Proc. 2016 Electrostatics Joint Conference

Influence of seeding particle type on velocity measurements in silicone oil under high voltage

Clément Gouriou, Christophe Louste, Philippe Traoré
Institut Pprime, CNRS, Université de Poitiers, ISAE-ENSMA,
F-86962 Futuroscope Chasseneuil, France
phone: 033 5 49 49 69 47
e-mail: clement.gouriou@univ-poitiers.fr

Abstract— **For several years, our research group develops EHD (ElectroHydrodynamic) actuators able to set dielectric liquid in motion. More precisely, these actuators are designed to produce electro-convective flows until 1m/s. These flows are jets (impinging jet, wall jet etc.) which can be used in various applications: mixing, flow control, cooling systems etc. The main advantages of these actuators are: direct conversion of electric energy into inertial energy (without movable part), low cost, and easily miniaturizable. ElectroHydroDynamic pumps could be used in microfluidic applications. Nevertheless, the fundamental physics of these flows remains complex, and in order to have a better understanding of these electroconvective flows we need a more reliable analysis method. The best method to date is the Particle Image Velocimetry (PIV). However in order to show the liquid movement, this method requires seeding particles, but these latter can be electrically charged and so on can be influenced by the electric field produced by the electrodes. In this work, we study the behavior of 3 types of seeding particles under high electric field in order to estimate the error induced by the electric field on the measurement of the liquid velocity.**

I. INTRODUCTION

The main purpose of this project is to develop a measurement method for EHD flows. In this paper we focus on the Particle Image velocimetry (PIV) method. A previous paper on EHD flow has demonstrated that changing the particle type affects the measured flow field recorded with PIV technique [1]. In a first part the PIV method is presented. Then a theoretical study based on the Pauthenier theory is used to determine properties that must be satisfied by particles in order to make good measurements. In a third step, an experimental study based on PIV method is led on an EHD wall jet of several tens of centimeter per second. This jet is produced with help of a planar actuator developed by Daaboul [2] and Zelu [3]. The produced flow field is recorded for various seeding particle types. Then results are compared and analyzed.

A. EHD force

Thanks to P. Atten [4] and A. Castellanos [5] who have proposed a theoretical description of the EHD flows, it is well known that electroconvective flows in dielectric liquids are created by the movement of space charges (cations or anions) under the influence of an electric field. The Coulomb force is mainly responsible for the movement. These charges are created by several complex phenomena like the conduction (linked to the association-recombination process [6]. They can be also created by the direct charge injection in the region of high electric field, or they can be generated by double layer phenomena [7]. The presence of space charge in an intense electric field (around thousands of volt), provokes the migration of the ions from one electrode to the other one and thanks to the viscous friction drags the molecules of the liquid away in an electro-convective movement [8].

B. *Principle of PIV Technique*

The Particle Image Velocimetry (PIV) is commonly used in fluid mechanics to study the velocity fields of any transparent fluids (air, water etc.). This technique enables to determine particle displacement over a precisely selected time using a double-pulsed laser technique. The 1st laser light sheet illuminates a plane in the flow, and the positions of particles (seeding) are recorded. The 2nd laser pulse illuminates the same plane which gives a second set of particles. Then a PIV algorithm [9] is used to compute the velocity vector field of the imaged region Fig. 1.

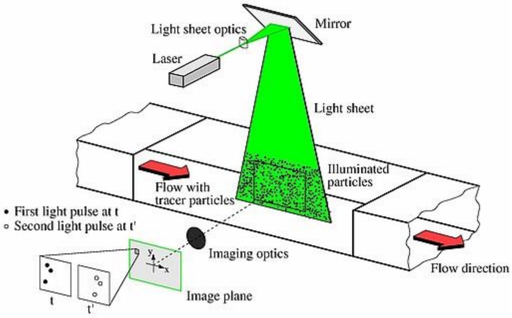

Fig. 1. PIV sytem

However this technique is based on the hypothesis that the particles strictly follow the fluid movement and don’t have their own behavior depending on other parameters (ex: gravity, coalescence etc.).

