ELECTRIC-FIELD-DRIVEN PHENOMENA FOR MANIPULATING
PARTICLES IN MICRO-DEVICES

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Compared to other available methods, ac dielectrophoresis is particularly well-suited for the manipulation of minute particles in micro- and nano-fluidics. The essential advantage of this technique is that an ac field at a sufficiently high frequency suppresses unwanted electric effects in a liquid. To date very little has been achieved towards understanding the micro-scale field-and shear driven behavior of a suspension in that, the concepts currently favored for the design and operation of dielectrophoretic micro-devices adopt the approach used for macro-scale electric filters. This strategy considers the trend of the field-induced particle motions by computing the spatial distribution of the field strength over a channel as if it were filled only with a liquid and then evaluating the direction of the dielectrophoretic force, exerted on a single particle placed in the liquid. However, the exposure of suspended particles to a field generates not only the dielectrophoretic force acting on each of these particles, but also the dipolar interactions of the particles due to their polarization. Furthermore, the field-driven motion of the particles is accompanied by their hydrodynamic interactions. We present the results of our experimental and theoretical studies which indicate that, under certain conditions, these long-range electrical and hydrodynamic interparticle interactions drastically affect the suspension behavior in a micro-channel due to its small dimensions.
Electric-field-driven Phenomena for Manipulating Particles in Micro-Devices

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Compared to other available methods, ac dielectrophoresis is particularly well-suited for the manipulation of minute particles in micro- and nano-fluidics. The essential advantage of this technique is that an ac field at a sufficiently high frequency suppresses unwanted electric effects in a liquid (for water, in particular, in the MHz-frequency range). To date very little has been achieved towards understanding the micro-scale field- and shear driven behavior of a suspension in that, the concepts currently favored for the design and operation of dielectrophoretic micro-devices adopt the approach used for macro-scale electric filters. This strategy considers the trend of the field-induced particle motions by computing the spatial distribution of the field strength over a channel as if it were filled only with a liquid and then evaluating the direction of the dielectrophoretic force, exerted on a single particle placed in the liquid. However, the exposure of suspended particles to a field generates not only the dielectrophoretic force acting on each of these particles, but also the dipolar interactions of the particles due to their polarization. Furthermore, the field-driven motion of the particles is accompanied by their hydrodynamic interactions.

We present the results of our experimental and theoretical studies [1-4] which indicate that, under certain conditions, these long-range electrical and hydrodynamic interparticle interactions drastically affect the suspension behavior in a micro-channel due to its small dimensions. As we shall demonstrate, this leads to the formation and propagation of the concentration front in suspensions subject to a high gradient electric field. This phenomenon provides a new method for strongly concentrating particles in focused regions of micro-devices. Potential applications of the field-driven phenomena for advanced life support and environmental monitoring & control systems for long-duration missions include a wide range of electro-micro-devices for multiphase separation, bubble manipulation, monitoring particulate and microbial background environment, etc. However, our experiments aboard the NASA research aircraft KC-135 [4] revealed that an unexpectedly pronounced effect of a relatively weak gravity imposes certain limitations on the use of ground-based tests for predicting the operation of electro-technologies in micro-gravity.

Principal publications
Dielectrophoretic Particle Concentrator

40 μm (W) × 6 μm (H) × 570 μm (L)  10 Vpp, 15-30 MHz

Source: Bennett, Khusid, Galambos, James, Okandan, TRANSDUCERS'03, Boston, MA
**Experimental Results**

1 µm polystyrene spherical beads in DI water, 0.1% (v/v)

Particle polarization \( \beta = -0.45 - 0.27i \)

Flow rate 0.24 pL/s to 9.6 pL/s; Re~10^{-5} - 10^{-3}

Source: Bennett, Khusid, Galambos, James, Okandan, Jacqmin, Acrivos, Appl Phys Lett, 83, 2003
Flowing Heterogeneous Mixture

Beads and bacterial cells (heat-killed staphylococcus aureus)

10 V<sub>ppp</sub>, 15 MHz  Flow rate 0.24 pL/s to 9.6 pL/s

Modeling

Single bolus

0.1%(v/v)-suspension
Flow rate 8.64 pL/s
Voltage 10V_{ptp}

Average flow velocity 36 µm/s

1, concentration
2, field strength

Two boluses

Source: Bennett, Khusid, Galambos, James, Okandan, Jacqmin, Acrivos, Appl Phys Lett, 83, 2003
**Field-induced Segregation**

