International Workshop on Electro-Hydrodynamics and Triboelectrostatics

Abstracts

1st session

Fluid and particles motion versus electrical quantities
Gérard Touchard
This presentation is a kind of historical review from the 6th century BC up to recent work. It mainly summarizes already known phenomena concerning the electrical effect induced by motion of fluid or particles and as well fluid or particles motion due to electrical phenomena.
Description of historical experiments and observation is made, then some simple experiments are presented which make in evidence different phenomena.
Finally several applications of EHD phenomena are briefly presented, like:
- Electrostatic painting
- Taylor pump
- EHD conduction pumping
- EHD ion drag pumping
- EHD travelling wave pumping
- Electrified jet
- Electrospinning
- Micropump
- Tribolelectrification and electrostatic hazard
- Separation and precipitation
- ....
-.....

Stability of subcritical electrohydrodynamics in dielectric fluids.
Mengqi Zhang,Fulvio Martinelli, Jian Wu, Peter J. Schmid and Maurizio Quadrio
We present the results of modal and non-modal linear stability analyses and then a weakly nonlinear stability analysis of electrohydrodynamics (EHD) in dielectric fluids, subject to the strong injection and confined between two infinite parallel electrodes, in both cases with and without cross-ow. The effect of electric charge diffusion has been taken into account and discussed thoroughly. For the linear stability analysis, we found in hydrostatic EHD that the fluctuation energy growth due to the linear non-normal effect is limited, which is thus not able to account fully for the subcritical features of hydrostatic EHD, nor the discrepancy between the theoretical Tc and the experimentally determined Tc (T: the electric Rayleigh number). The charge diffusion exerts a destabilizing effect on the flow in both modal and non-modal analyses. When a pressure-driven cross-flow is added in EHD, our results indicate that the cross-flow becomes more unstable and its transient growth is higher under the influence of electric field. From a point of view of the non-normal mechanism, this pronounced transient growth is due to the enhanced lift-up mechanism in the channel ow by the vertical flux provided by the electric field, helping to form the streamwise rolls. For the weakly nonlinear analysis, we found in hydrostatic EHD that the stronger the electric charge diffusion, the

smaller the destabilising effect of weakly nonlinear EHD ow in the early phase of the disturbance development. From these results, we can infer that the actual finite-amplitude critical Tf should be higher than the values predicted in the previous works without taking into account the charge diffusion effect. The weakly nonlinear EHD ow subject to a Poiseuille ow is then considered. Our results show that the electric field destabilizes the Poiseuille flow in the weakly nonlinear phase. Therefore, the subcritical Poiseuille flow becomes more vulnerable in its transition to turbulence. Interestingly, by looking into the detailed physical mechanism of this process, we found that it is not the electric field that contributes directly to the subcriticality of the EHD-Poiseuille system, but rather, the modified Poiseuille flow field by the electric field that renders the whole flow system more subcritical.

Thermo-electrohydrodynamic convection in a differentially heated vertical slot
Harunori Yoshikawa, Innocent Mutabazi, & Masato Nagata

Application of a high-frequency a.c. electric field to a non-isothermal layer of dielectric fluid generates convective flow though the Thermo-Electrohydrodynamic (TEHD) instability. The driving force is dielectrophoretic (DEP) one, which arises from the thermal variation of dielectric permittivity ε. This convection has attracted geophysicists' interest, as the DEP force can be regarded as thermal buoyancy force in an electric effective gravity $g_e \propto \nabla E^2$, where E is the applied electric field. One can simulate thermal convection under different gravity conditions through this analogy by using different geometrical configurations of electrodes. In particular, the analogy enables us to examine global scale geophysical flows in a laboratory experiment with concentric spherical electrodes, e.g., Mantle convection considered in the GeoFlow experiments [1].

A number of theoretical, numerical, and experimental investigations have been done recently in different electrode configurations [2]. In the present talk, we report a theoretical study on the TEHD convection for moderate Prandtl number fluids ($\mathrm{Pr} \le 10$) in a tall vertical slot, where the lateral walls serve as planar electrodes imposing a temperature gradient as well as an electric field to a fluid layer (Fig. 1a). If both Grashof and electric Rayleigh number, $Gr = \alpha \Delta T g d^3 / \nu^2$ and $L = \alpha \Delta T g_e d^3 / \nu\kappa$, respectively, are small, the flow system is in conduction regime, where natural convection develops to form a vertical shear flow except in the regions near the top and bottom walls. Either Gr or L exceeds a critical value, instabilities arise and a cellular secondary flow develops. The flow state in this convection regime is determined by seeking numerically an exact solution of governing nonlinear equations in the Fourier-Chebyshev spectral space. The flow behavior in the vicinity of the critical state is determined by following the path of solution in the Gr-L phase space. The Nusselt number Nu is computed to show that the Earth's gravity affects significantly the heat transfer in the TEHD convection (Fig. 1b).

