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.

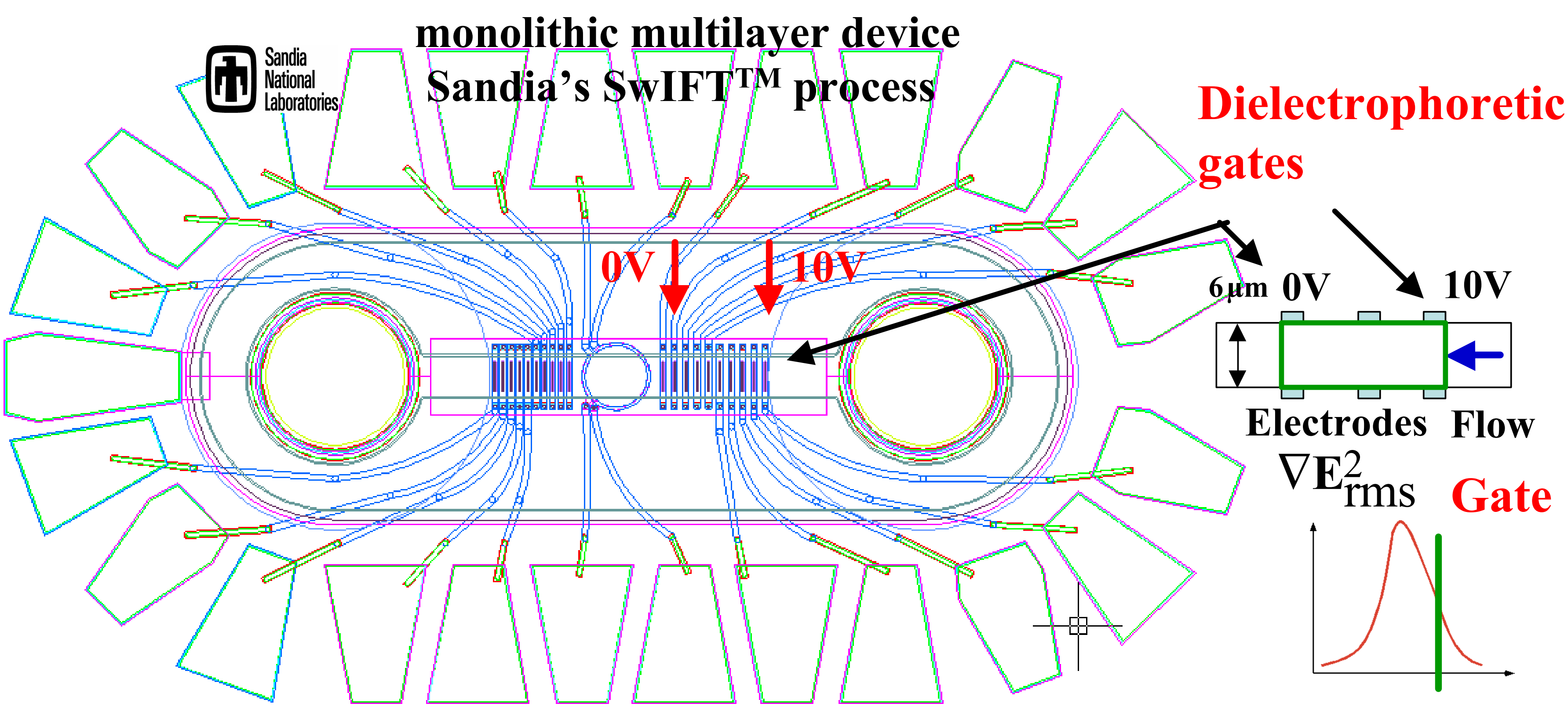
We present the results of our experimental and theoretical studies [1-4] which indicate that, under certain conditions, these long-range electrical and hydrodynamic interparticle interactions drastically affect the suspension behavior in a micro-channel due to its small dimensions. As we shall demonstrate, 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

1. Bennett, D., Khusid, B., Galambos, P., James, C.D., Okandan, M., Jacqmin, D., and Acrivos, A., Field-induced dielectrophoresis and phase separation for manipulating particles in microfluidics. *Appl. Phys. Lett*., (2003) **83**(23), 4866
2. Markarian, N., Yeksel, M., Khusid, B., Farmer, K., Acrivos, A., Limitations on the scale of an electrode array for trapping particles in microfluidics by positive dielectrophoresis, *Appl. Phys. Lett.,* (2003) **82** (26), 4839; Particle motions and segregation in dielectrophoretic micro-fluidics, *J. Appl. Phys*., (2003) **94**(6), 4160
3. Kumar, A., Qiu, Z., Acrivos, A., Khusid, B., and Jacqmin, D., Combined negative dielectrophoresis and phase separation in nondilute suspensions subject to a high-gradient ac electric field. *Phys. Rev. E*, (2004) **69**, 021402
4. Markarian, N., Yeksel, M., Khusid, B., Kumar, A., and Tin, P., Effects of clinorotation and positive dielectrophoresis on suspensions of heavy particles. *Phys. Fluids*, (2004) **16**(5), 1826

Dielectrophoretic Particle Concentrator

$40\ \mu m\ (W) \times 6\ \mu m\ (H) \times 570\ \mu m\ (L)$ 10 Vptp, 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 $\beta = -0.45 - 0.27i$

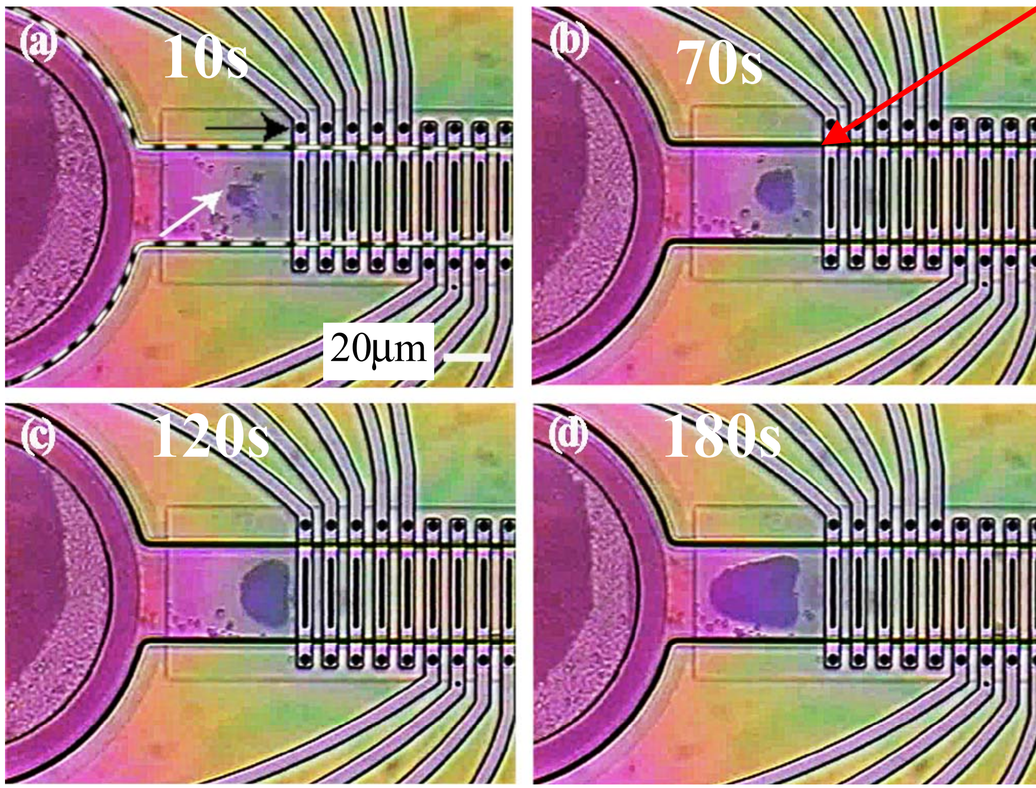
Flow rate 0.24 pL/s to 9.6 pL/s; Re~10^{-5}- 10^{-3}

