

Validity of the Particle Image Velocimetry Measurement in Dielectric Fluid Subjected to External Electric Field.

Mohammed Hussein Hamede^{1,*}, Yaroslau Sliavin¹, Vasyl Motuz¹, Christoph Egbers¹

¹:Department of Aerodynamics and Fluid Mechanics, BTU Cottbus-Senftenberg, Cottbus, Germany

*Corresponding author: Hamede@b-tu.de

Keywords: Particle Image Velocimetry, Dielectric fluids, Thermo-electro hydrodynamics, Heat Transfer.

ABSTRACT

The use of particle-based flow measurement techniques, like Particle Image Velocimetry (PIV) is always controversial when a fluid is subject to an external electric field. The predominant concern in such instances pertains to particle charging, a phenomenon attributable to the electric field. In some cases, it has been observed that tracer particles accumulate electric charges on their surfaces, which may influence the electric field distribution within the fluid volume (Jones (1995)). Another issue that must be addressed is the interaction between the particles and the applied electric field, and the sedimentation velocity resulting from this interaction. The main question then arises: whether, and to what extent, these particles can still be considered tracer particles for an accurate Particle Image Velocimetry if their velocity greatly exceeds that of the flow. The present study aims to investigate the aforementioned concerns by conducting a series of experiments considering different tracer particles. To this purpose, the velocity flow field of a dielectric fluid (silicone oil Elbesil B5) confined within concentric differentially heated, horizontal cylinders, was investigated for four different types of particles. The four used in the investigation particles are ORGASOL, hollow borosilicate spheres, PTFE (Teflon) and Vestosint. The measurement of the flow field is conducted by means of particle image velocimetry. The flow is exposed to an external high-frequency alternating current (AC) electric field. The velocity fields of the fluid flow were measured for all four particle types, then analysed and compared with numerical simulations. This process was undertaken to determine the most suitable tracer particles for use in such flow configurations.

1. Introduction

The application of electric fields to confined fluids has long been, and continues to be, an active area of research in fluid mechanics. The resulting electrohydrodynamic (EHD) phenomena have been investigated from multiple perspectives, ranging from fundamental studies of the underlying physical mechanisms to the implementation of such flow configurations in industrial applications,

particularly for flow control purposes. EHD flows can be driven by three primary forces: electrophoretic, dielectrophoretic (DEP), and electrostrictive. While electrophoretic and electrostrictive forces can operate under isothermal conditions, dielectrophoretic effects are typically associated with non-isothermal environments (Yoshikawa et al. (2013)).

Focusing on the dielectrophoretic force, its application can be broadly categorized into two main areas. First, it is used to mimic central forces present in geophysical and astrophysical systems, such as those occurring in planetary cores. Second, under non-isothermal conditions, DEP can act as a driving mechanism for convective flow dynamics (M. Hamede et al. (2025); Mutabazi et al. (2016)). The latter case is of particular interest for engineering applications, including heat transfer enhancement and heat exchanger technologies.

In both contexts – whether for advancing fundamental understanding or for enabling industrial applications – experimental investigation of such flow configurations is essential. Among the various experimental techniques available for flow diagnostics, particle-based methods, particularly for velocity field measurements, are widely considered as promising candidates. The fundamental premise of this measurement technique is the assumption that the seeded particles in the flow follow it with precision. By capturing the motion velocity field of these particles, it is possible to deduce the flow velocity field. Nevertheless, the utilisation of these materials in electrically driven flows gives rise to significant concerns. These suspended particles subjected to electric fields may acquire charge or become polarized, resulting in local perturbations of the electric-field distribution within dielectric fluids Melcher (1981); Jones (1995). Furthermore, the interaction between the particles and the applied electric field should be taken into account, as it may induce particle motion and lead to a sedimentation velocity arising from electrohydrodynamic effects (Hamdi et al. (2014); Daaboul et al. (2023); Daaboul & Louste (2025)). The influence of the applied electric field on the tracer particles introduces uncertainty regarding their ability to follow the fluid motion accurately. This prompts a critical question: under the presence of an external electric field, can these particles still be considered reliable indicators of the movement of the dielectric fluid within that field?