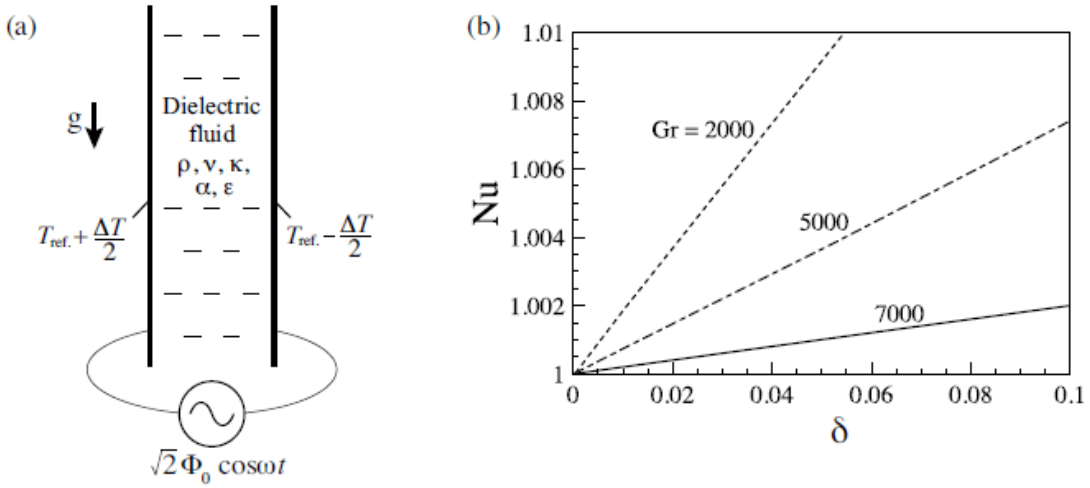

Figure 1. (a) Geometrical configuration. Space between two parallel planar electrodes of infinite height is filled by a dielectric fluid (density ρ, kinematic viscosity ν, thermal diffusivity κ, thermal expansion coefficient α, dielectric permittivity ε). (b)

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Electrode's arrangement impact on heat transfer enhancement in horizontal channels
Rahma Gannoun, Walid Hassen, Mohamed Naceur Borjini, Habib Ben Aissia

Electrohydrodynamic effect on natural convection in horizontal channels is investigated from a numerical point of view. The EHD effect is induced by narrow strip electrodes placed at the heated bottom wall of the channel. Thus the channel is subjected to the simultaneous action of a temperature gradient and an electric field; the vertical and top walls are adiabatic. The interactions between electric field, flow field and temperature field are analyzed. It can be concluded that charge density distribution, flow pattern and temperature distribution are substantially affected by the electrodes' arrangement, in fact four different electrode's arrangement were treated and it is noted that the optimum electrode's arrangement provides an increase of heat transfer of up to 13%.
The effect of the applied electric Rayleigh is studied in a second stage in order to highlight the importance of putting compromise between the supplied voltage and electrode's arrangement.

Keywords: Heat transfer enhancement; Electro-thermoconvection; Natural convection; electrode's arrangement; Computational fluid dynamics; Dielectric fluid.

Estimation of the injection law using dynamical current-voltage characteristics.
A.V. Gazaryan, V.A. Chirkov, A.A. Sitnikov, Yu.K. Stishkov

The improvement of injection EHD devices is hindered by the absence of the necessary information on the injection law (i.e., functional dependence of injection current density on the electric field strength). Investigation of the issue presents a great challenge because the

quantity measured experimentally is the total current that is dependent on some almost inseparable factors. Moreover, the present theoretical dependences contradict each other and have not been verified by the experiment. In view of this, the determination of injection function is an actual problem and this paper is devoted to an attempt to solve it.
The proposed approach bases on a comparison of the so-called dynamical current-voltage characteristics, which were obtained as a result of computer simulation and in the experiment. The computer simulation rests on the solution of the Nernst-Planck, Poisson and Navier Stokes set of equations using COMSOL Multiphysics software package. The computations involve a testing function of injection, whose form is iteratively refined by comparison with experimental data. The correctness of the proposed injection function was confirmed by comparing the velocity distributions, obtained using computer simulation and using PIV experiment.

Changing of the ionic wind direction in accordance with the inclination of the corona-producing electrode.