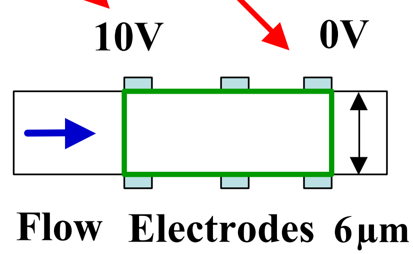
Flow →

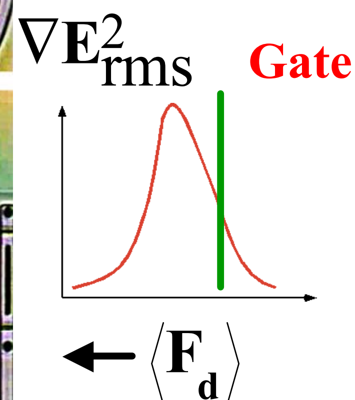
$10V_{ptp}$, 30 MHz

Dielectrophoretic gates

Phase transition





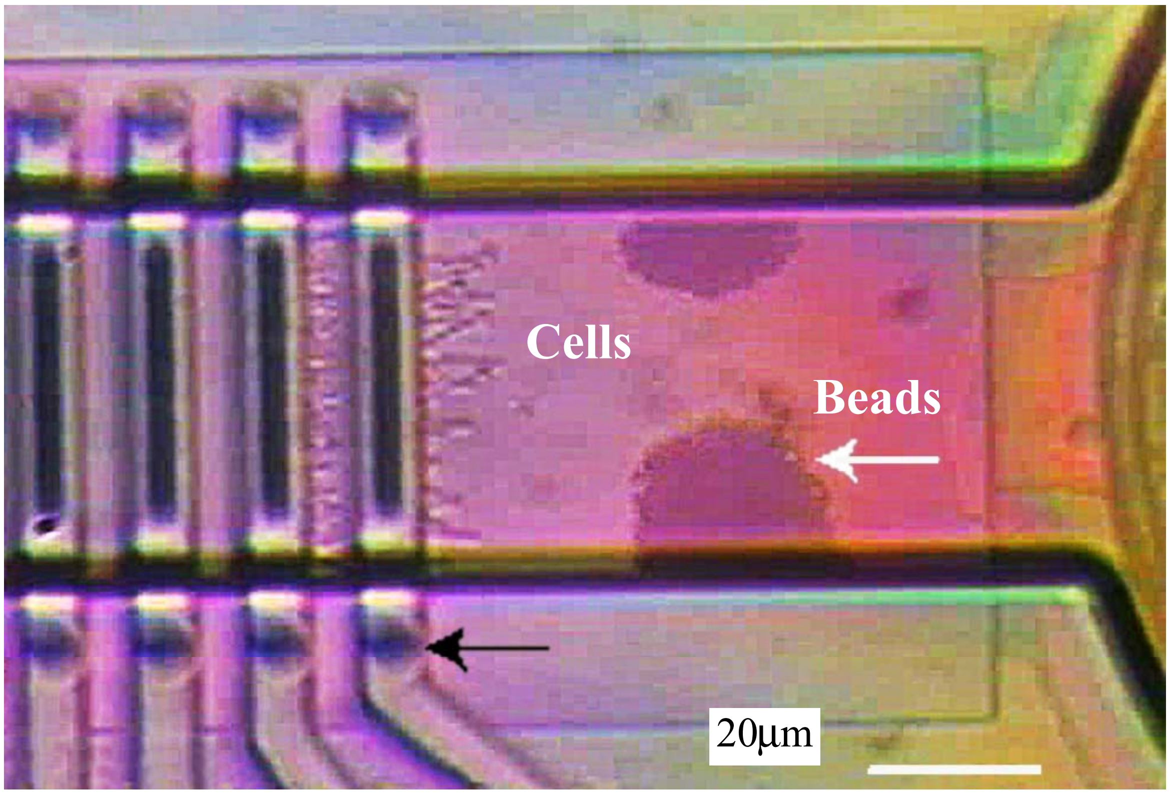


Source: Bennett, Khusid, Galambos, James, Okandan, Jacqmin, Acrivos, Appl Phys Lett, 83, 2003

Flowing Heterogeneous Mixture

Beads and bacterial cells (heat-killed staphylococcus aureus)