In this study, we investigate dielectrical fluid flow confined within a horizontally oriented, concentrically arranged, differentially heated cylindrical configuration. The working fluid, silicon oil B5, is subjected to an externally applied high-frequency alternating electric field. The behaviour of the thermo-electrohydrodynamic fluid flow in this configuration has been investigated and analyzed in detail in a previous study by M. H. Hamede et al. (2024). The application of an electric field to a dielectric fluid induces molecular polarization, which in turn generates an electrohydrodynamic (EHD) body force. When the frequency of the applied electric field exceeds the inverse of the fluid's charge relaxation time, the accumulation of free charges is suppressed. Under these conditions, the dielectrophoretic (DEP) force dominates over the Coulomb force. The resulting DEP-driven motion can be interpreted as analogous to buoyancy effects, leading to an artificial

body force often referred to as “electric gravity,” as discussed by Yoshikawa et al. Yoshikawa et al. (2013).

The primary objective of the present work is to assess the reliability of velocity field measurements obtained using particle image velocimetry. For the flow configuration under consideration, the mean flow structure is characterized by a pair of crescent-shaped, counter-rotating convective cells, which enhance heat transfer between the inner and outer cylinders. Previous findings have shown that the application of an electric field intensifies these convective structures, leading to increased flow velocities and a corresponding enhancement in heat transfer. To validate the PIV measurements, experiments are conducted under identical operating conditions while employing different tracer particles at the same concentration. The validation procedure is carried out in two steps. First, the experimentally measured velocity fields are compared with numerical results. Second, the influence of the tracer particles and their interaction with the applied electric field on the global flow response is evaluated, using heat flux as the primary indicator. The ultimate goal is to identify the most suitable tracer particles for accurate velocity measurements in electrohydrodynamically driven flows.

2. Experimental setup and measurement techniques

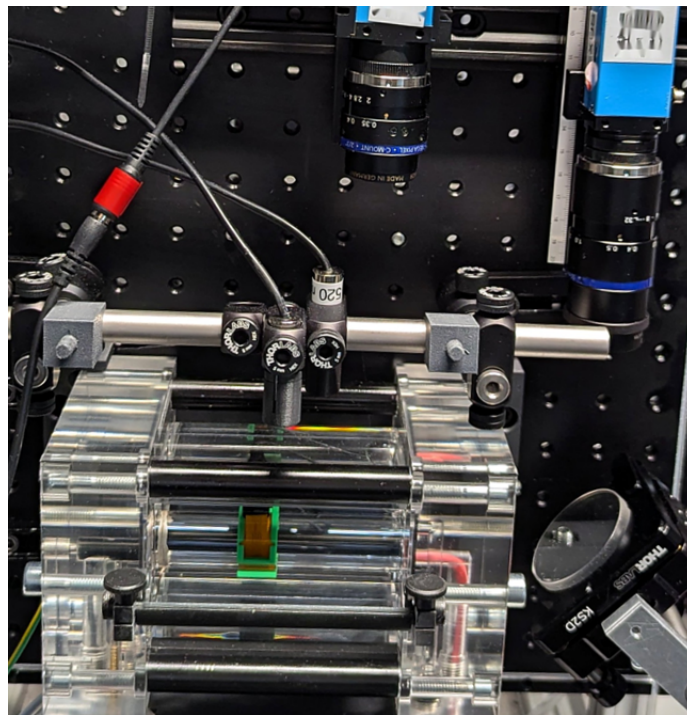


Figure 1. Experimental setup showing the annular test cell, the PIV system's optical arrangement and the heat flux sensor mounted around the outer glass cylinder in the green holder.

The experimental configuration consists of a concentric annular geometry formed by two coaxial cylinders (Figure 1). The inner aluminum cylinder ($R_i = 5$ mm) and the outer borosilicate glass cylinder ($R_o = 10$ mm) define a gap of width $d = 5$ mm, yielding a radius ratio $\eta = 0.5$. The system height is $L = 100$ mm, corresponding to an aspect ratio $\Gamma = 20$. The outer cylinder is coated internally with a transparent indium tin oxide layer serving as the electrode. The annular gap is filled with silicone oil Elbesil B5, whose properties at 25°C are $\nu = 5 \times 10^{-6}$ m²/s, $\kappa = 7.4 \times 10^{-8}$ m²/s, $\rho = 870$ kg/m³, and $\epsilon = 2.04 \times 10^{-11}$ F/m. An AC voltage $V(t) = V_p \sin(2\pi ft)$ is imposed on the outer cylinder, while the inner cylinder remains grounded. The forcing frequency is fixed at $f = 200$ Hz with amplitudes up to 20 kV. The thermal boundary conditions are controlled by circulating silicone oil (Elbesil B5) as a coolant within the acrylic enclosure. This external bath cools the outer cylinder by forced convection, whereas the inner aluminium cylinder is heated internally via a cartridge heater. The similarity in the refractive indices of the materials used for the outer cylinder and the walls of the coolant reservoir, as well as those of the working fluid and the coolant, helps to minimise optical distortion.

