Elucidating the Mechanism Governing Particle Alignment and Movement by DEP

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Introduction: Dielectrophoresis (DEP) has been increasingly regarded as an important technique to manipulate small particles such as biological cells in bioengineering applications. Modeling plays a significant role in advancing the DEP field as it helps to explain experimental observations and provides guidance in experiment design. Not being able to coherently explain various phenomena with the conventional DEP theory, we realized that an in depth elucidation of how particles interact with each other is necessary but missing in the current knowledge of DEP. We propose a new way to simulate movement of multiple particles under DEP and implement it computationally in COMSOL 4.4 using Mathematical particle tracing module. The modeling results show very good agreement with experimental observations including the formation of pearl chains and antenna-like structures as well as capturing cells in flow.

Computational Methods: In particle tracing module, forces exerted on a single particle by environment and particle-particle interaction have to be well defined. A particle experiences following forces (not including interaction) :

DEP force: $$F = (\vec{P} \cdot \nabla)\vec{E} \quad (1)$$

Gravitational force: $$F_g = vol \cdot \rho_{particle} \cdot g \quad (2)$$

Buoyancy force: $$F_b = vol \cdot \rho_{medium} \cdot g \quad (3)$$

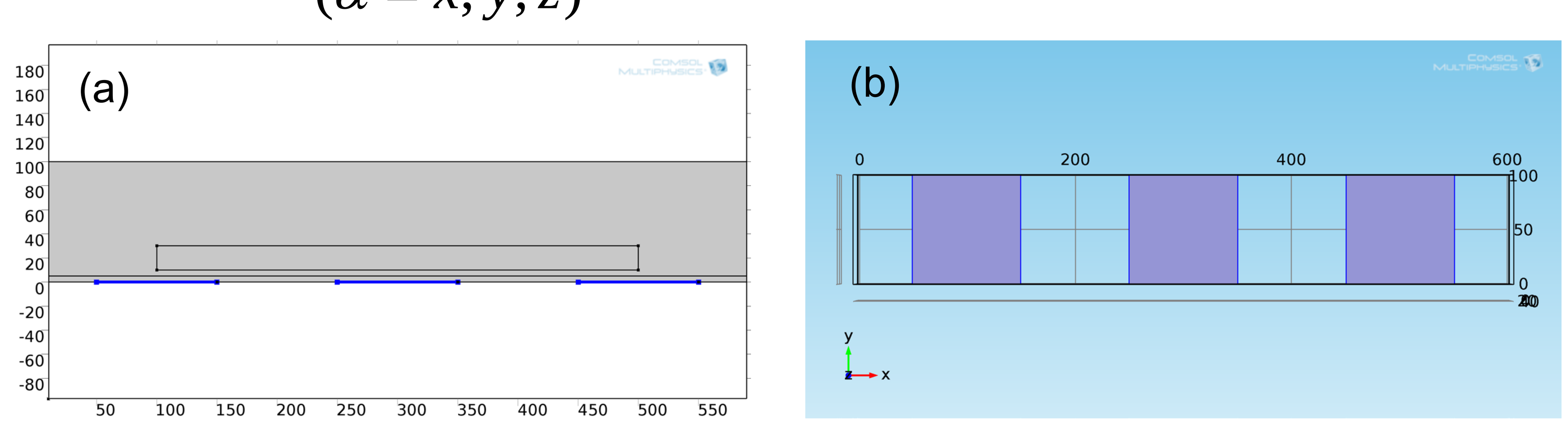
Hydrodynamic force: $$F_h = 6\pi r \eta v \quad (4)$$

Upward normal force: $$F_n = k(d + r - qy) \cdot (qy < (d + r)) \quad (5)$$

A particle is also subject to particle-particle interaction:

Dipole interaction: $$E_{particle} = \frac{1}{4\pi\varepsilon_0 R^3}(3(\vec{P} \cdot \hat{R})\hat{R} - \vec{P}) \quad (6)$$