10 V_{ptp}, 15 MHz **Flow rate 0.24 pL/s to 9.6 pL/s**



Flow

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

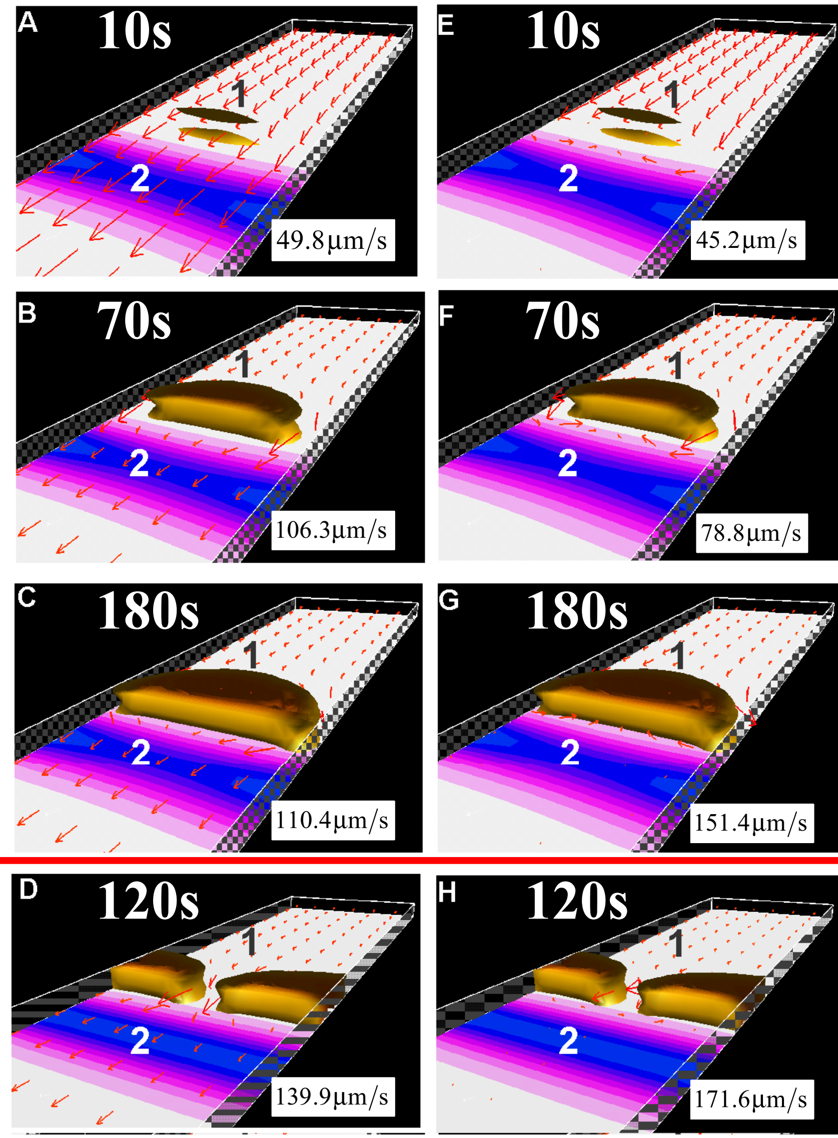
Modeling

Flow velocity **Particle velocity**

8.73%

45.4%

56.4%



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

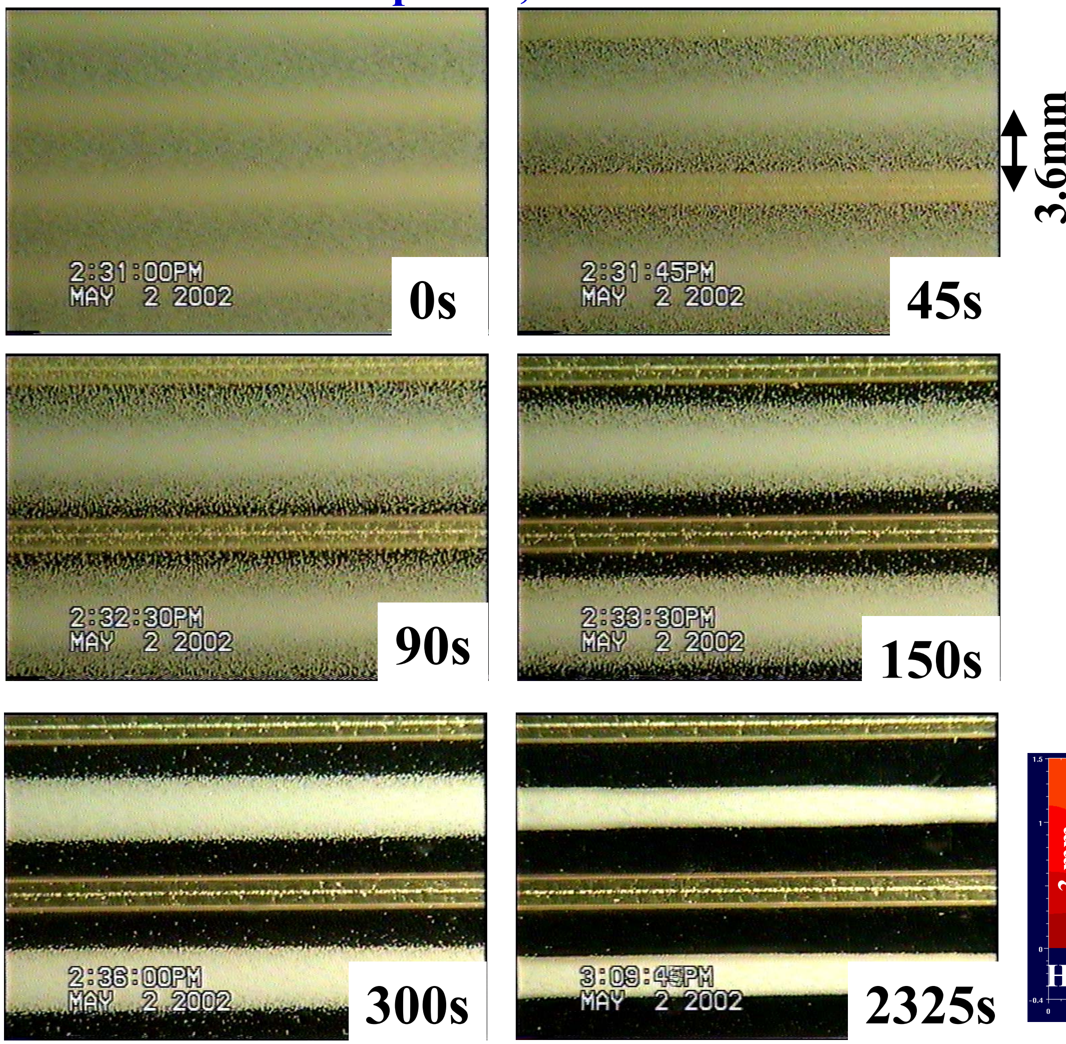
Source: **Bennett, Khusid, Galambos, James, Okandan, Jacqmin, Acrivos, Appl Phys Lett, 83, 2003**

