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Testing Different Tracer Types in Particle Image Velocimetry Measurements in Electrohydrodynamics

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Abstract— A powerful technique used to visualize fluid flows is the Particle Image Velocimetry (PIV) method. It allows having instantaneous velocity fields with a single measurement shot. However, this technique requires seeding the fluid with fine tracer particles. These particles are illuminated by a Laser source and images are captured in order to obtain a velocity field pattern of the global scene. In electrohydrodynamics, in addition to classical fluid mechanics problems, further complications emerge as a result of adding these tracer particles. The major problem in such cases is particle charging which is caused by the presence of an electric field. These particles accumulate electric charges on their surface and may affect the electric field distribution in the device. In addition, the particles can move faster than the surrounding fluid, and therefore, PIV measurements become inaccurate because the assumption of identical velocity for both the fluid and the particles is not valid anymore. Moreover, the seeding particles can stick together, form filaments, or adhere to surrounding solid walls, thus blocking charge transfer with the dielectric liquid. Furthermore, the particles could capture all the electric charges on their surface such that the liquid is not charged anymore, which weakens the fluid motion. The particle charging phenomenon depends on the operating fluid and the type of seeding particles used for PIV measurements. The main objective of the current work is to highlight the effect of particle type on PIV results. In this context, a hydrofluoroether dielectric liquid (HFE-7100) is tested in a cylinder-to-cylinder configuration. A DC voltage of up to 30 kV amplitude is applied between the two cylindrical electrodes. PIV measurements are then conducted and repeated with four different types of seeding particles: PMMA, PTFE, SiO₂, and Vestosint. The obtained results were not similar and the fluid behavior does not seem to be independent of the presence of the particles. To conclude, one must be careful when selecting the appropriate tracer type for each fluid and each experiment, especially when an electric field is applied.

Keywords— Dielectric Liquid, Electrohydrodynamics, Hydrofluoroether, Particle Image Velocimetry, Seeding Particles

I. INTRODUCTION

Over the years, dielectric liquids have shown numerous advantages for several industrial applications. Electrohydrodynamic (EHD) applications consist of applying

an electric field on the liquid to induce fluid motion. They range from heat transfer enhancement devices [1], to electrostatic pumps [2], to spraying applications [3], and many more. Several research teams around the globe work on the development of EHD devices working with dielectric liquids.

Three EHD regimes can set a fluid into motion: the first one is conduction [4], which occurs at relatively low electric fields. It is caused by the dissociation-recombination phenomenon and because of the formation of heterocharge layers in the vicinity of the electrodes, the ions are attracted by the electrodes of opposite polarity. The second regime is injection [5], which requires a threshold electric field to happen. It consists of homocharge layers which repel the injected electric charges and therefore the surrounding fluid. The third one is induction [6], which requires a gradient or a discontinuity of the electric conductivity. This can be obtained in the case of a thermal gradient, for example, and a motion of the fluid can be induced.

Three main forces can act on the fluid when an electric field is applied. These forces are:

- The Coulomb force which is proportional to the electric charge of a particle.
- The dielectrophoretic force which is proportional to the gradient of permittivity of a particle.
- The electrostriction force which is related to polarization of a particle and change of its shape under the application of an electric field.

In general, and depending on the scale of the application, one force can dominate over the others so that they become negligible compared to the dominant one. In order to completely understand the behavior of a dielectric liquid when exposed to an electric field, many measurement techniques can be used. Some of them involve the use of Laser for visualization purposes. The Particle Image Velocimetry (PIV) method and the Laser Doppler Anemometry (LDA) method are the most common techniques used for this purpose. Both methods require