C. *Limits of the PIV in charged liquids*

In our EHD application, the liquid is subjected to a high electric field and free ions are present. Indeed, the seeding particles are submitted to the electric field and could acquire an electric charge. Then their motion may be influenced by the electric field. Due to the Coulomb force charged particles may have a relative velocity to the fluid V_{mig} [1]:

$$\vec{V}_{mig} \approx \frac{q.\vec{E}}{6\pi\mu R} \qquad (1)$$

Where q is the particle charge, R the particle radius, μ is the dynamic viscosity and $\vec{E}$ is the electric field vector. The PIV technique has already been used to measure flow fields in charged dielectric liquids by [2] [3] [10] [11]. Nevertheless too few studies were led to prove the validity of this technique. Moreover it has been demonstrated by [1] that in specific geometry the measured flow velocity depends on the particle material. In this work we make a theoretical analysis to investigate the relationship between the electrical particle properties and the maximum particle charge. Then we lead an experimental study on the influence on both particle types and seeding particle concentration on a planar dielectric barrier actuator.

II. THEORETICAL STATEMENTS

A. Particle charge by Pauthenier[12]

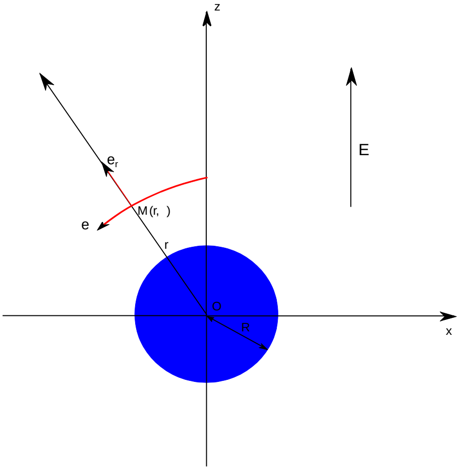

Fig. 2. Dielectric particle in outer electric field,
$OM = r = R(1+\nu)$

Let us consider a dielectric particle plunged in a dielectric liquid and subjected to an outer electric field (Fig. 2.). The total radial component of the electric field is expressed as following:

$$\overrightarrow{\mathrm{E}_r} = \left(E\ \cos\theta + \mathrm{E}\ \cos\theta \left[2\left(\frac{\varepsilon_{int}-\varepsilon_{ext}}{\varepsilon_{int}+2\,\varepsilon_{ext}}\right)\frac{R^3}{r^3}\right] + \frac{q}{4\pi\,\varepsilon_{ext}}\frac{1}{r^2}\right)\overrightarrow{e_r} \qquad (2)$$

Now we consider that the maximal charge admitted by the particle is obtained when the electric force becomes repulsive on all the circumference of the particle, which means:

$$\overrightarrow{\mathrm{E}_r}.\vec{r} \geq 0, for\ r = R\ and\ \forall\,\theta$$

According to Pauthenier theory, the maximum charge can be expressed as:

$$q_{max} \geq \underbrace{4\pi R^2\varepsilon_{ext}\ \left[2\left(\frac{\varepsilon_{int}-\varepsilon_{ext}}{\varepsilon_{int}+2\,\varepsilon_{ext}}\right)+1\right]}_{K} * \mathrm{E} \qquad (3)$$

q_{max} is expressed in Coulomb as the product between a factor K and the external electric field $\vec{\mathrm{E}}$. ε_{int} is the electric permittivity of the particle and ε_{ext} is the electric permittivity of the liquid. We notice that the difference between the permittivity of the particle and the one of the dielectric liquid has a non-negligible influence on the factor K and therefore on the maximum charge. In order to minimize this latter, the particle permittivity must be as smaller as possible. It can also be noticed that the smaller the particle radius is, the smaller the particle charges.

III. SETUP DESCRIPTION AND THEORETICAL MAXIMUM CHARGE ESTIMATION

In this study, an EHD (ElectroHydroDynamic) actuator is designed to produce an EHD force from the high voltage electrode to the ground electrode. This actuator developed by Daaboul [10] is dived in a dielectric liquid (silicone oil) Fig. 4. , and is supplied by a high voltage DC source. This latter is triggered manually to produce a square signal of several tens of seconds.

A. EHD actuator

A schematic of the planar actuator is presented Fig. 3. It produces an electro-convective wall jet. This actuator is composed of a blade (high voltage electrode) of stainless steel (60mm x 20mm) with a sharp edge whose radius of curvature is around 5µm and partially embedded of Epoxy® resin. The ground electrode is an aluminum sheet (60mm x 40mm) embedded by a thin layer of Epoxy® resin (3mm thickness). These 2 electrodes are pasted on both sides of a dielectric plate of glass of 3mm thickness. This actuator is powered by a Spellman SL1200® high voltage source DC (0;-30kV).