NASA/CP—2004-213205/VOL2

Field-induced Segregation

Top view, 10%

GR
HV



GR
HV

GR
HV

Neutrally buoyant polyalphaolefin spheres in corn oil

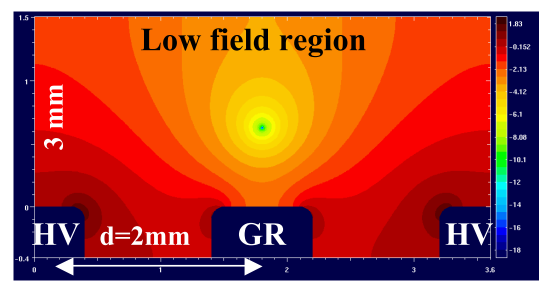
$\mathrm{Re}(\beta) = -0.15$

for 100-1000 Hz

5kv, 100Hz, without flow

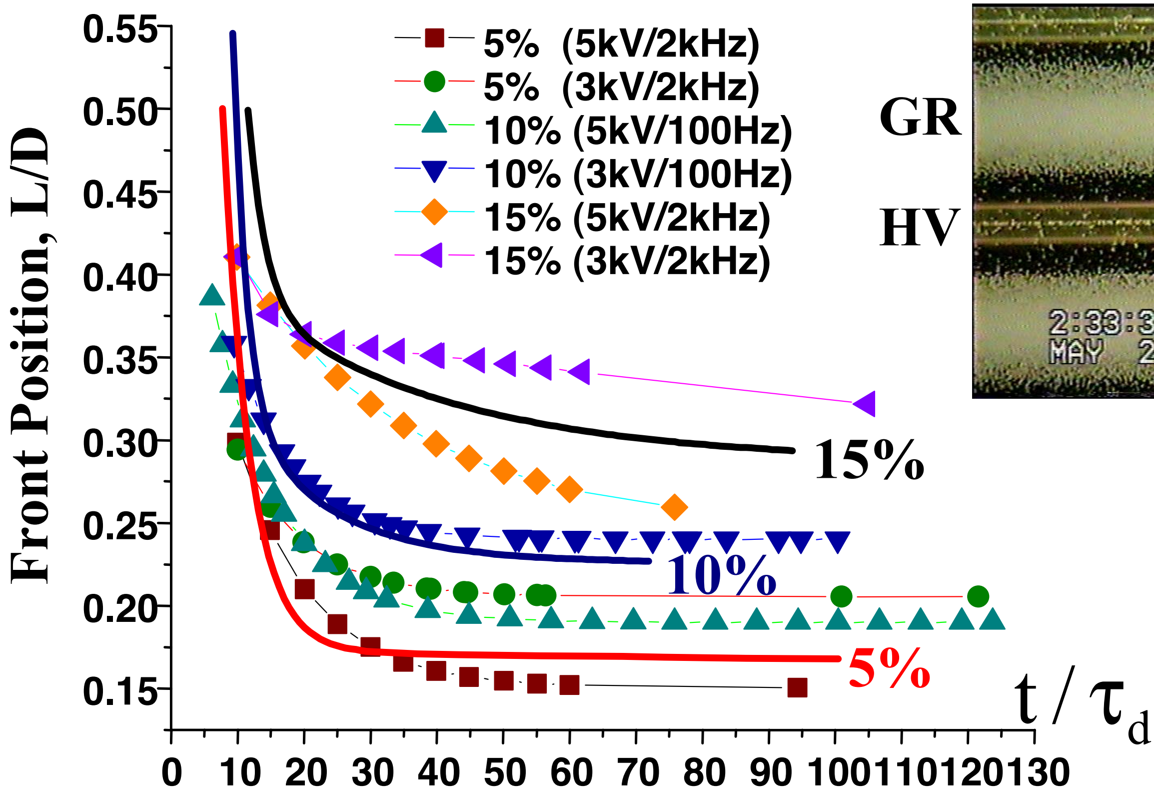
$V_{rms}/d = 2.5$ **kV/mm**

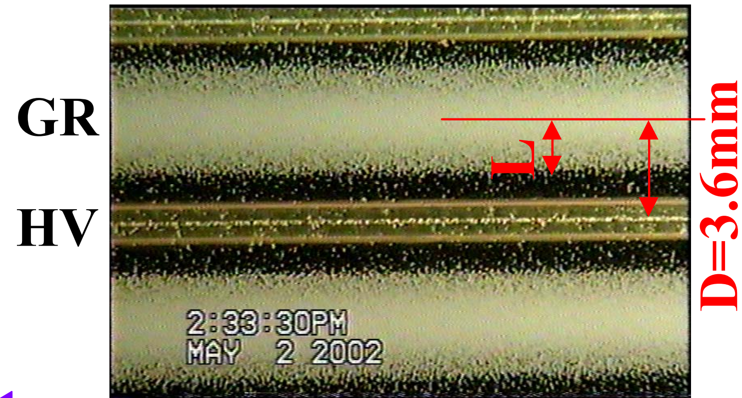
Electric-field strength



Source: **Kumar, Qiu, Khusid, Jacqmin, Acrivos, Phys. Rev. E, 69, 2004**

Comparison with Experiments

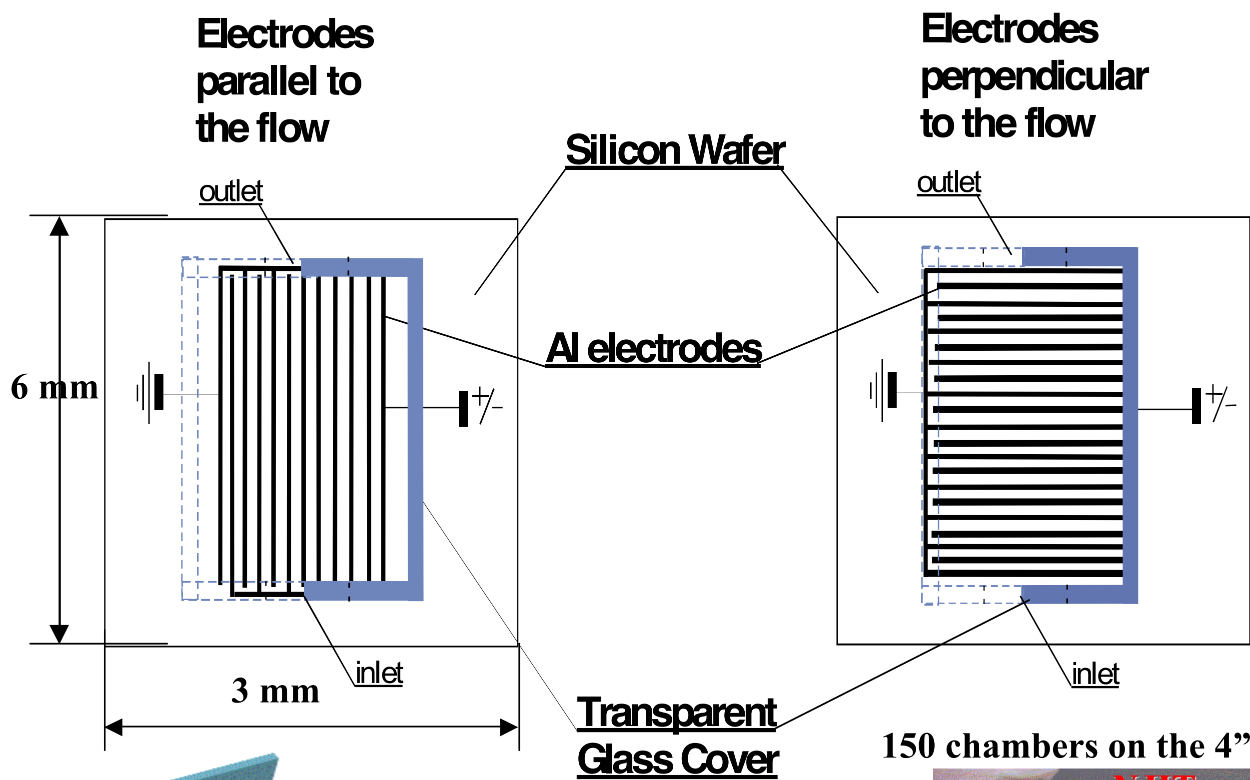




Dielectrophoretic time $$\tau_d = \frac{3d^4\eta_f}{a^2\varepsilon_0\varepsilon_f\left|\mathrm{Re}(\beta(\omega))\right|V_{rms}^2}$$

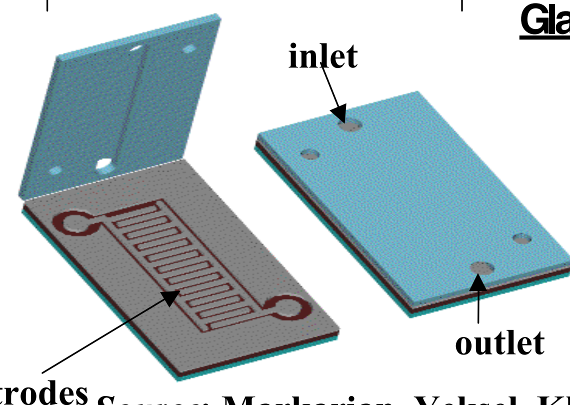
Source: **Kumar, Qiu, Khusid, Jacqmin, Acrivos, Phys. Rev. E, 69, 2004**