I.A. Elagin, D.I. Begal, A.V. Samusenko, I.A. Ashikhmin, Yu.K. Stishkov

The work reports the experimental study of the ionic wind structure in the needle-plane electrode system. The positive corona was studied. With the electrode gap and voltage fixed, the needle inclination angle was varied. To visualize the flows and obtain the velocity distributions in the region of interest with a high spatial resolution, a modern laser anemometry unit was used.
The volume charge density drops sharply in the direction from the needle to the plane, so the effective action region of the Coulomb forces contributing most to the acceleration of air flows has typically a size on order of 1 mm. The direction of the Coulomb forces in the region is governed mainly by the geometry and the spatial position of the corona-producing electrode. The narrow central jet of the ionic wind has been shown to change its direction substantially in accordance with the inclination angle of the corona-producing electrode.
3D computer simulation of ionic wind is implemented in unipolar approximation. Ions flux variation rate constraint is the form of boundary condition on high voltage electrode. The computer model provides opportunity to reveal Coulomb volume force distribution peculiarities which occur by inclination angle variation. Computed air velocity distributions are compared with experimental PIV-data.

Dynamical current-voltage characteristics and their application for the investigation of EHD phenomena.

V.A. Chirkov, A.A. Sitnikov, Yu.K. Stishkov

EHD technologies that bases on the electroconvection phenomena are very promising ones and, moreover, they have already found industrial application. However, to provide their development one has to carry out comprehensive investigation of EHD-flow pattern, which, in turn, calls for choosing seeding particles, control of reproducibility and stability with time, and, at last, understanding the prevailing charge formation mechanism.
The corresponding research can be simplified and its quality can be increased if one supplement the investigation with measuring so-called dynamical current-voltage characteristics (DCVC), i.e. classical current-voltage ones obtained with the voltage sawtooth modulation. Such an approach has a lot of advantages over other techniques for the diagnostics of the dielectric-liquid state: the simplicity, the sensitivity and the rapidity of the data acquisition. Moreover, the measurement of a DCVC allows one to control factors strongly affecting the total electric current passing through a high-voltage device such as the

presence of mechanical impurities, change in the intensity of EHD flows and the injection charge formation, etc.
The paper presents the description of experimental set-up, simulation technique, and the original results demonstrating the advantages of using DCVC for the investigation of EHD phenomena.

2nd session

Electrohydrodynamics of dispersed drops of conducting liquid: from drops deformation and interaction to emulsion evolution
Pierre Atten
The interaction and behaviour of droplets of conducting liquid suspended into an insulating medium and subjected to an electric field are considered, in particular with relevance to electrical treatment of water-in-oil emulsions. Firstly, the action of an electric field on two close drops is examined. In the static case of anchored drops which attract each other, results are recalled concerning the interfaces deformation and disruption under the field action. In the dynamical case of free drops, their spacing decreases with time until interface instability creates a bridge; in the asymptotic case of very close small droplets, a model is presented which predicts the time for draining the oil film between the droplets. The formation of a bridge between the drops does not necessarily lead to their merging. Examples of partial coalescence and bouncing with charge exchange are presented and qualitative explanations are proposed. The two-drop behaviour under field leads to some insight on the evolution of a water-in-oil emulsion subjected to an AC electric field. In a stagnant emulsion, electrocoalescence results first in a fast increase of the droplets mean size and, finally, in a quasi steady arrangement of nearly equally spaced big drops in rows aligned with the field. In a flowing emulsion, the shear and turbulence play the major role in promoting quasi collisions of droplets, the electric field leading to coalescence if the film draining time is lower than the time of close proximity of drops.

Antonio Castellanos and Galilean Electromagnetism : A Historical Perspective.
Germain Rousseaux
In this presentation, I will talk of Galilean Electromagnetism, a subject of great interest for Antonio Castellanos. Indeed, Galilean Electromagnetism consists in the quasi-statics approximation(S) of Classical Electromagnetism compatible with Galilean Relativity. It has many implications in EHD, MHD, electronics, theoretical Physics... I will underline the contribution of Antonio and his influence on my own understanding of Galilean Electromagnetism.

Long jets generated by ac electric fields in a microfluidic flow-focusing junction.
Pablo García-Sánchez, Elena Castro-Hernández and Antonio Ramos
We use a microfluidic flow-focusing device with integrated electrodes and show that very long water jets can be formed upon application of AC voltages (see figure 1). We report measurements of the jet length as a function of water conductivity and amplitude and frequency of the signal. For frequencies below a threshold value, we find an abrupt transition from a well-behaved uniform jet to highly unstable non-axisymmetric liquid structures. We study the electrical response of the long jet via a distributed parameter circuit model. The

model allows us to estimate the voltage amplitude at the tip of the long jets revealing that, for any combination of the electrical parameters, jet breakup occurs for a critical value (V_{pp}~550 volts for our experimental conditions). In order to understand the effect of electrical forces against surface tension, we perform an analysis of the free energy of the system. The analysis predicts a jet length that is close to the experimental measurements.

Experimental study of Electrohydrodynamic conduction pump with a symmetric geometry.