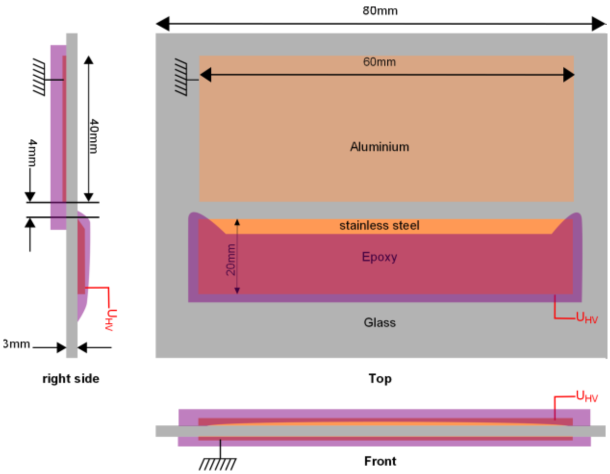

Fig. 3. Planar EHD actuator

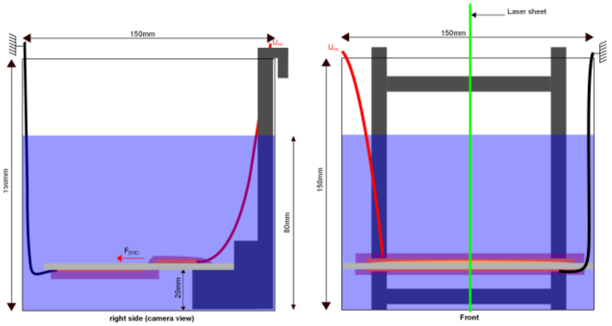

Fig. 4. Planar actuator and its shelf dived in the dielectric liquid

B. *PIV setup*

The PIV system is composed of a YAG laser whose wavelength is 532nm and which delivers a power of 120 mJ. The camera "LaVision" has a field width of 1200x1600 pixels and is able to film at a frequency of 5 Hz. In function of the flow velocity produced by the actuator we vary the time delay between 2 frames from 1ms to 3ms.

As shown on the Fig. 5, the experimental cell is laid on a metallic shelf and is lighted up by a laser sheet. The camera and the laser setup are placed perpendicularly.

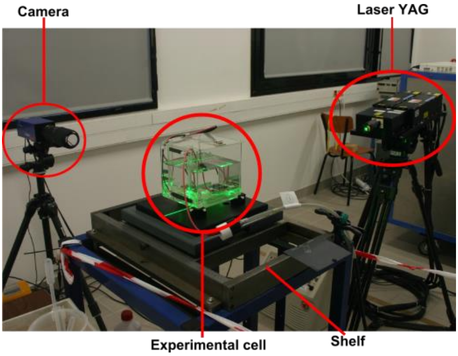

Fig. 5. PIV system and experimental cell

C. *Maximum charge*

We consider 3 types of seeding particles commonly used for PIV, whose mean radius is equal to 20µm. The only difference between each type of particle is the electric permittivity, as shown on the Table 1.

TABLE 1: ELECTRIC PROPERTIES OF SEEDING PARTICLES

	liquid	**seeding particles**		
Properties	**silicone oil**	**PTFE**	**PMMA**	**glass**
Relative electric permittivity	2.59	2.1	3.1	5

***K* factor $*10^{-20}$C.m/V**		1	1.29	1.7

Now, let us consider these 3 particles plunged into the dielectric liquid under an applied electric field produced by a planar actuator. This electric field can be calculated by the use of the Maxwell software (Fig. 6.). As the electric field $\vec{E}$ isn't constant, we focus our study on 3 characteristic points A(-2.5mm;1mm), B(-12.5mm;1mm), C(-22.5mm;1mm) located in the center of the electro-convective wall jet produced by the planar actuator. The HV electrode tip is defined as the origin of the graph Fig. 6. In that way, we can estimate the electric field and then the maximum charge of each particle.