Multi- Channel Apparatus

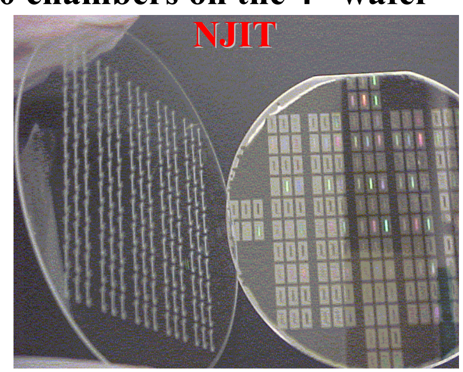


Electrode spacing = 2, 5, 10 µm

H = 30 µm

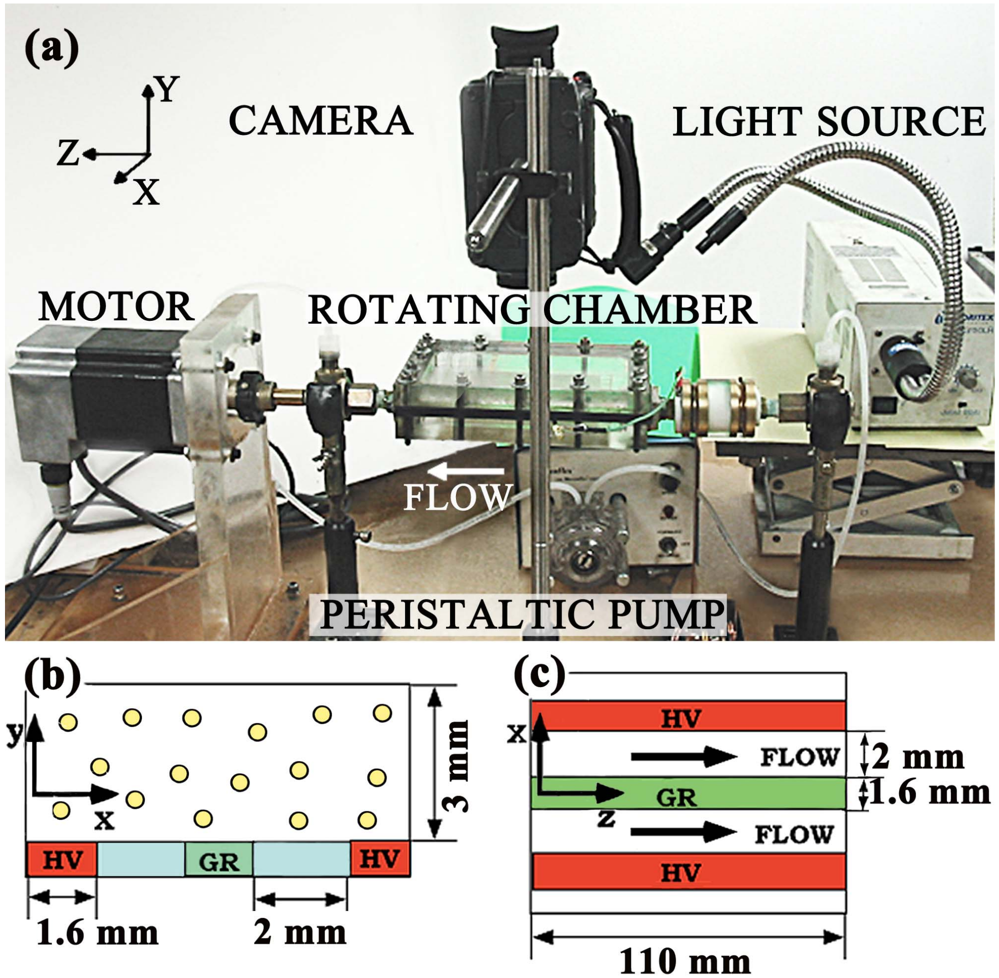


150 chambers on the 4" wafer



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

KC-135 Experiment

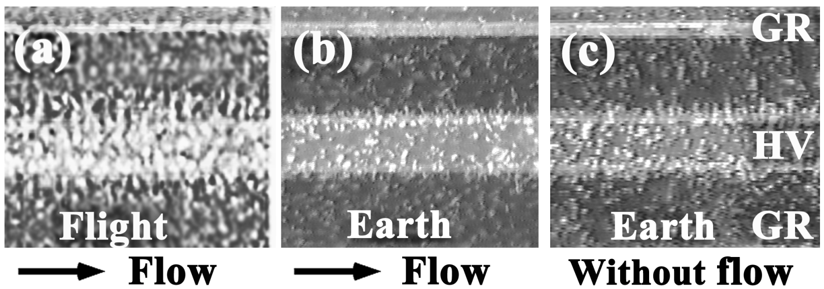


Source: **Markarian, Yeksel, Khusid, Kumar, Tin, Phys. Fluids, 16, 2004**

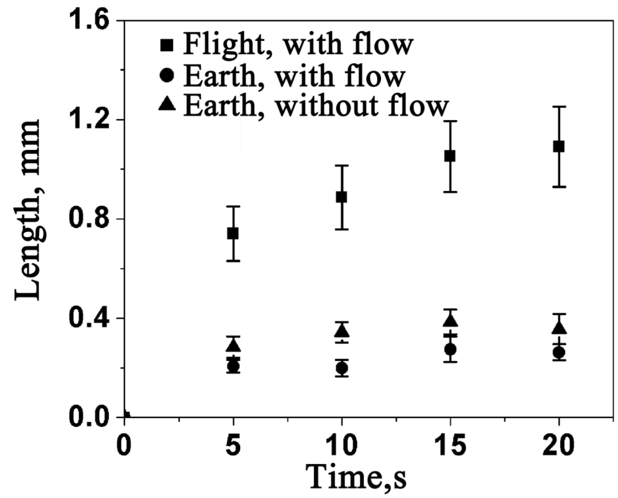
Dielectrophoresis in Microgarvity

5kv, 100Hz,

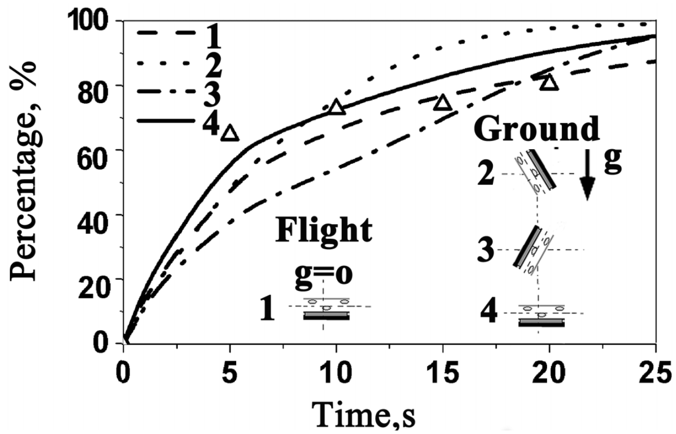
Aggregation patterns, 10s



Bristle length

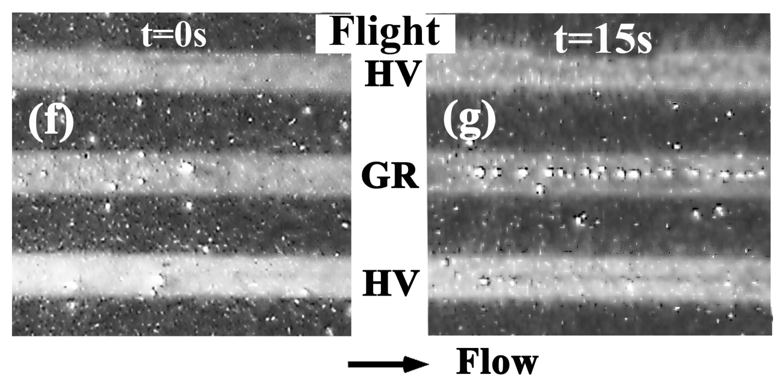


Particle accumulation



Computations and flight experiments

Air bubbles



Source: **Markarian, Yeksel, Khusid, Kumar, Tin, Phys. Fluids, 16, 2004**

Microsensor Technologies for Plant Growth System Monitoring

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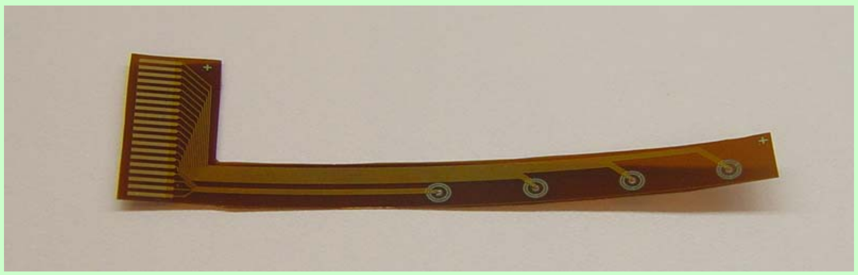