Flow characterization is performed using PIV in a single measurement plane, combined with heat flux measurements at the outer boundary. The flow is seeded with tracer particles and illuminated by a continuous laser sheet aligned in the radial–azimuthal (r – θ) plane at mid-height. Image acquisition is carried out using a GigE camera (ImagingSource DMK 33GX174) equipped with optical filtering. Image sequences are recorded at 6 Hz and processed using the MATLAB MatPIV package. Calibration follows established described by M. H. Hamede et al. (2023).

Heat transfer is quantified by a HukseFlux sensor wrapped around the outer cylinder, covering most of its circumference. The sensor operates as a thermopile, converting temperature differences into a voltage proportional to the local heat flux. It has an active area of 15×85 mm² and a sensitivity of $S = (8.81 \pm 0.44) \times 10^{-6}$ V/(W/m²). The output signal is conditioned prior to acquisition using high-precision instrumentation. All measurements are conducted under controlled laboratory conditions. Before each experiment, steady thermal conditions corresponding to the target ΔT are established. The working fluid is gently mixed prior to acquisition to ensure a homogeneous distribution of tracer particles.

2.1. Tracer particles selection

As stated earlier, the aim of this work is to evaluate different tracer particles and determine the most suitable candidates for velocity measurements in the flow configuration investigated. To this end, five types of tracer particles are considered:

- ORGASOL 2001 EXD NAT 1 and ORGASOL 2002 ES3 NAT 3 (Arkema S. A.), with mean radii of $R_p = 5$ μ m and $R_p = 15$ μ m, respectively.

Table 1. The material characteristics of the different tracer particles used in this study.

	Density (kg/m^3)	Electric Conductivity (S/m)	Relative Permittivity (ϵ_r)
ORGASOL	1015	2.9	10^{-13}
Vestosint	1015	3	10^{-13}
HGS	1100	4.6	10^{-14}
PTFE	2140	2.1	10^{-16}

- VESTOSINT 2157 (Evonik Industries), with a mean radius of $R_p = 5 \mu m$.
- Hollow glass spheres (HGS) made of borosilicate glass (Potters), with a mean radius of $R_p = 5 \mu m$.
- Polytetrafluoroethylene (PTFE, Teflon) particles, with a mean radius of $R_p = 5 \mu m$.

The characteristics of the tracer particles are summarized in Table 1. For all particle types, the concentration relative to the working fluid is kept constant at 0.1 g/L throughout the experiments.

The particle selection was based on investigating tracers composed of different materials and exhibiting different physical properties. Prior to the experiments, the sedimentation velocity of a spherical particle subjected to the DEP force was estimated using the expression proposed by Seelig et al. (2019):

$$\mathbf{V}_{sed} = \frac{\epsilon R_p^2 V_p^2}{6\rho\nu (\ln \eta)^2} \frac{(\epsilon_p - \epsilon)}{(\epsilon_p + 2\epsilon)} \mathbf{e}_r. \quad (1)$$

For the tracer particles considered in this study, and for a maximum applied electric potential of $V_p = 16$ kV, the sedimentation velocity $\mathbf{V}_{sed}$ varies between 8×10^{-6} m/s for ORGASOL 2001 particles and 6.3×10^{-5} m/s for the hollow glass spheres (HGS). Even in the latter case, the predicted sedimentation velocity remains negligible compared with the characteristic flow velocity. Nevertheless, whether $\mathbf{V}_{sed}$ alone constitutes a sufficient criterion for tracer particle selection is further examined in the next section.

Although some of the investigated particles, such as VESTOSINT and PTFE, have already been considered in previous studies (Daaboul et al. (2023)), the present work aims at performing a systematic comparison between the different tracer types. In particular, VESTOSINT and ORGASOL particles are compared since they are composed of similar base materials, while PTFE particles are assessed against the remaining tracers in terms of measurement accuracy. Furthermore, two ORGASOL particle sizes are investigated in order to evaluate the influence of particle size on the interaction with the applied electric field.