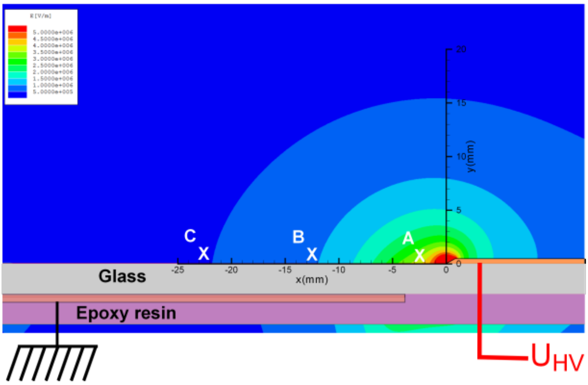

Fig. 6. Theoretical electric field generated by a planar actuator (U_{HV}=-30kV)

The values of the local electric field on the points A, B and C are given in Table 2.

TABLE 2: THEORETICAL ELECTRIC FIELD

	Characteristic point		
Property	**A**	**B**	**C**
Electric field $*10^6$ V/m	3.3	0.98	0.51

We deduce from the electric field intensities (Table 2) the theoretical values of the maximum charge reached by the 3 types of particles: PTFE, PMMA, Glass on the points A, B and C. Variations of the maximum charge q_{max} obtained with the formula of Pauthenier (6) is described below.

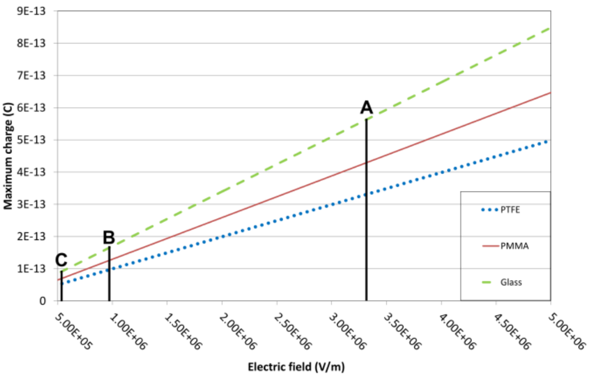

Fig. 7. Theoretical maximum charge as a function of outer electric field for 3 type of seeding particle

Firstly, we see Fig.7 that the maximum charge of a particle grows linearly with the outer electric field. Moreover the higher is the electric permittivity of the particle, the bigger is the slope of maximum charge in function of the electric field. We deduce from this graph that the PMMA and the PTFE particles are charging less than the glass particle and therefore they could be less influenced by the electric field and theoretically more suitable for seeding application.

Secondly we observe that whatever the observed point; if we take the PTFE particle as a reference, the PMMA particle gets a maximum charge 30% higher than the PTFE particle, and the glass particle acquires a maximum charge 70% higher than the PTFE particle. This means that the difference of permittivity between each type of seeding particle implies a substantial difference of maximum charge. We know that a charged particle plunged in an outer electric field gets a velocity (named 'velocity of migration') depending on its own charge. Consequently, the difference of maximum charge between the 3 types of seeding particle could lead to different velocities of migration which have to be minimized. In the next part, we study the experimental kinetic behavior of the 3 particle types in order to see if the differences of maximum charge have an influence on the velocity measured by PIV.

IV. EXPERIMENTAL RESULTS

The planar actuator is powered by a voltage step of -30kV and each run lasts few tens of seconds. The produced electro-convective flow is an EHD wall jet which has a maximum velocity of around 25cm/s in its core and which extends to several centimeters. The velocity is recorded by PIV technique at 5Hz. As the data distribution is assumed to be Gaussian, we make a statistical analysis on the 3 points A, B, C (shown on Fig. 3.) to get a mean velocity and associated standard error.

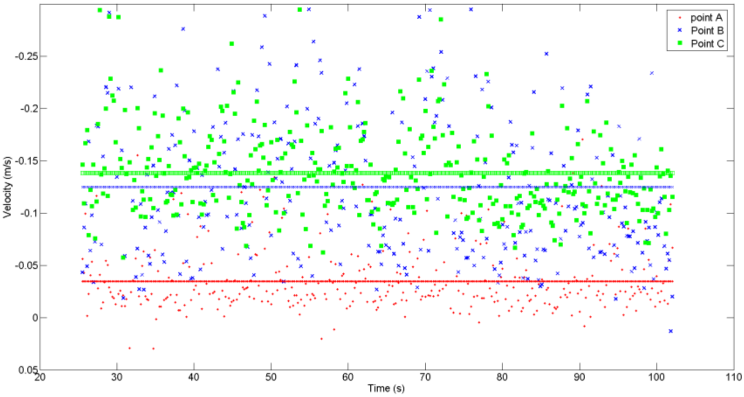

Fig. 8. Velocity versus time for glass particles (-30kV)

On Fig.8. we observe the velocities measured on the points A, B, C as a function of the time. We remark that the standard deviation is in the range of the mean velocity, which illustrates a high dispersion of the values. Nevertheless, the standard error of the mean velocity on several hundreds of values is around 10% with a confidence range of 99.7% and isn't presented on the next graph. This variability is inherent to the electro-convective jet which is set in motion by ions displacement.