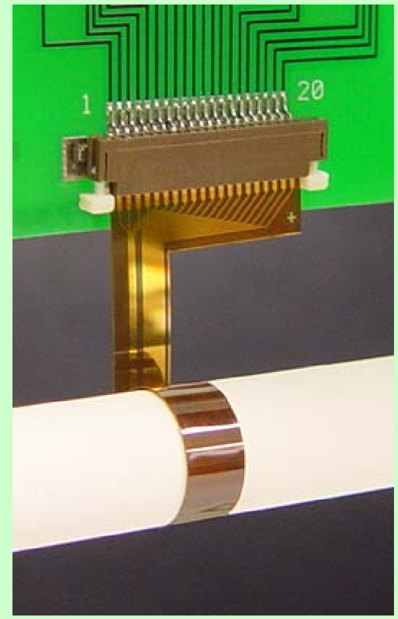
- Critical need of precise control of root zone; wetness, oxygen, nutrients, temperature.
- Ideal sensor configuration; miniaturization, multiple, array, low power, robustness.
- Thin film flexible microsensor strips for dissolved oxygen and wetness detection.
- Flexible microfluidic substrate for rhizosphere 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)

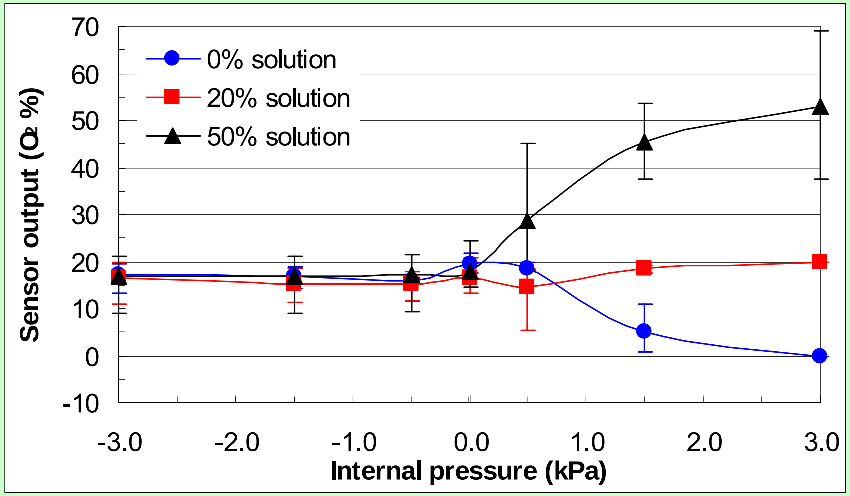




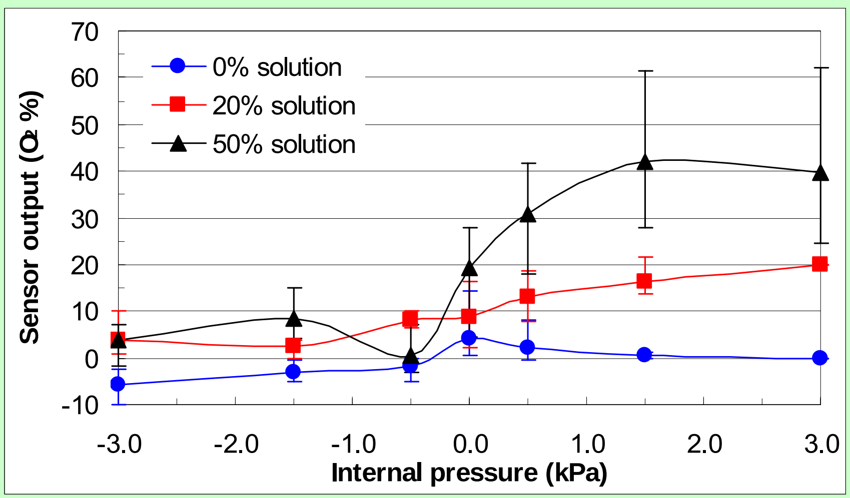
3 inches

- Wetness sensor strip (4-electrode conductivity measurement along the porous tube surface)

Dissolved oxygen measurement on the porous tube surface

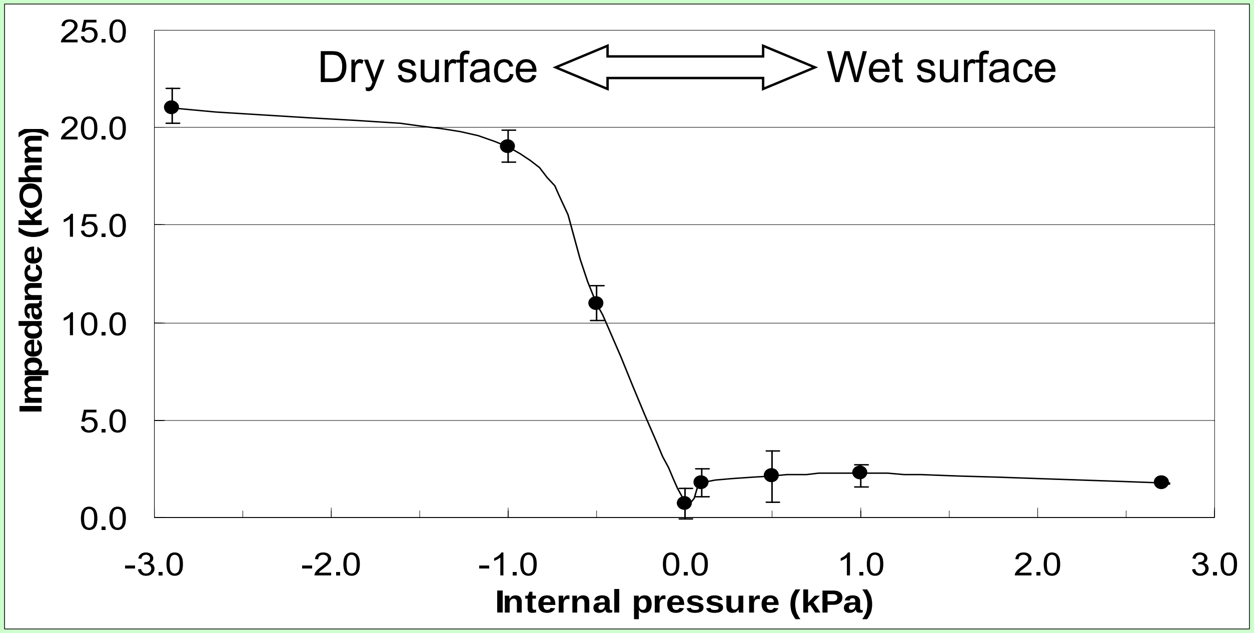


- With a commercial oxygen probe;
- Reflecting O_2 value of inner sol. at (+) pressures.
- Convergence to 20% value (air-sat. value) at (-) pressures.