Sachin Modh, Cristophe Louste, Philippe Traoré.

This paper presents the results of a parametric study of an electrohydrodynamic pump with a symmetric geometry. In an ElectroHydroDynamic pump, liquids are pumped or mixed without any mechanical parts. Three types of Electrohydrodynamic pumps can be founded in the literature: the ion drag pump, the electro-osmosis pump and the conduction pump. In a conduction pump, heterocharge layers develop on the electrode surfaces. These charge layers are created by the process of dissociation of neutral electrolyte species into ions and the recombination of the generated ions. In the presence of an electric field, a Coulomb force is produced inside the heterocharge layers, and the liquid is set in motion.

In the present work, the conduction pumping mechanism is experimentally investigated with four different washer-type electrode geometries (Inner diameter 0.5mm to 3mm, outer diameter 12mm, thickness 1mm,) and five different types of spacers (Inner diameter 10mm, outer diameter 12, thickness 5mm to 1mm,). In this paper, the working fluid is a dielectric liquid (HFE-7100). The maximum static pressure difference achieved with one electrode pair is 600Pa at 14KV. Measured pressure heads and current levels are compared for different sizes of circular holes and spacers. The generated pressure makes conduction pumping attractive for mass transport and heat transfer applications.

Validation of the Particle Image Velocimetry (PIV) for flow control around NACA 0015 with EHD actuator in silicone oil.

Clément Gouriou

For several years, our research group develops EHD (ElectroHydrodynamic) actuators able to set the 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, physics of these flows remains complex, and in order to have a better understanding of these electroconvective flows we wish a more reliable analysis method. The most suitable method to date is the Particle Image Velocimetry. However in order to show the liquid movement, this method requires seeding particles, and these latter can electrically charge and so on can be influenced by the electric field produced by the electrodes.

In this work, we study the behavior of seeding particles under high electric field in order to estimate the error induced on the measurement of the liquid velocity. In a first part, we realize a theoretical study, describing the process of particle charging due to a surrounding electric field. This preliminary work enables to determine both the theoretical maximum charge of the

seeding particles and the time necessary to reach the maximum charge. In a second step, a comparative experimental study based on two velocity measurement methods has been led with help of a planar actuator which generates wall jet of several tens of centimeters per second. Firstly, velocity has been estimated with a differential pressure measurement based on the Pitot tube method, for various seeding particle concentrations. Secondly, measurements have been done with the Particle Image Velocimetry method. Several types of particles have been tested. The result analysis reveals that-the Particle Image Velocimetry method is suitable but only under precise conditions. Finally, we have led experiments of flow control around a NACA0015 airfoil equipped with an EHD actuator in a silicone oil tunnel. For different velocities from 5cm/s to 30cm/s of inlet flow we have studied the influence of the EHD actuation on the academic flow around the airfoil for different angle of incidence.

This study opens the way to a more reliable analysis of the velocity measurements in charged dielectric liquids with help of Particle Image Velocimetry. Moreover the use of EHD force opens a new field of investigation for flow control in dielectric liquids.

The phenomenon of particle charge isn't limited to Particle Image Velocimetry, but it is also an essential parameter in many of industrial processes like electrostatic precipitators (smoke filter), electrostatic separator or in ElectroHydroDynamic filter (ex: waste oil filter). The analysis developed in this study should be also useful to the whole of these application's domains.

Key words: dielectric liquids, EHD actuator, particle charging, Particle Image Velocimetry, electro-convective jet.

Air gap modeling in a uniform electrical field with silicone and glass Barriers under direct voltage in very sever conditions of pollution.

Talit Boughani, Rabah Boudissa, Fatma Bouchelga, Klaus Dieter Haim

The main objective of this paper consists in the comparison of the performance in DC voltage of a short air gap with non uniform electric field protected by silicone or glass barriers under very severe pollution conditions. The choice of the system of investigation is carried out on rod and plane electrodes with the lowest dielectric strength.

The essential influence parameters on the performance of the system are summarized in the severity of the barrier's level of pollution and the nature of the used material. These tests were supported by a visualization of the breakdown path followed by the electric discharge on the barrier. An experimental device allowing the displacement of the barrier inside air gap was made.

The results emanating from this study show that under conditions of pollution, the effective electric protection offered by the silicone barrier is 66 % highly efficient than the glass barrier.

The quantification of the voltages due to the slip of the electric discharges on the two faces of the polluted barrier is made possible by a mathematical model of the disruption of the air gap of the system, made within the framework of this study.

Key words – Small air gap, Silicone and glass barrier, Severe conditions of pollution,Water droplets, Hydrophobicity, Electrical discharge, DC performance.