We also notice that the mean velocity increases along the wall:

$$\overline{V_A} \approx -3.4\, cm/s \mp 0.3 < \overline{V_B} \approx -12.5\, cm/s \mp 0.5 < \overline{V_C} \approx -13.8\, cm/s \mp 0.8$$

Same experiments are performed with the 3 types of particles (glass, PMMA, PTFE) at various particle concentrations. Then the camera records the particle displacements and the mean velocity is estimated on the 3 points A, B, C of the wall jet.

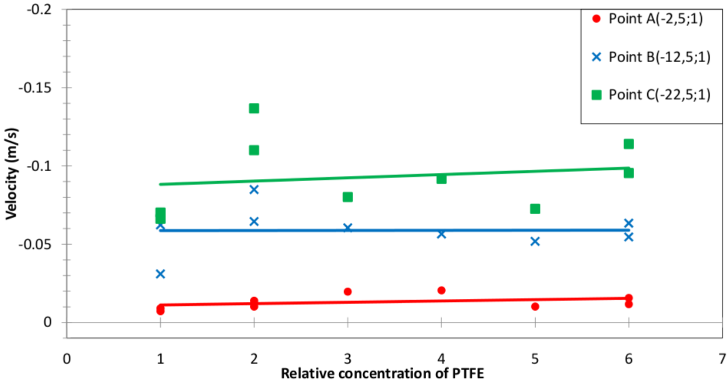

Fig. 9. Velocity as a function of PTFE relative concentration (-30kV)

Fig. 9. presents a typical result obtained with a particle type at various relative concentration. It seems that the concentration of PTFE particle doesn't have any clear influence on the mean velocity. This behavior is also observed with the particles of PMMA and Glass.

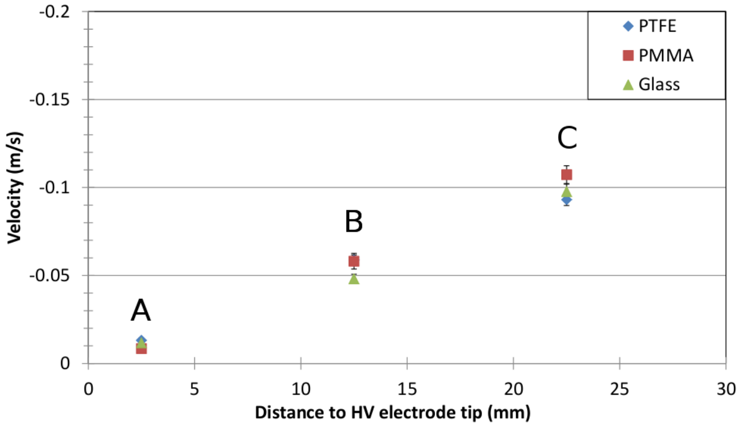

Fig. 10. Velocity measurements as a function of particle's type (-30kV)

The Fig. 10. presents the mean velocities measured on the 3 characteristic points as a function of the distance of the HV electrode tip for 3 particle types. We remark that the 3 velocities measured with the 3 particle types are almost superimposed on the points A, B, C. This reveals that the velocity measured is similar whatever the particle type. Finally we measure in point 'A' a mean velocity of -1.1cm/s ±0.3; in point 'B' a velocity of -5.5cm/s ±0.7 and in point 'C' a velocity of 9.9cm/s ±0.9. Thanks to this last graph, we can reasonably think that the particle type has no influence on the velocity measured with PIV for this EHD wall jet.