Top view, 10%

Neutrally buoyant polyalphaolefin spheres in corn oil

Re(β) = -0.15 for 100-1000 Hz

5kv, 100Hz, without flow

\( V_{rms/d} = 2.5 \text{ kV/mm} \)

Source: Kumar, Qiu, Khusid, Jacqmin, Acrivos, Phys. Rev. E, 69, 2004
Comparison with Experiments

Dielectrophoretic time

\[ \tau_d = \frac{3d^4 \eta_f}{a^2 \varepsilon_0 \varepsilon_f |\text{Re}(\beta(\omega))| V_{\text{rms}}^2} \]

Source: Kumar, Qiu, Khusid, Jacqmin, Acrivos, Phys. Rev. E, 69, 2004
Multi-Channel Apparatus

Electrodes parallel to the flow

Silicon Wafer

Electrodes perpendicular to the flow

Al electrodes

Transparent Glass Cover

150 chambers on the 4” wafer

Electrode spacing = 2, 5, 10 µm

H = 30 µm

KC-135 Experiment

Source: Markarian, Yeksel, Khusid, Kumar, Tin, Phys. Fluids, 16, 2004
Dielectrophoresis in Microgravity

5kv, 100Hz,

Aggregation patterns, 10s

Bristle length

Particle accumulation

Air bubbles

Source: Markarian, Yeksel, Khusid, Kumar, Tin, Phys. Fluids, 16, 2004
Microsensor Technologies for Plant Growth System Monitoring

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- Critical need of precise control of root zone; wetness, oxygen, nutrients, temperature.
- Ideal sensor configuration; miniaturization, multiple, array, low power, robustness.
- Thin film flexible microsensor strips for dissolved oxygen and wetness detection.
- Flexible microfluidic substrate for rhizosphere monitoring and manipulation.
Experimental setup with a porous tube growth system

• Dissolved oxygen microsensor strip
  (3-electrode amperometric measurement by enwrapping the porous tube surface)

• Wetness sensor strip (4-electrode conductivity measurement along the porous tube surface)
Dissolved oxygen measurement on the porous tube surface

- With a commercial oxygen probe;
  - Reflecting O$_2$ value of inner sol. at (+) pressures.
  - Convergence to 20% value (air-sat. value) at (-) pressures.

- With a microsensor array;
  - Reflecting O$_2$ value of inner sol. at (+) pressures.
  - Scattering around 0% value at (-) pressures (due to surface dryness and absence of sensor permeable membrane).
Wetness measurement on the porous tube surface

- A steep decrease of surface impedance at the transition from (-) to (+) pressure.
Experimental setup with a particulate growth system
(Turface® 1-2 mm size particulate)

- Dissolved oxygen and wetness measurements within an unsaturated Turface® media.
- Repeated flooding and suction of nutrient solution using the embedded porous tube.
Dissolved oxygen measurements within the particulate

- With a commercial oxygen probe;
  - Convergence to $O_2$ value of inner sol. with repeated flooding.
  - Convergence to 20% value (air-sat. value) with suction.

- With a microsensor array;
  - Better reflection of $O_2$ value of inner sol. with repeated flooding.
  - Better reflection of $O_2$ value of inner sol. with repeated suction.

Intelligent Microsystem Laboratory (http://web.umr.edu/~ckim) University of Missouri–Rolla
Wetness measurement within the particulate

- Variations of the impedance due to repeated solution flooding and suction.
Flexible microfluidic substrate for rhizosphere monitoring and manipulation

- Root hair growth on the surface of a porous membrane with underlying microfluidic channels and microsensor arrays.

- Exemplary layout of planar microfluidic substrates.
Conceptual growth system using flexible microfluidic rhizosphere substrate

- Rhizosphere manipulation using embedded microchannels (e.g. change of nutrient solution composition).
- Rhizosphere *in situ* monitoring using embedded microsensor arrays or remote optical sensors.
- Root growth pattern analysis using optical imaging.

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Summary

• Demonstration of feasibility of microsensor for porous tube and particulate growth systems.
  – Dissolved oxygen.
  – Wetness.

• Flexible microfluidic substrate with microfluidic channels and microsensor arrays.
  – Dynamic root zone control/monitoring in microgravity.
  – Rapid prototyping of phytoremediation.
  – A new tool for root physiology and pathology studies.

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