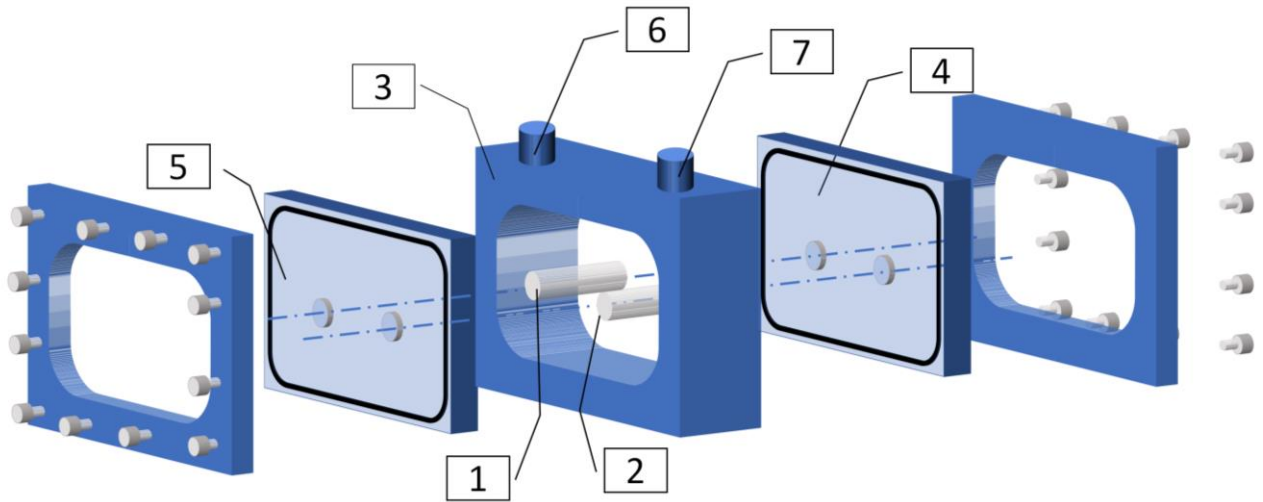


Fig. 1. Exploded view of the experimental cell.

seeding the liquid with tracer particles to be able to record their motion with the help of a high speed camera. The images are then analyzed using a specific software to obtain the velocity field. Without the application of electric field, the tracer particles exactly follow the motion of liquid particles and the measurements are assumed to be truthful. However, when an electric field is applied, the tracer particles accumulate electric charges on their surface and many measurement problems start to appear [7]. When the particles are charged, they undergo forces of different magnitude than that of the liquid particles. As a result, their motion may be different. In addition, the electric field distribution in the fluid can be distorted by the presence of these charges particles and the flow will be affected. Moreover, because of the difference of permittivity between the seeding particles and the liquid, they will behave differently when exposed to the same electric field. Furthermore, the difference of density between these particles may cause them to float or sink in the liquid.

The main objective of this work is to conduct PIV measurements on EHD flows with several types of tracer particles. The purpose is to compare the obtained results and provide a set of conditions for correct selection of seeding particles types for a desired dielectric liquid.

II. EXPERIMENTAL SETUP

A. Experimental Device

The device used for experimental measurements is presented in Fig. 1. It consists of two identical copper cylinders, (1) and (2), mounted in parallel configuration. The cylinder-to-cylinder geometry was selected because it maintains a lower electric field on the surface of the electrodes. The aim is to have EHD conduction in the fluid and avoid EHD injection which starts at the threshold electric field, usually obtained when the electrodes have sharp edges. The test cell, (3), has dimensions of $10\text{ cm} \times 8\text{ cm} \times 5\text{ cm}$, is made of PMMA and is installed with anti-leakage joints, (4) and (5). It is then filled with a hydrofluoroether dielectric liquid before the seeding particles are added. Air bubbles are evacuated through the upper holes, (6) and (7).

The operating fluid is HFE-7100, studied in [8], whose properties at a temperature of 25°C are shown in Table I.

TABLE I. PROPERTIES OF HFE-7100 AT A TEMPERATURE OF 25°C . [9]

| | |
|-----------------------------|-----------|
| Density (kg/m^3) | 1480 |
| Electric Conductivity (S/m) | 10^{-8} |
| Relative Permittivity | 7.4 |

PIV measurements are conducted using a LaVision GmbH system (Fig. 2). Each test consists of 1000 instantaneous images captured at a frequency of 5 Hz, and then the average velocity field is calculated. Images are then processed and analyzed on Davis 8.0 software.