Normal force: $$F_{ij} = k(q\alpha_i - q\alpha_j)(\exp((2r - d_{ij})/l) - 1) \cdot (2r >= d_{ij})$$
$$(\alpha = x, y, z) \quad (7)$$



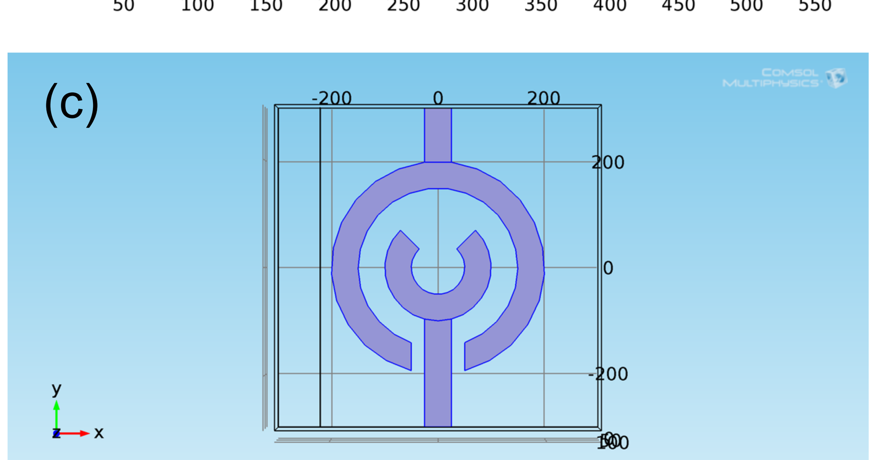
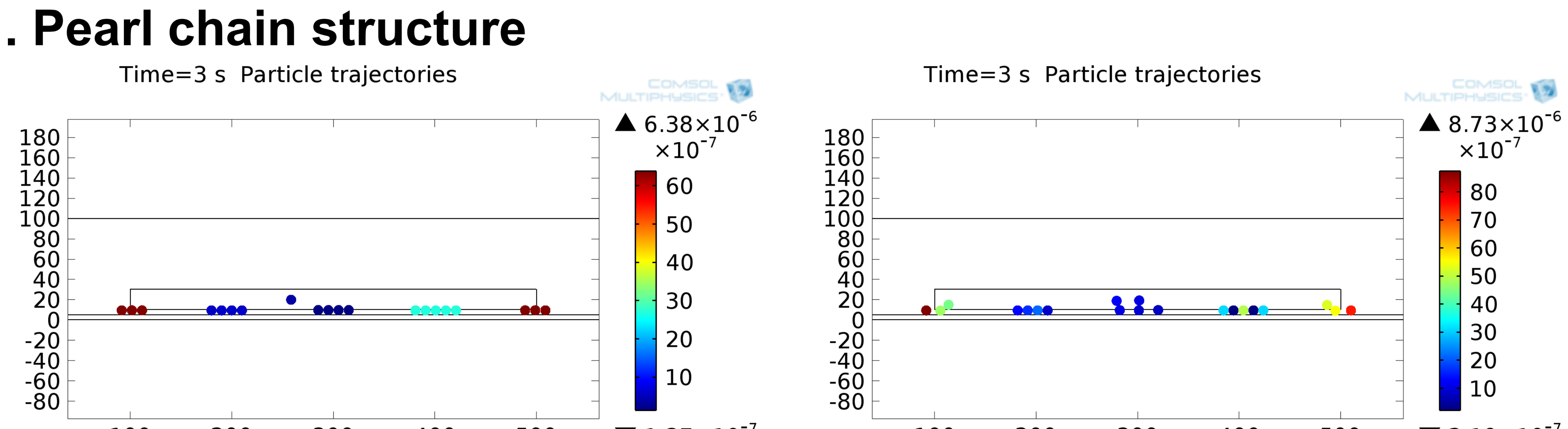


Figure 1. Geometry of model showing electrode designs and chamber structure (a)2D model; Identical to side view of 3D model with parallel electrodes. (b) Top view of 3D model with parallel electrodes. (c) Top view of 3D model with concentric electrodes.