3. Results

In order to achieve the objectives of this study, it is necessary to select a specific flow configuration. The present study focuses on the DEP-driven force in a confined, differently heated annular geometry in a horizontal configuration. The rationale behind this selection is that, as previously examined by M. H. Hamede et al. (2024), the stable crescent-shaped natural convection cell can withstand high electric fields of up to approximately 15-16 kV. With an increase in the applied electric field, the convection cells experience an enhancement in strength without altering the mean flow organization. This facilitates the capture of the flow and the comparison of velocity mean profiles, even in cases involving higher electric fields. A further rationale pertains to the numerical analysis of the flow in the prevailing configuration undertaken by M. H. Hamede et al. (2024). This facilitates a comparative analysis of the current findings with numerical data. Nevertheless, the objective of this study is not to investigate this flow dynamics in itself, but rather to utilise it for the purpose of investigating the paper's stated objective. Furthermore, all results about this study are derived from experiments, and the numerical data will be taken from M. H. Hamede et al. (2024). Further details about the numerical calculation and method can be found there. No details will be presented here.

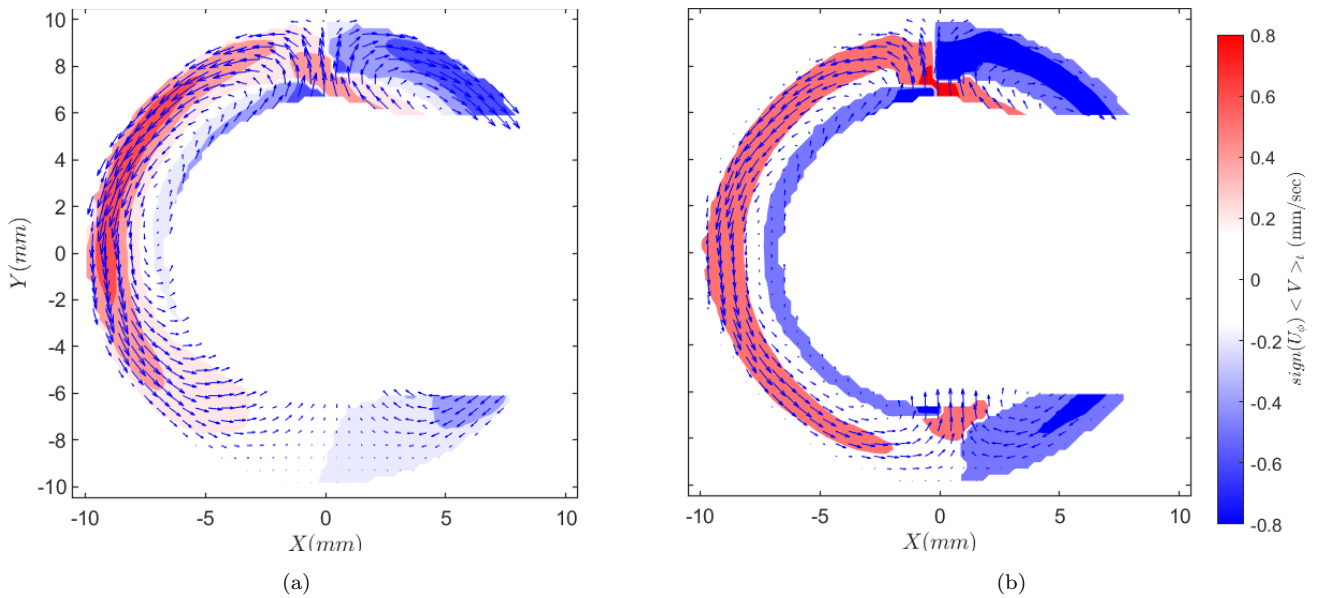


Figure 2. Flow velocity field evaluated by PIV measurements at the radial-azimuthal plane in the apparatus mid-height for $\Delta T = 7K$ and (a) $V_p = 0$ kV, (b) $V_p = 16$ kV. The plots present the temporally averaged velocity magnitude multiplied by the sign of the temporally averaged azimuthal velocity component. The superimposed arrows indicate the direction of the flow and its magnitude.

3.1. Velocity field

Figure 2 presents quiver plots of the velocity field for $\Delta T = 7$ K under (a) $V_p = 0$ kV and (b) $V_p = 16$ kV. Although the magnitude of the velocity field differs significantly between the two cases, the overall flow structure remains unchanged. The hot fluid rising along the heated inner cylinder and the cold fluid descending near the cooled outer cylinder generate a pair of crescent-shaped convective cells. These velocity field distributions are shown in order to illustrate the mean velocity profiles, used in the subsequent analysis for assessing the reliability of the tracer particles.