3rd session

Electrohydrodynamics: equations and their application to paradigmatic flows

A.T. Pérez

Abstract: In this lecture we analyze the application of Electrohydrodynamic equations to three paradigmatic flows. The first one is the stability and electroconvection due to unipolar injection of charge. We will give an overview on this historical problem, stressing its mathematical difficulties and the different theoretical and numerical approaches that have been used to overcome these difficulties. The second part of the lecture will be devoted to Electrohydrodynamic plumes. These flows arise when charge is injected from a sharp electrode, a blade or a point, for instance. Since EHD plumes are shear flows the boundary layer equations simplify the mathematical problem and, under some restrictions, a self-similar solution may be found. The two most relevant geometries, 2D plumes and axis-symmetric plumes, will be discussed. Also some general ideas on turbulent plumes will be presented. The third and last part of the lecture will deal with interfacial flows. In particular we will discuss the electric boundary conditions on a moving boundary, focusing on the role of tangential stresses in generating EHD flows. As an example of interfacial flow, rose-window instability will be analyzed.

Lattice Boltzmann modelling of electro-hydrodynamic flows in dielectric liquids.

Jian Wu, Kang Luo, Hong-Liang Yi

Electrohydrodynamics (EHD) is an interdisciplinary science dealing with the interaction of fluids with electric field[1]. The complex physics involved inelectro-convective phenomena together with some promising applications draw a wide attention to this very active field. Some representative applications include EHD pumps, electronic cooling, heat transfer augmentation, active flow control with electric field, charge injection atomizers, electrospinning, etc.

During the last three decades, the lattice Boltzmann (LBM) method has experienced rapid development and has become an established numerical scheme for complex flows [2]. However, only until recent years, LBM has been introduced into EHD [3]. This is in contrast with the fact that LBM has long been applied in magnetohydrodynamics (MHD) since the early 1990s[4]. EHD and MHD can be viewed as two special subjects due to the interaction between the electromagnetic field and flow motion. The objective of this study is to further

extend the application of LBM to model electrohydrodynamic flow in single-phase dielectric liquids.
A wide range of EHD phenomena can be modeled with a coupled mathematical model that includes the Navier-Stokes equations, the Poisson's equation and the Nernst-Planck equation. For non-isothermalfluid,the energy equation is also required. In this study, we have proposedfourconsistent lattice Boltzmann equations (LBEs)based on a unified set of lattice grid to calculate the fluid flow, electrical potential, chargedensity distributionand the temperature field, respectively. A Chapman-Enskog analysis has been performed to recover the LBEs to the macroscopic governing equations, which place our LBM on a solid theoretical basis. Our LBM has been validated with severalrepresentativetest cases of injection induced electro-convectionand electro-thermo-convectionwith simple or complex geometries. All results obtained with the LBM are found to be highly consistent with the available analytical solutions or the results obtained by a conventional finite volume method, which demonstrates LBM is a promising alternative for simulations of EHD flows.

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EHD conduction pumping in microchannels.

Pedro Vazquez

Electrohydrodynamics (EHD) deals with the interaction between electric fields and fluid flow. One of the successful applications of EHD is the conduction pumping in liquids of low conductivity. This mechanism has been applied for pumping liquids in systems with typical sizes ranging from cm to hundreds of μm. It has been shown to enhance significantly the heat evacuation in pool boiling systems.
In this paper we discuss the extension of the EHD conduction pumping to small sized pumps, down to 10 μm. For this size, the effect of the surface charge on the dielectric may play a role in the electric field and charge distributions. We present a physical model along with the results of numerical simulations obtained applying this model to a typical fluid used in experiments.

EHD flow caused by field-enhanced dissociation: computer simulation and PIV investigation.

S.A. Vasilkov, V.A. Chirkov, Yu.K. Stishkov

Specific mechanisms of charge formation, i.e. injection and field-enhanced dissociation, take place in low-conducting liquids under the influence of a strong electric field. Though the field-enhanced dissociation (or the Wien effect) is frequently referred to as the pure theoretical phenomenon or is considered in the context of the electric current passing through the cell, the effect was recently demonstrated to be capable of providing the formation of intense electrohydrodynamic (EHD) flows. However, there is still a question if the Onsager theory is suitable for EHD flow description. This question was addressed in the present work.
The research uses a specific electrode arrangement, two flat parallel electrodes with a dielectric plate having a small circular hole between them. Its main feature is that the region

of the strong electric field is located far from metal electrode surfaces (in the hole), which permits one to preclude the injection charge formation and to observe field-enhanced dissociation that causes EHD flow.
The EHD flow was studied by virtue of particle image velocimetry (or PIV) technique and the results were compared with those of computer simulation. The latter was performed using software package COMSOL Multiphysics that lets one solve the complete set of EHD equations and to take into account field-enhanced dissociation. The comparison of experiment and simulation results let one estimate applicability of Onsager theory in the context of EHD flows.

