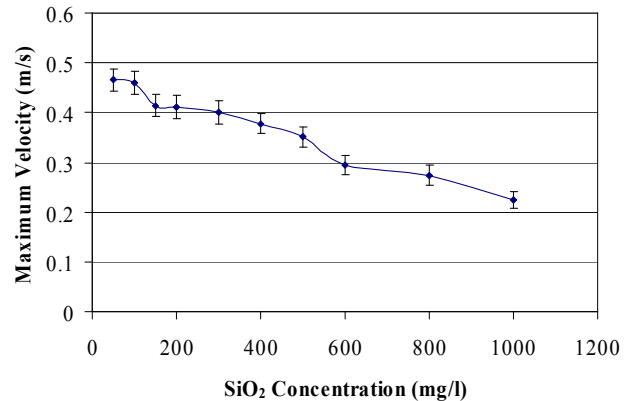


Fig. 7. Evolution of the maximum velocity with the seeding concentration for a 40 kV negative injection.

On the other hand, while approaching the plate ( $x$  going from 17 to 20 mm), the deceleration is almost the same for the several concentrations. This effect shows that the phenomena intervening here are mainly mechanical and due to the liquid viscosity. The tested concentrations are low enough to be able to affect the viscosity. Note that the electric field in this region is very low [9] compared to the one on the blade tip.

In Fig. 7 the maximum velocity is not affected up to a concentration of 100 mg/l. Beyond this value it decreases with the seeding concentration. A too high concentration of seeding particles has an important effect on the injection phenomenon.

## IV. CONCLUSION

The PIV measurements on the charged plume between a blade and a flat pate carried out for various seeding concentrations show that a concentration of less than 100 mg/l must be adopted to have a satisfactory result. In fact, with such a concentration, it was demonstrated that the electric current is not modified. In this paper it was proven that the global shape of the jet and the velocity of the charged plume are not affected for low concentrations. PIV measurements are therefore adaptable on EHD flows. Otherwise a high concentration allows having a same general shape of the flow but the velocity is influenced by the seeding particles which have a significant effect on the electric charge injection.

An accuracy test was made for the several tested cases to determine the experimental error that can be obtained in measurements. A precision range going from 1% for some cases to 10% for more inaccurate ones was obtained. Even with the presence of seeding particles, the statistical distribution always follows a normal law. The experimental results could be considered truthful.

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**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.



**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.