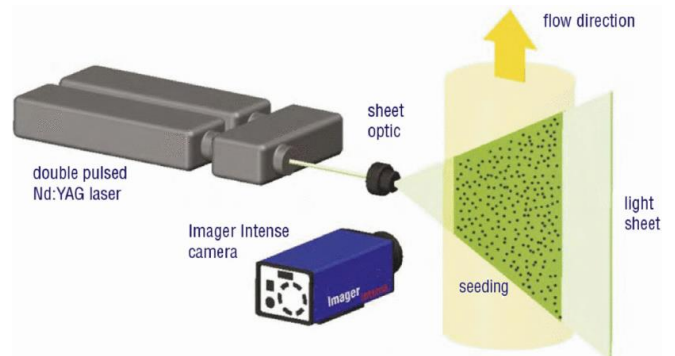


Fig. 2. PIV measurement apparatus (© LaVision GmbH). [10]

B. Experimental Procedure

After each experiment, the test cell was cleaned, dried, mounted, filled with the dielectric liquid, tested against leakage, and then the seeding particles were added. The concentration of these particles did not exceed 20 mg/l which is considered acceptable for having negligible interference with the dielectric liquid when exposed to an electric field [11]. Four types of seeding particles are tested: PMMA, PTFE (Teflon), SiO_2 , and Vestosint 2070. Table II lists the relevant properties of these particles.

TABLE II. PROPERTIES OF SEVERAL SEEDING PARTICLES. [12]

| Seeding Particles | PMMA | PTFE | SiO_2 | Vestosint |
|-----------------------------|------------|------------|----------------|------------|
| Density (kg/m^3) | 1180 | 2150 | 2500 | 1020 |
| Electric Conductivity (S/m) | 10^{-17} | 10^{-16} | 10^{-14} | 10^{-10} |
| Relative Permittivity | 2.9 | 2.1 | 4.6 | N/A |

The high voltage was provided by two Spellman SL-100 DC power supplies. One electrode (left) was connected to the high voltage and the other electrode (right) was grounded. The polarity was also inverted between the cylinders to verify the symmetry of the device. The symmetry results were satisfactory but they are not presented in this paper.

III. EXPERIMENTAL RESULTS

Several scenarios were investigated with voltages ranging from 0 V to 30 kV. In this paper, only the behavior of several tracer types at a voltage of 2 kV (left cylinder) is compared. The liquid behavior with increasing the applied voltage will constitute the subject of a future study. All the tests were conducted at a temperature ranging between 24°C and 28°C.

A. Repeatability of the Tests

The tests were repeated several times to verify the repeatability of the experiment. Fig. 3 and Fig. 4 show a sample comparison between 2 similar tests conducted with Vestosint with a time gap of 30 minutes. The number of seeding particles was much larger at the beginning of the test than at the end. One can clearly notice that most of the particles disappeared from the first test to the second one. These particles were charged enough to be attracted by the electrode of opposite polarity. Similar results were also obtained with SiO₂ particles. On the other hand, PMMA and PTFE tracers delivered better results, despite having a large difference in terms of conductivity and permittivity with that of the liquid. A thorough investigation of the liquid flow in function of the applied voltage will be conducted in a future work.



Fig. 3. Sample PIV image at the beginning of a test with Vestosint.

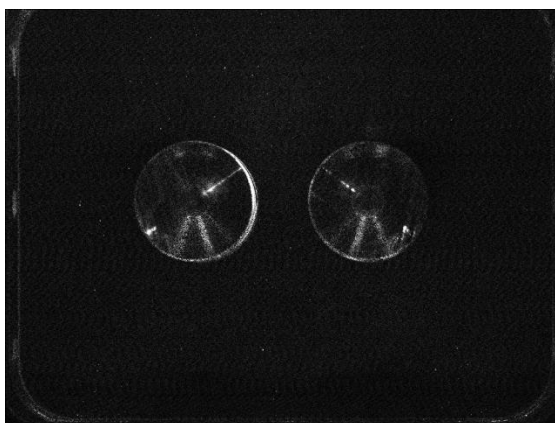


Fig. 4. Sample PIV image at the end of a test with Vestosint.