A preliminary plasma based flow control simulation study with Oracle3D
Umesh Set, Francisco Durán-Olivencia, Philippe Traoré, Pédro Vazquez, Eric Moreau
Oracle3D is an in-house three dimensional, parallel, incompressible flow solver developed by the EHD group of Institut Pprime, Poitiers. In order to advance the solver to handle complex flow control simulations with Plasma actuators, a simple single species plasma model namely Suzen-Huang (SH) model was implemented in the code. A typical single DBD (dielectric barrier discharge) actuator, 3D configuration was simulated to qualitatively assess the capability of Oracle3D with basic plasma models. These preliminary results were compared with those found in the literature and with some COMSOL simulations. The qualitative results, distribution of velocity and force vectors as well as charge density contours, are encouraging and match with literature and COMSOL results. The maximum Coulomb force generated and the attained maximum flow velocity were also found comparable with available results. The maximum flow velocity attained was 0.68 m/s, with similar configuration COMSOL result was 0.72 m/s. Currently, a three species plasma model and compressible implementation in Oracle3D are being dealt with.

Numerical Simulation and Experimental study of EHD Flow Generated by Microplasma Actuator.
Marius Blajan, Akihiko Ito, Jaroslav Kristof, Hitoki Yoneda, and Kazuo Shimizu
The dielectric barrier discharge (DBD) plasma actuators have advantages over conventional type actuators such as no moving parts, faster response time and also simple construction. A small size Dielectric Barrier Discharge microplasma actuator can generate discharge at low discharge voltage of around 1 kV. Therefore, it is easy to control the applied voltage and insulate it. The generated EHD flow was observed using incense particles that were tracked by the high speed camera. An AC voltage was applied to the microplasma actuator. Various types of induced flow could be obtained by changing the shape of the electrode such as ring type microplasma actuator, multi-electrode type microplasma actuator, and so on. The observation with the high speed camera showed at various time intervals the modification of the flow by the microplasma. Due to the high intensity of the microplasma light emission near the active electrodes the flow was difficult to measure thus a numerical simulation code was developed. The numerical simulation of the flow was developed starting from the model developed by Suzen et. al. which considered that due to the fact that the gas particles are weakly ionized we can assume that the electric potential could be split in the potential of the external electric field and potential of the charge density of plasma. Furthermore the body-force was determined by calculating the potentials. The body force was implemented in the Navier-Stokes equations which were solved using projection method in primitive variables on a collocated mesh and the simulated flow was obtained. The numerical results gave us valuable information about the flow.

A Consistent Fluid Approach (CFA) to model electrical discharges
Francisco Durán-Olivencia , Philippe Traoré, Christophe Louste
Widely known, corona discharges arise within those regions where electric fields are very strong, usually as a result of a sharp electrode like needles, blades, wires, etc. One of the most remarkable features of corona discharges is the highly non-uniform spatial distribution of the corresponding electric field. Besides, the coupled system consisting of the Poisson equation (electric potential problem) along with the problem related to the transport of species becomes highly nonlinear, due to the dependency on the electric field distribution of the transport coefficients and the reaction rates in the continuity equations for charged species (cold plasma approximation). Under these circumstances, the robustness of the numerical scheme is crucial to deal with numerical instabilities linked with rapid evolution of electrical discharges, where shock fronts and discontinuities may be developed in the vicinity of sharp electrode. Nonetheless, in such a conditions others instabilities may also emerge as a consequence of the limit of validity of fluid approach to describe the dynamics of species.
This work presents a physical limiter to combine the numerical and theoretical problem as a whole.

4th session

Water flows induced by AC electric fields in microsystems
Antonio Ramos
Handling colloidal particles and small volumes of fluid in micro-systems is of great interest for the lab-on-a-chip (LOC) technology. LOC is a device that integrates biochemical laboratory functions on a single chip to achieve automation and high-throughput detection. Manipulation by electrical forces has the advantages of voltage-based control, no moving parts, and dominance over other forces.The latter is an example of the scaling laws of physical systems: in the range above a few millimeters the electrical forces are rather ineffective, but in the micrometer scale (and below) the electrical forces dominate.
The control of particles and liquids using dc electric fields has been widely used in microsystems, particularly, by employing electrophoresis and electroosmosis. However, the high voltages required generate electrolysis and the electrodes must be placed outside the device. AC electric fields generated by microelectrodes mounted inside microchannels can be used instead, with advantages such as lower power requirements, simple integration, and little or no electrolysis issues. In addition, electrical properties of particles and fluids change with signal frequency, which opens new ways of actuation.
The aim of this talk is to discuss about the flows of aqueous solutions that are generated by microelectrodes subjected to AC voltages in microsystems. AC electric fields act either in the liquid bulk (e.g., electrothermal flows1,2), or in the double layer at electrode-electrolyte interfaces (e.g. AC electro-osmosis1,2). In both cases, the applied electric field actuates upon the charge that is induced by the electric field itself. The electrical force is quadratic with the electric field amplitude and, therefore, it has a non-zero time-average for an AC electric field.
Electrothermal motion in an aqueous solution arises from the action of an electric field on inhomogeneities in the liquid conductivity and permittivity induced by temperature gradients. These can be produced by the applied electric field through Joule heating, or caused by external heat sources.
AC electroosmotic flow usually is generated when an AC electric field is both charging an electrode/electrolyte interface and acting on the induced charge in the diffuse double layer.