V. CONCLUSION

As a conclusion we can say that unlike the results obtained by [1], the particle types used in this experiment with this planar actuator have no influence on the measured velocity. This is probably due to the velocity of our electro-convective jet. It seems that due to the high velocity, particles aren't maintained in the high electric field zone for a long time. Then they cannot reach their maximum charge limit. In that way the particles are able to follow the hydrodynamic field and reveal the velocity of the fluid as presented in the Fig. 11.

We now have to verify that the presence of seeding particle doesn't have any influence on the EHD wall jet. In a future work we will study the velocity of this electro-convective jet thanks to a pressure method, which is completely independent of the presence of seeding particle.

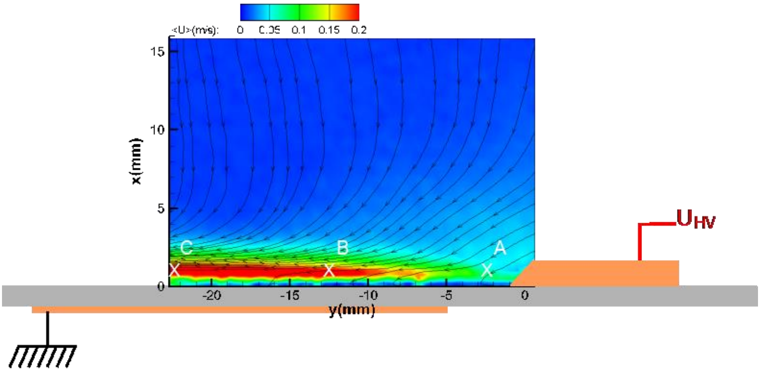

Fig. 11. Velocity field obtained by PIV with PMMA seeding particle (planar actuator -30kV DC)

VI. THANKS

This study was performed in the framework of the French government program **«Investissements d'Avenir»**, (LABEX INTERACTIFS reference ANR-11-LABX-0017-01).

REFERENCES

[1] C. Gouriou, C. Louste, et P. Traoré, « Study of the particle's charge in liquid: Application of the PIV technique in dielectric liquid under high voltage », présenté à MPEE, Saint Petersbourg, 2015.

[2] C. Louste, M. Daaboul, et H. Romat, « A study of vortex shedding induced by dielectric barrier injection », *J. Electrost.*, vol. 67, n° 2‑3, p. 348‑353, mai 2009.

[3] C. Louste, Z. Yan, P. Traoré, et R. Sosa, « Electroconvective flow induced by dielectric barrier injection in silicone oil », *J. Electrost.*, vol. 71, n° 3, p. 504‑508, juin 2013.

[4] P. Atten, « Electrohydrodynamic instability and motion induced by injected space charge in insulating liquids », *IEEE Trans. Dielectr. Electr. Insul.*, vol. 3, n° 1, p. 1‑17, févr. 1996.

[5] A. Castellanos, *Electrohydrodynamics*. Springer Science & Business Media, 1998.

[6] Y. Feng et J. Seyed-Yagoobi, « Understanding of electrohydrodynamic conduction pumping phenomenon », *Phys. Fluids 1994-Present*, vol. 16, n° 7, p. 2432‑2441, juill. 2004.

[7] A. P. Washabaugh et M. Zahn, « A chemical reaction-based boundary condition for flow electrification », *IEEE Trans. Dielectr. Electr. Insul.*, vol. 4, n° 6, p. 688‑709, déc. 1997.

[8] P. ATTEN, « Mouvement d'un fluide en présence d'un champ électrique », *Tech. Ing. Génie Électr.*, vol. 4, n° D2850, p. 1–12, 1999.

[9] R. J. Adrian, « Scattering particle characteristics and their effect on pulsed laser measurements of fluid flow: speckle velocimetry vs particle image velocimetry », *Appl. Opt.*, vol. 23, n° 11, p. 1690, juin 1984.

[10] M. Daaboul, C. Louste, et H. Romat, « PIV measurements on charged plumes-influence of SiO2 seeding particles on the electrical behavior », *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, n° 2, p. 335‑342, avr. 2009.

[11] P. Traoré, M. Daaboul, et C. Louste, « Numerical simulation and PIV experimental analysis of electrohydrodynamic plumes induced by a blade electrode », *J. Phys. Appl. Phys.*, vol. 43, n° 22, p. 225502, juin 2010.

[12] M. Pauthenier et M. Moreau-Hanot, « La charge des particules sphériques dans un champ ionisé », *J. Phys. Radium*, vol. 3, n° 12, p. 590‑613, 1932.