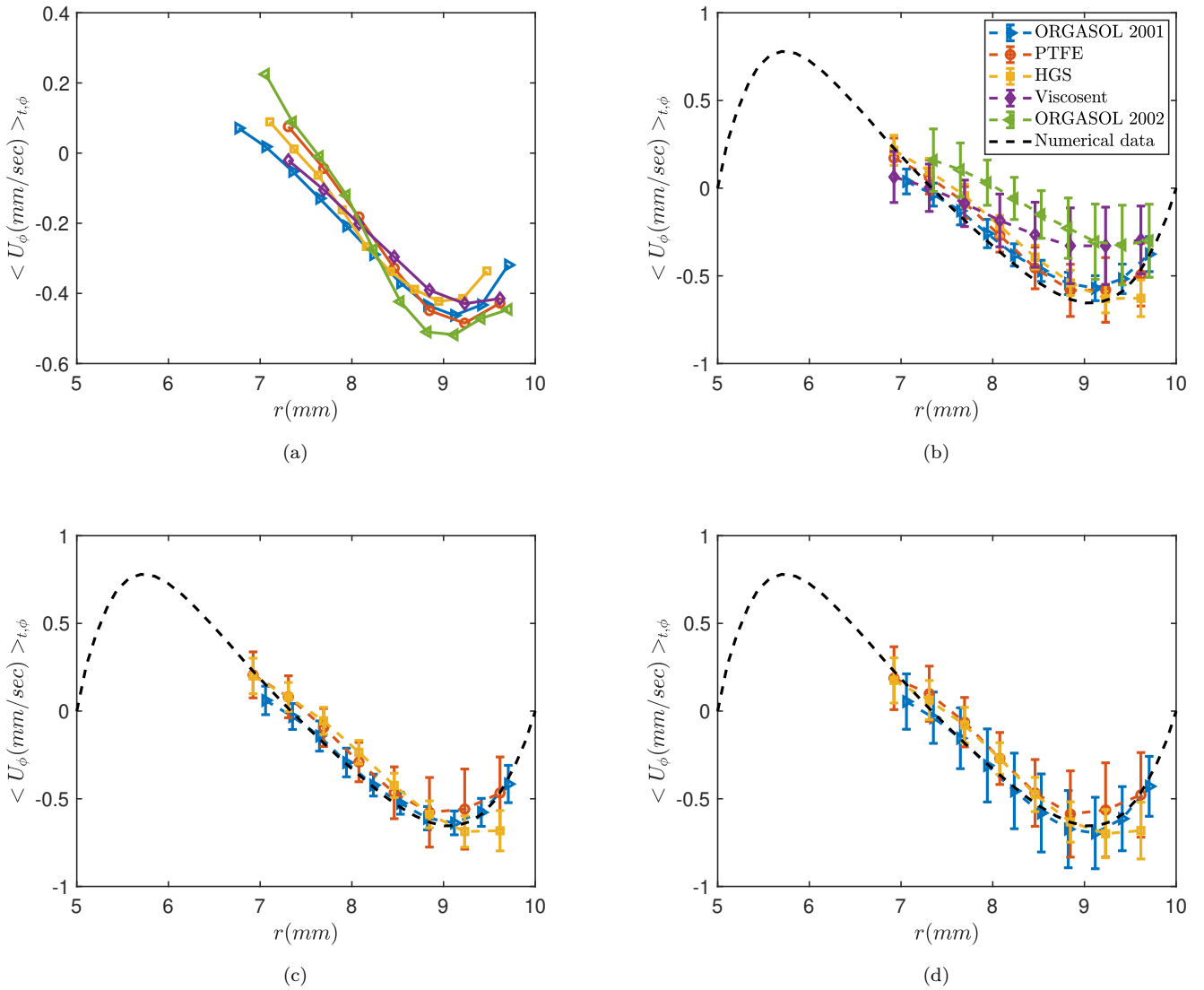


Figure 3. Spatially and temporally averaged radial profiles of the azimuthal velocity component (U_ϕ) for $\Delta T = 7$ K under (a) $V_p = 0$ kV, (b) $V_p = 10$ kV, (c) $V_p = 12$ kV, and (d) $V_p = 14$ kV. The error bars indicate the standard deviation of the experimental measurements. The profiles obtained from PIV measurements using different tracer particles are compared with the corresponding numerically computed mean profiles.