The force that the tangential component of the electric field exerts on the double-layer charge generates the fluid flow.
AC electroosmosis is usually observed at low signal frequencies (about 1 kHz and less), while Electrothermal flow is usually observed at higher frequencies.

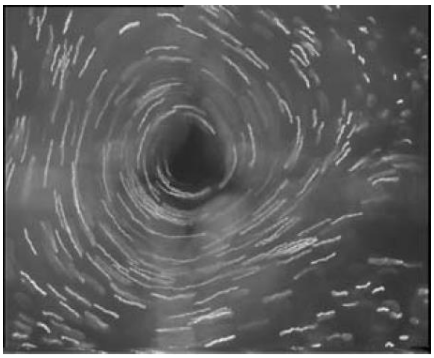

Figure 1: Top view of a rotating aqueous solution placed on top of four coplanar electrodes driven by electrothermal forces in the bulk.

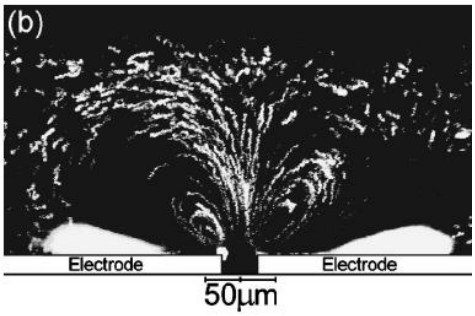

Figure 2: Horizontal view of two counter-rotating rolls on top of two coplanar electrodes driven by electrical forces in the double layer.

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Tribo-electrostatic Separation of Mixed Granular Insulators.

Lucien Dascalescu, Thami Zeghloul

Electrostatic separation is a generic term for a class of methods that make use of electric field forces for the selective sorting of charged or polarized bodies. Granular mixtures of two or more insulating materials can be processed after appropriately tribocharging the constituents. Several tribocharging devices have been developed in relation with various electrostatic separation applications, including minerals beneficiation and plastic wastes recycling. What are the main factors that affect the efficiency of these devices? How the size, the shape and the surface conditioning of the granules may modify the outcome of tribocharging and electrostatic separation processes? The researches performed at the PPRIME Institute during the last fifteen years bring only partial responses to these questions. Cooperation with other laboratories that are active in the field is expected to refine the understanding the triboelectric phenomena that occur at the interface between two colliding granules and to pave the way for the development of more effective tribo-electrostatic separation technologies.

Discrete element modeling of triboelectric charging of insulating materials in vibrated granular beds.

J.C. Laurentie, P. Traoré, L. Dascalescu

The triboelectric charging of granular insulating materials is very difficult to predict because of the complex physical mechanism involved in this process. The aim of this talk is to describe in detail the implementation of a numerical model of the tribocharging process taking place in vertically-vibrated beds of granular plastics. The charge exchanged in granule-to-granule and granule-to-wall collisions is computed by taking into account some electrical properties of the respective materials, their area of contact and the effect of the electric field generated by a system of high-voltage electrodes and by the charges of the granules themselves. The electrical model is coupled with the Discrete Element Method (DEM) which undertakes the whole granular dynamics and allows to compute accurately the contact surface of two colliding particles which is involved in the triboelectric charging model. Beside the numerical simulations an experiment has been conducted with mixtures of mm-size polyamide and polycarbonate granules in a laboratory vibrated bed to validate the model. The numerical results have been found to be in good agreement with the experimental ones. An application of such study in then presented through an exemple of electro-separation of the charged particles.

Measurement of electric charge in gas dispersed particles using Particle Tracking Velocimetry.

Miguel Angel Sanchez Quintanilla

We present an experimental set-up in which the electric charge on particles carried by a gas stream is measured. In the set-up, the particles are forced to collide with the walls of a grounded metal pipe and then pass between two electrodes connected to a high voltage AC source. Those particles that have acquired electric charge by impact experience an electric force that makes them oscillate as they travel through the volume between the electrodes. The total charge given to the particles in suspension is measured from the electric current flowing to the pipe, while the magnitude of the electric charge on each individual particle and its sign is measured from the amplitude and phase of the particle's oscillation relative to that of the electric field created by the electrodes. The average particle charge is found to be dependent on the particle size, while the electric charge on the particles is found to have a bipolar distribution, with some particles carrying positive and other negative charge. The physical mechanisms that explain both results are discussed.