As observed earlier in Fig. 3 and Fig. 4., during the PIV measurements some seeding particles were disappearing from the images while the experiment was running. These particles were probably attracted by the two cylinders and by the walls of the PMMA cell. This interpretation was confirmed when the cell was cleaned after each set of experiments. Additional measurements with SiO₂ and Vestosint particles were impossible to complete because of the particle deposition problem.

B. Velocity Fields

Figs. 5 to 8 show the velocity distribution in the device for the 4 types of seeding particles at a voltage of 2 kV. The velocity magnitude, V , is presented in meter per second and the axes, x and y , are expressed in millimeters. The two grey circles represent the two cylindrical electrodes. The two white regions below them are shaded zones with no data because the device was illuminated with a Laser sheet from above. A first observation is that the difference between these results is clear and evident. Only PMMA and PTFE tracers gave comparable results in terms of velocity vectors. A fluid flow is generated by EHD conduction around the left cylinder and is directed towards the left wall of the cell. It impinges on the wall to create two flows, upwards and downwards. Because of the conservation of mass in the fluid, there is formation of two contra-rotary vortices, the upper one being clockwise and the lower one anti-clockwise. A weaker flow appears to exist between the two cylinders. Additional measurements are required in this region.

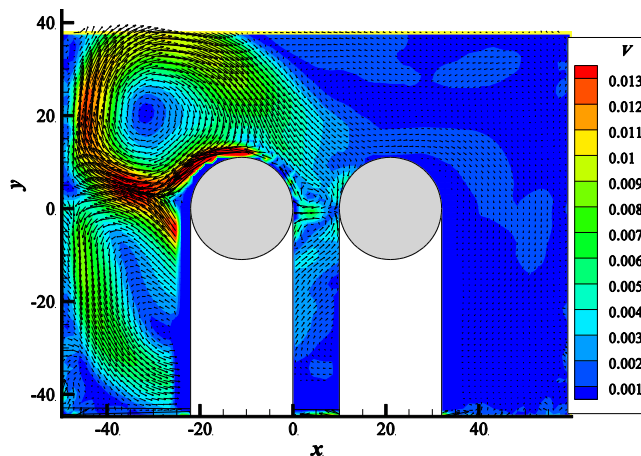


Fig. 5. Velocity vectors and contours with PMMA tracers.

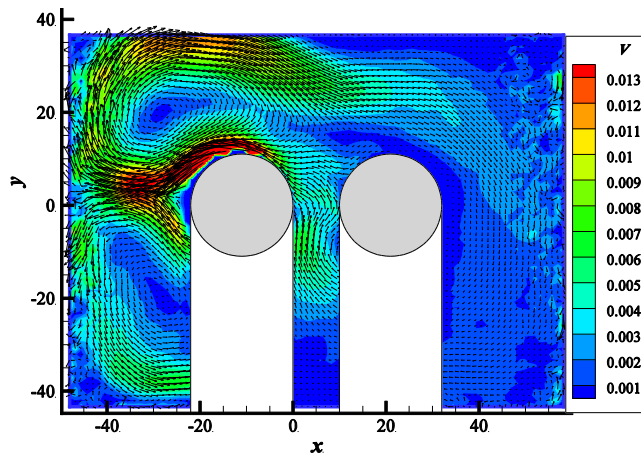


Fig. 6. Velocity vectors and contours with PTFE tracers.