Figure 3 shows the radial profiles of the spatially and temporally averaged azimuthal velocity component U_ϕ , which is the dominant component of the flow velocity field in the bulk. The profiles are evaluated over a single pair of the crescent-shaped convective cell shown in Figure 2. The measurement procedure is identical for all experimental cases. After setting the flow parameters, a waiting time of approximately 10 minutes is imposed before data acquisition. This duration exceeds both the characteristic thermal and viscous time scales, ensuring that the flow reaches a statistically steady state. The measurements are then recorded over a period of 1 minute, and the presented profiles correspond to temporal averages over this interval.

For the case without an applied electric field ($V_p = 0$), Figure 3(a) shows that the velocity profiles obtained using most of the investigated tracer particles with characteristic sizes of approximately $10\ \mu\text{m}$ collapse reasonably well onto a single curve. The only profile exhibiting a noticeable deviation corresponds to the measurements performed using ORGASOL 2002 particles of size $30\ \mu\text{m}$, which are approximately three times larger than the remaining particles. This discrepancy can likely be attributed to the increased sedimentation effects caused by buoyancy.

After applying the electric field, the differences between the profiles become more pronounced. Figure 3(b) presents the results for $V_p = 10\ \text{kV}$. In this case, the profiles obtained using ORGASOL 2002 and VESTOSINT particles exhibit significant deviations from both the numerical results and the profiles measured using the other tracer types. In contrast, the profiles obtained using HGS, PTFE (Teflon), and ORGASOL 2001 particles remain in relatively good agreement, with only minor discrepancies compared with the numerical data. However, it can be observed that the HGS profile departs from the others in the vicinity of the outer cylinder wall. Another important observation is that the standard deviation associated with the PTFE measurements is larger than that obtained with ORGASOL $10\ \mu\text{m}$ and HGS particles. This behavior becomes increasingly pronounced in Figures 3(c) and (d) as the electric potential V_p is further increased. From the results presented

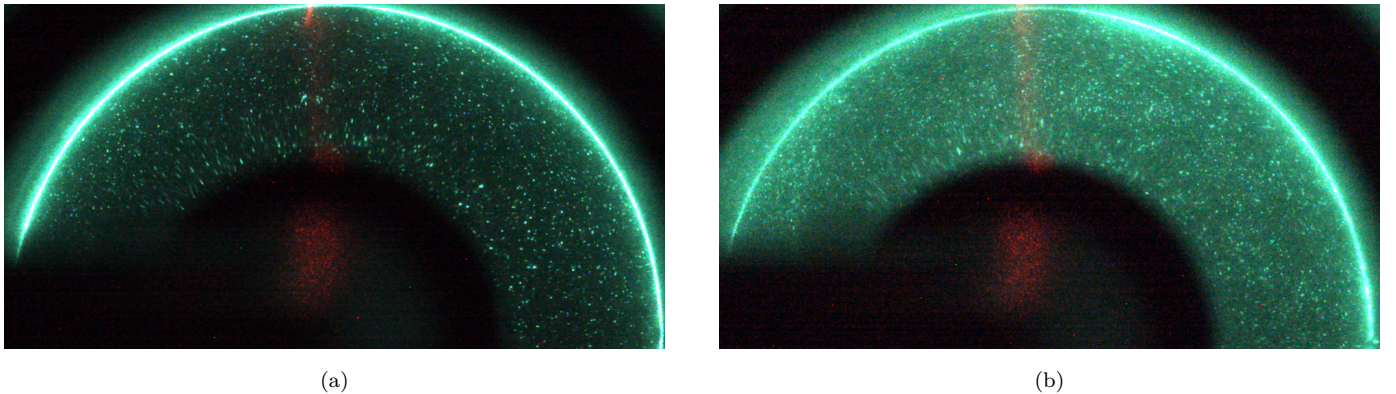


Figure 4. Raw PIV images for $\Delta T = 7\ \text{K}$ under (a) $V_p = 0\ \text{kV}$ and (b) $V_p = 14\ \text{kV}$. The images illustrate the distribution of ORGASOL 2001 tracer particles under the two operating conditions.

above, an initial conclusion can be drawn indicating that the ORGASOL 2001 particles provide the highest measurement accuracy among the investigated tracer types. This observation is further

supported by Figure 4, where the particle distributions are compared for the cases of $V_p = 0$ kV and $V_p = 14$ kV. It can be observed that the particle distribution remains nearly unchanged after the application of the electric field, suggesting that the ORGASOL 2001 particles are only weakly affected by the imposed electric forcing.