Electric charge limits on settled powders.

Javier Pérez

We have built a set-up to charge powder samples while dispersed in an air stream and measure the electric charge both in the dispersed particles and the bulk powder formed by settling of the particles. Materials have been tested varying particle size, dispersing gas and storage and dispersing gas relative humidity. In a modified version of this set-up, the charge distribution of the individual particles is measured by imaging the trajectories of the particles in an oscillating electric field. In this experiment, apart from the parameters mentioned before, we have also tested the effect of the hydrophobic/hydrophilic nature of the particle surface. The electric charge in a bulk powder dissipates in a time of order of minutes, indicating that the powder has an effective electrical conductivity. Results on the electric charge on dispersed

particles and bulk powders and it time evolution is compared with the predictions of a simplified model"

Electrostatic and other basic interactions of remote particles

Elena F. Grekova

We consider the problem of two pointwise interacting remote bodies. We obtain formulae for the potential energy of their interaction, force and moment acting from one body upon another. We suppose that each two points of the bodies interact with a potential energy $d\Pi = f(l)\, d\mu_1\, d\mu_2$, where l is the distance between these two points, $f(l)$ is a known function depending on the kind of interaction, $\mu_{1,2}$ is the measure depending on the character of interaction (mass, charge). Suppose the distance between centres of mass of the bodies $R \gg |\mathbf{r}_1 - \mathbf{r}_2|$, $\mathbf{r}_i$ is the vector connecting the centre of mass of the body i and its point. Then we can show that the potential energy of interaction may be expressed in terms of series

$$\Pi = \sum_{s=0}^{\infty} \frac{1}{R^s} \sum_{k=0}^{[s/2]} \underbrace{\mathbf{e}_0 \dots \mathbf{e}_0}_{s-2k} \cdot \dots \cdot F^{(s-k)}(0) 2^{s-k} \sum_{k_1+k_2+k_3=k} \frac{(-1)^{k_3}}{2^{k_1+k_2} k_1! k_2! k_3!} \sum_{m=0}^{s-2k} \frac{(-1)^m}{m!(s-2k-m)!} \left(\int\limits_{(\mu_1)} r_1^{2k_1} \underbrace{\mathbf{r}_1 \dots \mathbf{r}_1}_{m+k_3} \, d\mu_1 \cdot \dots \cdot \int\limits_{(\mu_2)} r_2^{2k_2} \underbrace{\mathbf{r}_2 \dots \mathbf{r}_2}_{s-2k-m+k_3} \, d\mu_2 \right)$$

Here $\mathbf{e}_0$ is a unit vector directed from one center of mass to another one

$$F(x) \stackrel{\text{def}}{=} f(R\sqrt{1+x})$$

Here and further we omit the symbol of tensor product $\otimes$.

One can consider various interactions (gravitational, electrostatic, van der Waals etc.) choosing $f(l)$ and μ. For electrostatic interaction the last expression results in

$$\Pi = \frac{k_e q_1 q_2}{R} + \sum_{s=1}^{\infty} \frac{k_e}{R^{s+1}} \sum_{k=0}^{[s/2]} \left(-\frac{1}{2}\right)^k \frac{(2(s-k)-1)!!}{k!(s-2k)!} \sum_{k_1+k_2+k_3=k} \frac{(-2)^{k_3}}{k_1! k_2! k_3!} \sum_{m=0}^{s-2k} \frac{(-1)^{s-2k-m}}{m!(s-2k-m)!} \underbrace{\mathbf{e}_0 \dots \mathbf{e}_0}_{m} \cdot \dots \cdot \int\limits_{(q_1)} r_1^{2k_1} \underbrace{\mathbf{r}_1 \dots \mathbf{r}_1}_{m+k_3} \, dq_1 \cdot \dots \cdot \int\limits_{(q_2)} r_2^{2k_2} \underbrace{\mathbf{r}_2 \dots \mathbf{r}_2}_{s-2k-m+k_3} \, dq_2 \cdot \dots \cdot \underbrace{\mathbf{e}_0 \dots \mathbf{e}_0}_{s-2k-m}.$$

Here $k_e = (4\pi\varepsilon_0\varepsilon)^{-1}$ is the Coulomb constant ($9 \cdot 10^9 \mathrm{N} \cdot \mathrm{m}^2\mathrm{C}^{-2}/\varepsilon$). Using this expression we can calculate force and torque acting upon a charged particle from the side of another remote particle. This could be useful for simulations of aggregation and sedimentation in fluidized beds and suspensions of charged or triboelectrified powders.

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