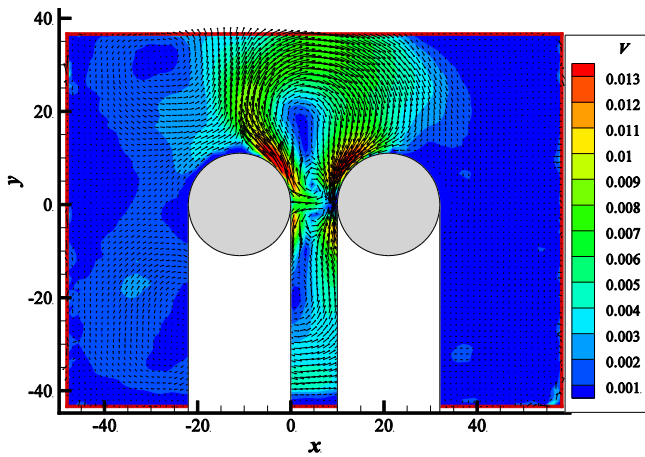


Fig. 7. Velocity vectors and contours with SiO_2 tracers.

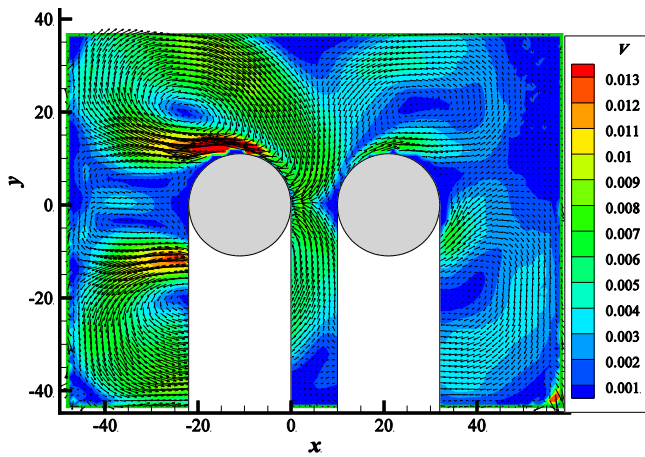


Fig. 8. Velocity vectors and contours with Vestosint tracers.

IV. DISCUSSION

The measurements with SiO_2 and Vestosint tracers showed not only a completely different velocity field with a completely different flow shape, but also incoherent results. The measurements were not repeatable, and this was caused by the reduction of the number of particles in suspension in the liquid.

On the other hand, the repeatability tests were also conducted with PMMA and PTFE tracers and results showed that PMMA velocity values decreased with time while PTFE results remained unchanged. These facts eliminate the choice of PMMA as convenient tracers for PIV measurements in HFE-7100. Moreover, even with PTFE particles, the velocity magnitude remains inaccurate and requires additional experiments. The reason is that one cannot judge based on only one criterion. A thorough study will be conducted with PTFE particles for a voltage ranging between 0 and 30 kV.

V. CONCLUSION

The EHD behavior of HFE-7100 was investigated in this paper. PIV measurements were conducted in a cylinder-to-cylinder geometry. Four seeding particles types were investigated: PMMA, PTFE, SiO_2 , and Vestosint. The only type that showed decent results was the PTFE. Two tracers (SiO_2 and Vestosint) showed erroneous results because of several parameters, mainly the deposition of particles on the cylinders and the cell surfaces. There were almost no particles in the liquid few minutes after the start of the

experiment. The last type (PMMA) showed similar results to PTFE but only at the beginning of the test because EHD forces were apparently weakened as the experiment was running.

Two important conclusions can be drawn from the experimental results. The first one is that the choice of seeding particles type is essential for having clean and satisfactory measurements. The mechanical and electrical properties of the tracers must not cause measurement problems like sedimentation in the liquid, particle charging and deposition on the electrodes, etc. The second conclusion is that most tracers interfere with the liquid and different behaviors are obtained when they are exposed to the same electric field. After several tests, it was found that the PTFE seeding particles were the only ones to give logical results in terms of consistency and repeatability. A future study describing the behavior of the fluid with respect to the applied electric field will be conducted in the near future.

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