3.2. Heat flux

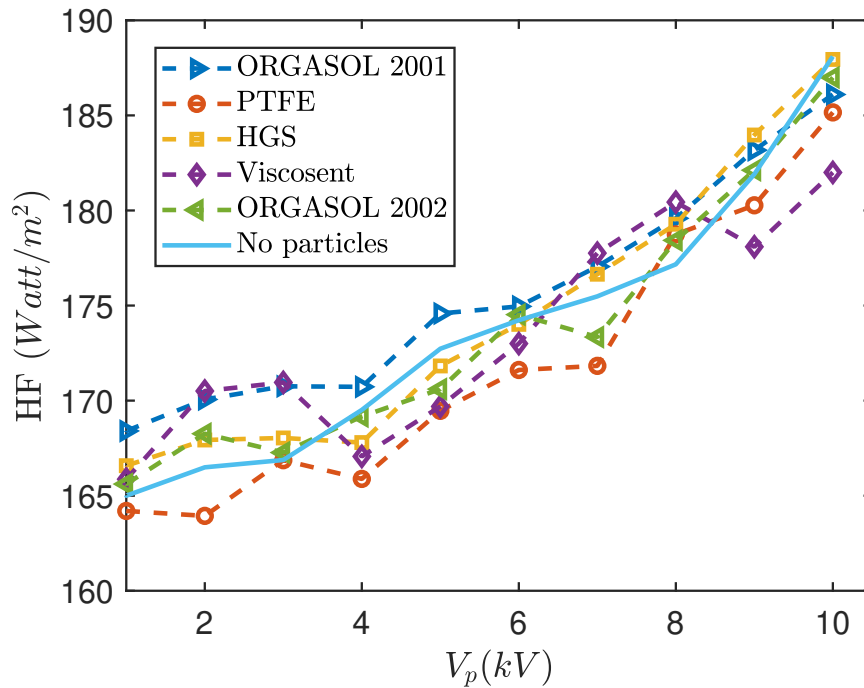


Figure 5. Average heat flux (HF) for $\Delta T = 7$ K as a function of the applied electric potential (V_p), for flows seeded with different tracer particles and compared with the reference case of pure fluid without added particles.

The initial hypothesis of this study was that the sedimentation velocity induced by the interaction between the tracer particles and the applied electric field could generate additional shear within the flow, thereby modifying the flow dynamics. To evaluate this hypothesis, the heat flux was measured for the different experimental cases. The rationale behind this approach is that any additional shear induced by the particles, or any enhancement of conductive heat transfer caused by their presence, would affect the overall heat transfer of the system and consequently modify the measured heat flux. To investigate this effect, the heat flux was first measured in the absence of tracer particles. This reference case serves as a benchmark for evaluating the influence of the particles on the global flow response. Subsequently, measurements were repeated after introducing the different tracer particles into the flow, and the resulting heat flux values were compared with those obtained for the pure fluid. In parallel, velocity field profiles were measured once the

flow had reached its saturated state. The corresponding results are presented in Figure 5. The results indicate that, for the investigated tracer particles, no significant influence on the measured heat flux is observed. The small discrepancies between the measured values and the reference case without particles remain within the uncertainty range of the heat flux sensor. These findings, together with the previously estimated values of V_{sed} for the different particle types, suggest that the inaccuracies observed in the PIV measurements for certain particles—particularly VESTOSINT and ORGASOL 2002—cannot be attributed solely to the additional particle velocity induced by the electric field interaction. Therefore, another mechanism must be responsible for the observed measurement discrepancies.

4. Discussion and conclusion

From the results presented above, as well as from the analysis of the raw PIV images, a significant decrease in the number of visible particles within the annular gap was observed for the cases involving VESTOSINT and ORGASOL 2002 particles as the applied electric potential V_p increased. The apparent disappearance of tracer particles from the bulk flow under the action of the applied AC electric field can be attributed to polarization adhesion strength (PAS), corresponding to the attractive interaction between polarized particles and nearby solid surfaces.

Unlike conventional electrostatic adhesion, PAS does not require the particles to carry a permanent electric charge. Instead, when exposed to an external electric field, the particles become polarized through induced dipole formation. These induced dipoles interact both with local electric field gradients and with image charges generated at dielectric interfaces, producing an attractive force toward the surrounding walls or electrode surfaces.