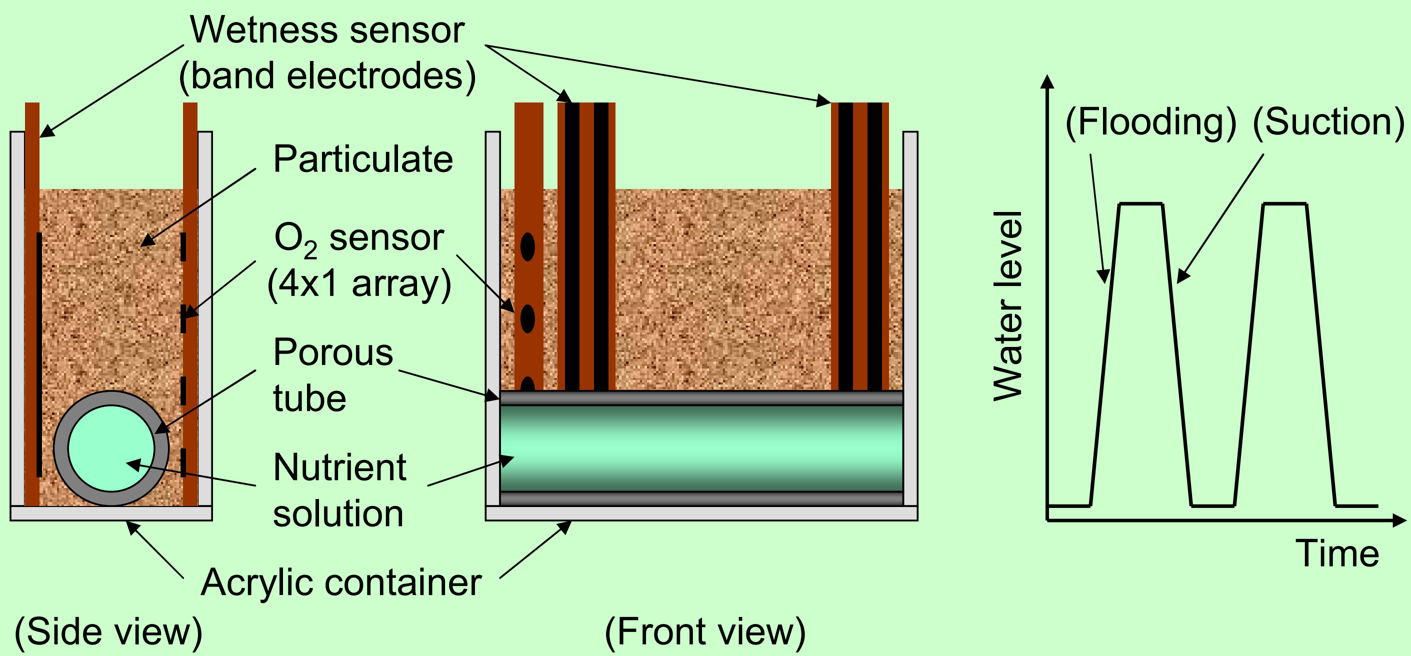
- With a microsensor array;
- Reflecting O_2 value of inner sol. at (+) pressures.
- Scattering around 0% value at (-) pressures (due to surface dryness and absence of sensor permeable membrane).

Wetness measurement on the porous tube surface



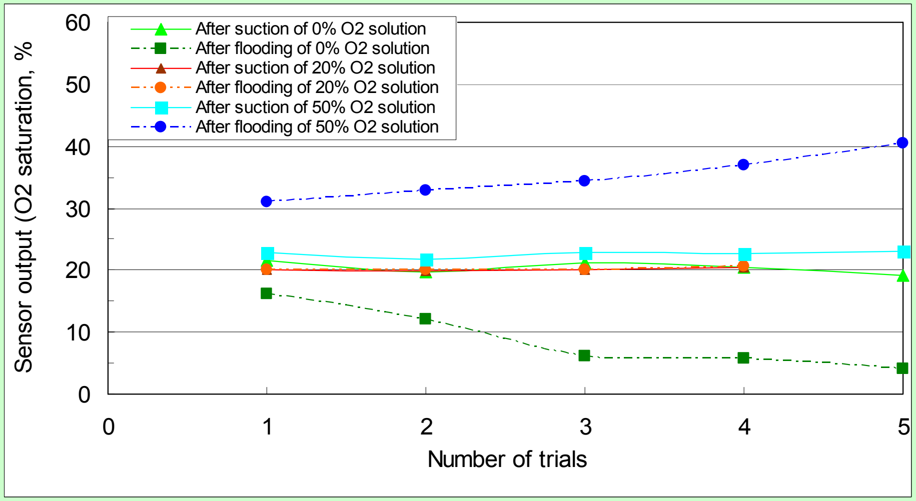
- A steep decrease of surface impedance at the transition from (-) to (+) pressure.

Experimental setup with a particulate growth system (Turface® 1-2 mm size particulate)

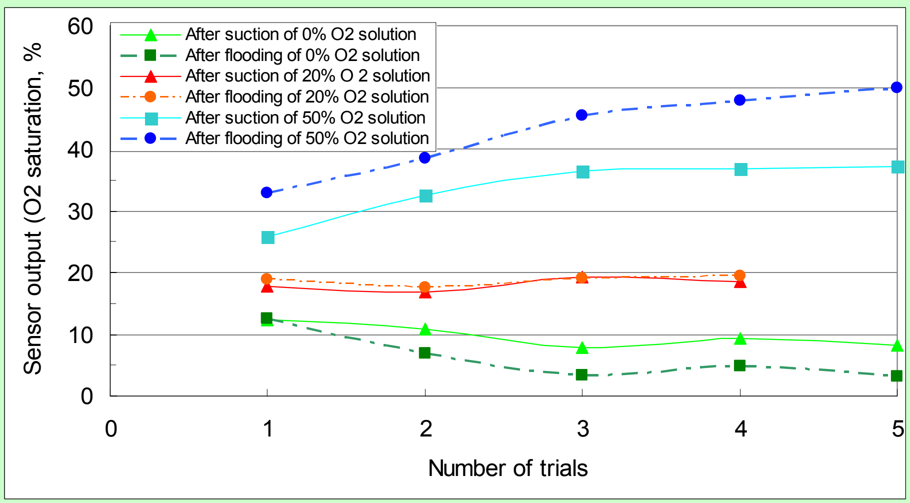


- Dissolved oxygen and wetness measurements within an unsaturated Turface® media.
- Repeated flooding and suction of nutrient solution using the embedded porous tube.