Results: Simulation results are compared with experimental observations. Three cases are examined: pearl chain structure, antenna-like structure and capturing of cells in flow.

1. Pearl chain structure



(a) (b)

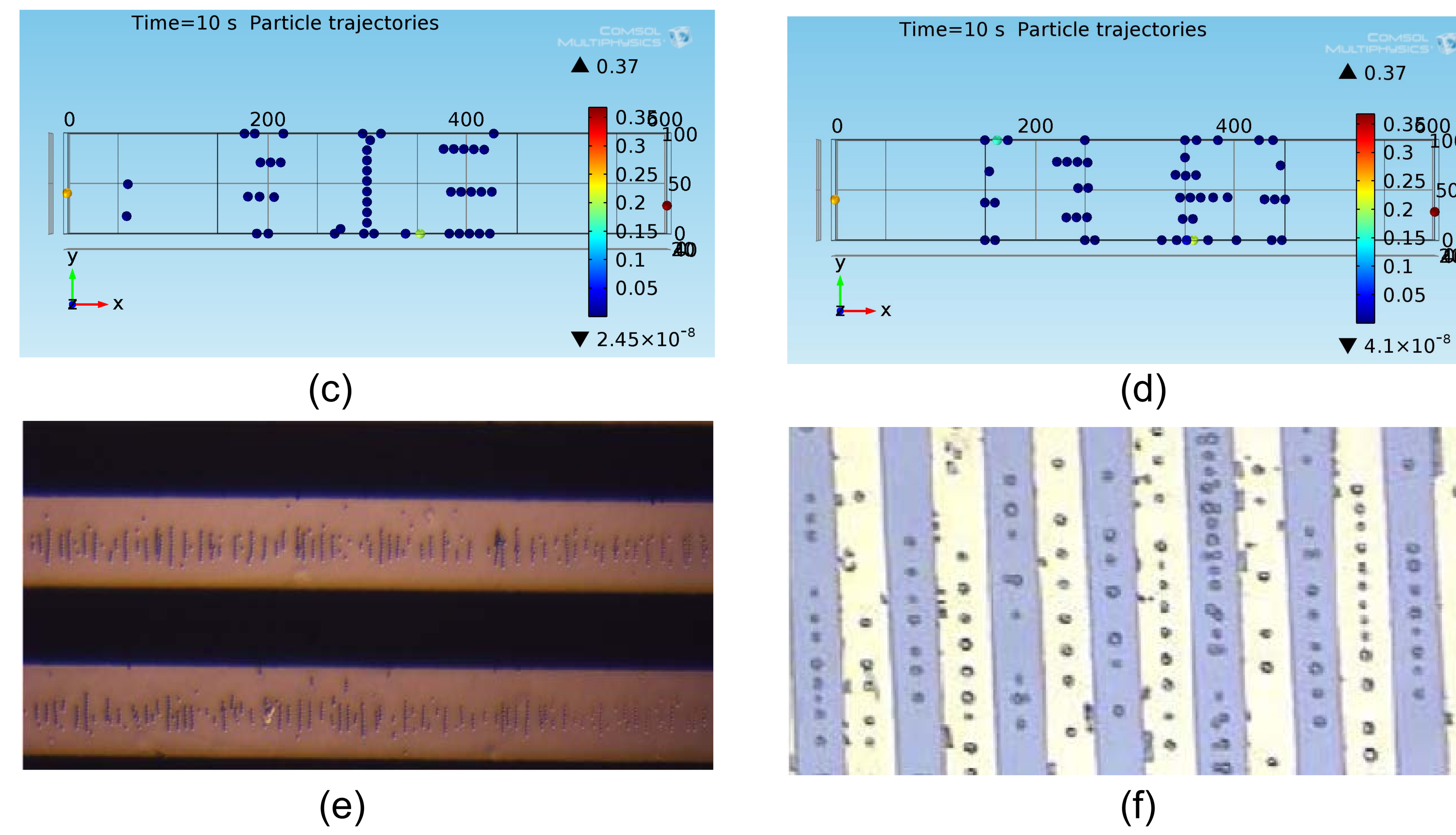


Figure 2. (a)-(b) 2D modeling of alignment of particles in electric field generated by parallel electrodes. (a) Particle-particle is not included. (b) Particle-particle is included. (c) Top view of 3D modeling results of alignment of particles under nDEP. (d) Top view of 3D modeling results of alignment of particles under pDEP. (e) Alignment of 4.5 um polystyrene beads in the gap between electrodes. (f) Alignment of 4.3 um polystyrene beads in gap and on top of electrodes.

