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.
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 Vptp, 15-30 MHz

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

1\(\mu\)m 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\(\sim\)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_{pp}, 15 MHz  Flow rate 0.24 pL/s to 9.6 pL/s

Source: Bennett, Khusid, Galambos, James, Okandan, Jacqmin, Acrivos, Appl Phys Lett, 83, 2003
Flow velocity 0.1\%(v/v)-suspension
Flow rate 8.64 pL/s
Voltage 10V_{ptp}
Average flow velocity 36 \mu m/s

1, concentration
2, field strength

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

Top view, 10%

![Images of particle segregation over time](image)

- Neutrally buoyant polyalphaolefin spheres in corn oil
- $\text{Re}(\beta) = -0.15$
- for 100-1000 Hz
- $5\text{kv}, 100\text{Hz}$, without flow
- $V_{\text{rms}}/d = 2.5 \text{ kV/mm}$

*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**

- **Silicon Wafer**
- **Al electrodes**
- **Transparent Glass Cover**
- **Electrodes parallel to the flow**
- **Electrodes perpendicular to the flow**
- **Inlet**
- **Outlet**
- **Electrode spacing = 2, 5, 10 µm**
- **H = 30 µm**

- **150 chambers on the 4” wafer**

*Source: Markarian, Yeksel, Khusid, Farmer, Acrivos, Appl Phys Lett, 82, 2003*
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.

Intelligent Microsystem Laboratory (http://web.umr.edu/~ckim) University of Missouri-Rolla
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)

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Dissolved oxygen measurement on the porous tube surface

- With a commercial oxygen probe;
  - Reflecting O\textsubscript{2} value of inner sol. at (+) pressures.
  - Convergence to 20% value (air-sat. value) at (-) pressures.

- With a microsensor array;
  - Reflecting O\textsubscript{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.
Wetness measurement within the particulate

- Variations of the impedance due to repeated solution flooding and suction.

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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.
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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