Dissolved oxygen measurements within the particulate

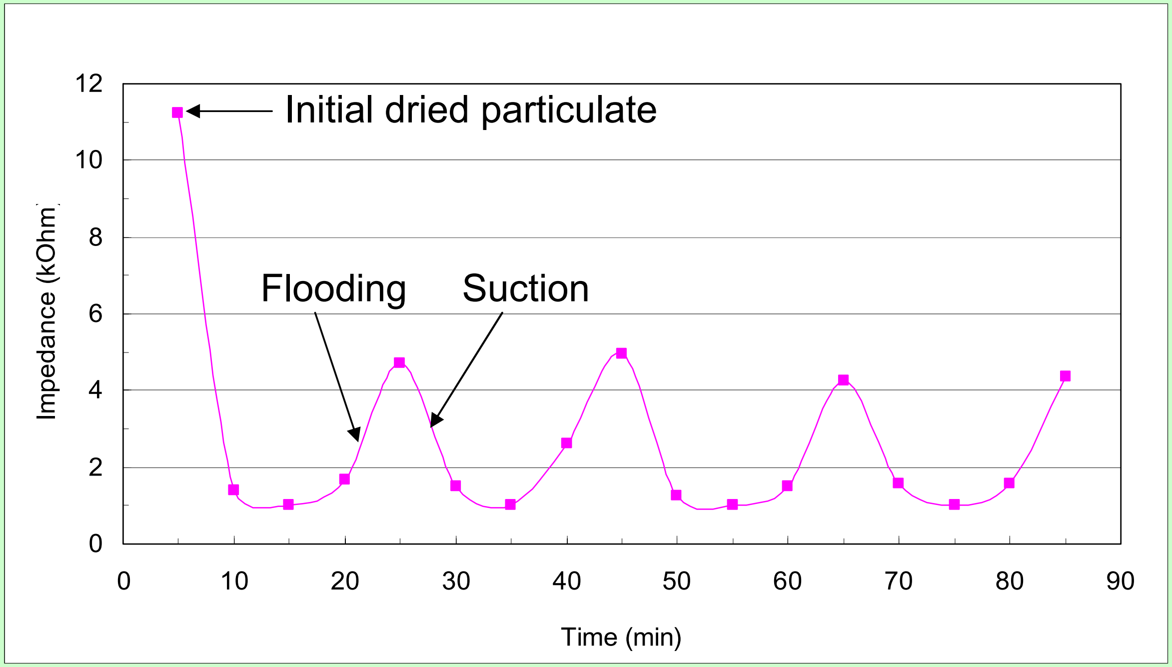


- With a commercial oxygen probe;
- Convergence to O_2 value of inner sol. with repeated flooding.
- Convergence to 20% value (air-sat. value) with suction.



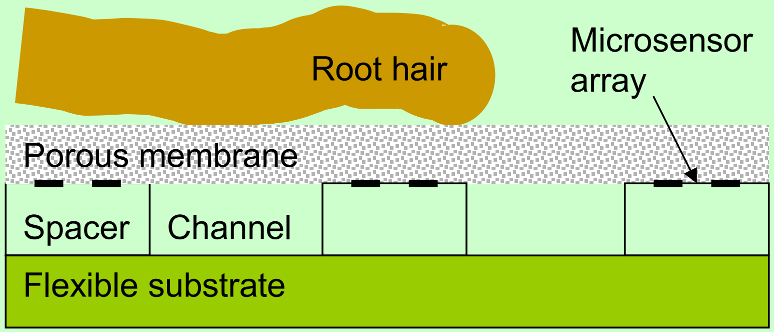
- With a microsensor array;
- Better reflection of O_2 value of inner sol. with repeated flooding.
- Better reflection of O_2 value of inner sol. with repeated suction.

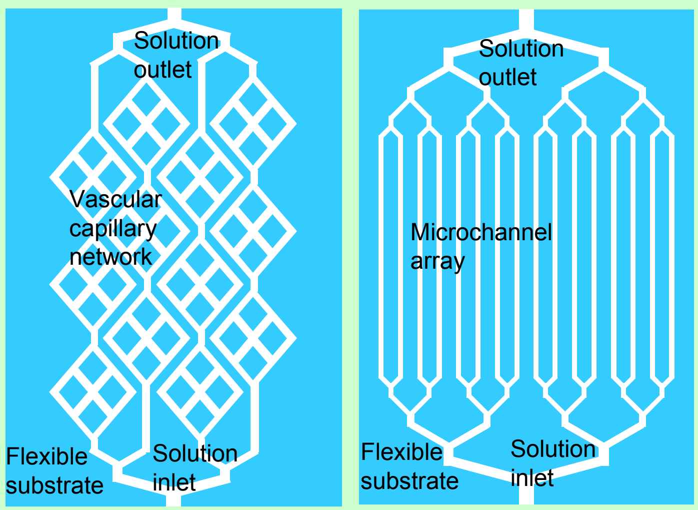
Wetness measurement within the particulate



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

Flexible microfluidic substrate for rhizosphere monitoring and manipulation

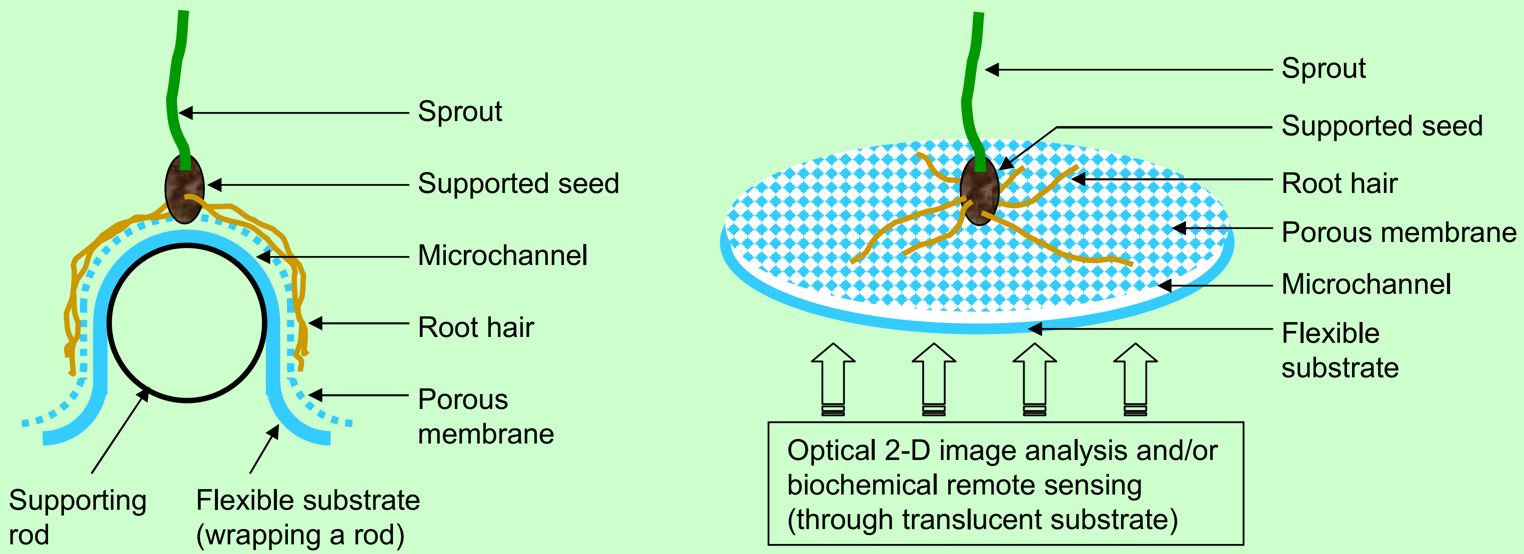




- Root hair growth on the surface of a porous membrane with underlying microfluidic channels and microsensor arrays.
- Exemplary layout of planar microfluidic substrates.

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

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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