In the present configuration, although the dielectric permittivity mismatch between the VESTOSINT particles and the silicone oil is relatively small, the applied high-voltage AC electric field remains sufficient to induce particle polarization. Consequently, the particles tend to migrate toward regions of stronger electric field gradients, particularly near solid boundaries. Once close to the wall, polarization adhesion forces may retain the particles near the surface, progressively decreasing their concentration within the bulk flow region. As a result, an apparent depletion of particles inside the measurement domain is observed during operation. A similar behavior is also observed for the ORGASOL 2002 particles. In the case of the HGS particles, this effect is present but less pronounced, mainly appearing in the vicinity of the walls where the particle concentration decreases significantly, and can be attributed to HGS high electric permittivity value.

Although VESTOSINT and ORGASOL particles are both polyamide-based materials with relatively similar density and dielectric permittivity, their behavior under high-frequency high-voltage AC electric fields differs substantially. This suggests that the dominant governing parameter is not solely the bulk dielectric permittivity, but also the surface state of the particles, including surface

functional groups, additives, morphology, residual impurities, triboelectric charging tendency, and particle size. This observation is further supported by the comparison between ORGASOL 2001 and ORGASOL 2002 particles, where the larger particle size appears to enhance PAS effects and consequently increase measurement inaccuracies.

In summary, the results of the present study indicate that ORGASOL 2001, PTFE, and HGS particles can be considered reliable tracer particles for PIV measurements in silicone-oil dielectric fluids subjected to external electric fields. Among these tracers, ORGASOL 2001 exhibits the best overall performance and the weakest sensitivity to PAS effects. Nevertheless, the conclusions of this study cannot be generalized to all dielectric fluids and tracer materials, since the particle behavior under applied electric fields is influenced by several factors beyond dielectric permittivity alone.

Acknowledgements

The authors acknowledge the support of Mohammed Khader Ahmed, who worked as a student and assisted during the PIV measurements. This work was funded by Deutsches Zentrum für Luft und Raumfahrt (DLR) in the framework of the project "Dielektrophoretisch induzierte Konvektion (DEPIK)" under Grant No. 50WM2244. We also want to sincerely thank Tark Raj Bista for technical support.

References

- Daaboul, M., & Louste, C. (2025). Validity of particle image velocimetry measurements in electrohydrodynamic flows. *Experimental Techniques*. doi: 10.1007/s40799-025-00806-4
- Daaboul, M., Matar, I., Nassar, M., & Louste, C. (2023). Testing different tracer types in particle image velocimetry measurements in electrohydrodynamics. *IEEE 22nd International Conference on Dielectric Liquids*. doi: 10.1109/ICDL59152.2023.10209310
- Hamdi, M., Havet, M., Rouaud, O., & Tarlet, D. (2014). Comparison of different tracers for piv measurements in ehd airflow. *Experiments in Fluids*, 55 (1702).
- Hamede, M., Siliavin, Y., Motuz, V., & Egbers, C. (2025). The effect of flow initial conditions and geometry on the saturation of the thermo-electrohydrodynamic instability within microgravity conditions. *Physics of Fluids*, 37(094129).
- Hamede, M. H., Merbold, S., & Egbers, C. (2023). Experimental method for investigating the formation of flow patterns in a very wide gap taylor-couette flow ($\eta = 0.1$). *tm - Technisches Messen*, 90(5).

- Hamede, M. H., Roller, J., Meyer, A., Heuveline, V., & Egbers, C. (2024). Dielectrophoretic force-enhanced thermal convection within a horizontal cylindrical annulus. *Physics of Fluids*, 36(12).
- Jones, T. (1995). Electromechanics of particles. *Cambridge University Press, New York*.
- Melcher, J. (1981). Continuum electromechanics. *MIT Press, Cambridge, MA*.
- Mutabazi, I., Yoshikawa, H., Tadie, M., Travnikov, V., Crumeyrolle, O., Futterer, B., & Egbers, C. (2016). Thermo-electro-hydrodynamic convection under microgravity: A review. *The Japan Society of Fluid Mechanics*, 48(6):061413, 17. doi: 10.1088/0169-5983/48/6/061413
- Seelig, T., Meyer, A., Gerstner, P., Meier, M., Jongmanns, M., Baumann, M., ... Egbers, C. (2019). Dielectrophoretic force-driven convection in annular geometry under earth's gravity. *Int. Journal of Heat and Mass Transfer*, 139, 386-398.
- Yoshikawa, H. N., Crumeyrolle, O., & Mutabazi, I. (2013). Dielectrophoretic force-driven thermal convection in annular geometry. *Phys. Fluids*, 25, 024106.