2. Antenna-like structure

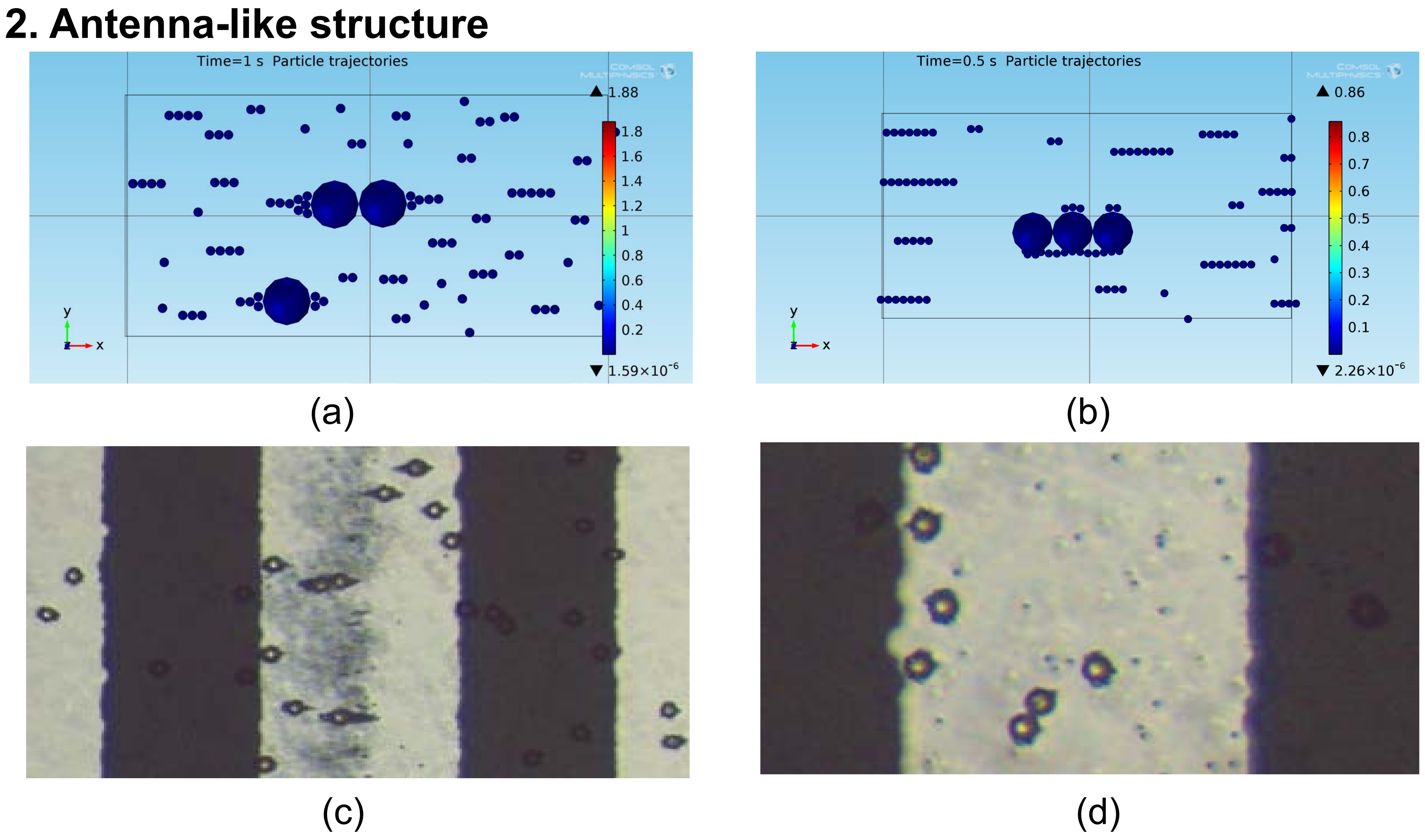
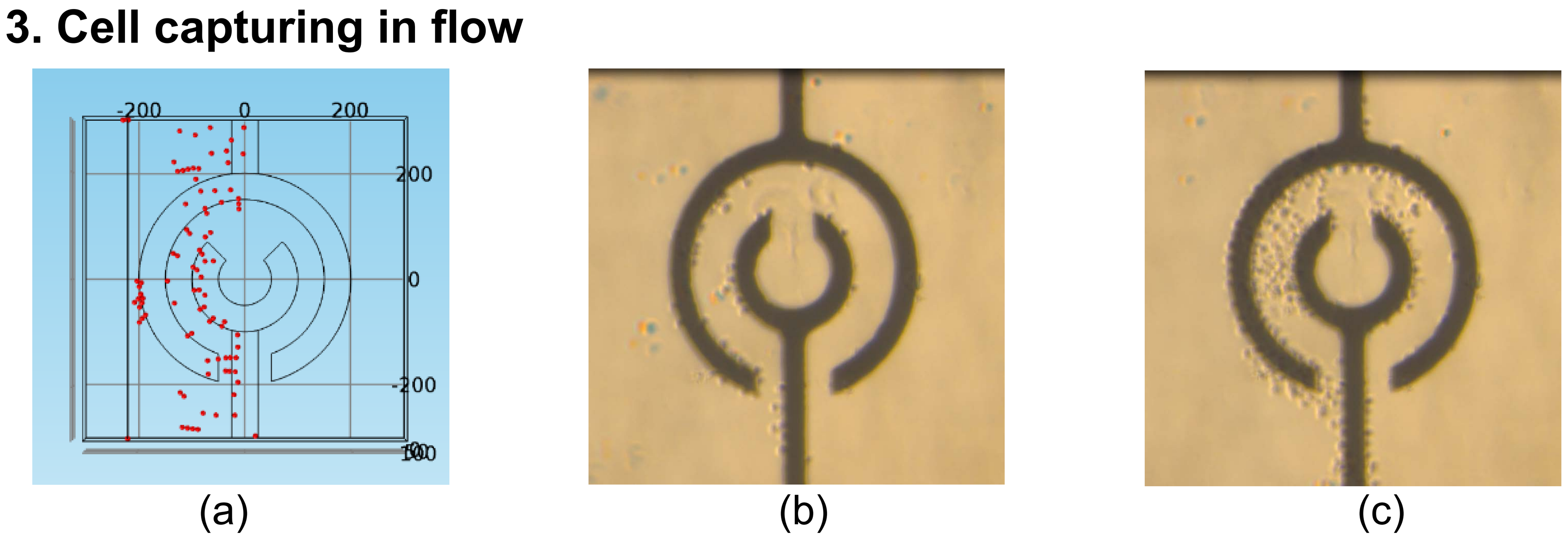


Figure 3. (a)-(b) 3D modeling results of formation of antenna-like structures. (a) High frequency. (b) Low frequency. (c)-(d) Images of antenna-like structures formed by mixed beads. (c) 20 MHz. (d) 100 kHz.

3. Cell capturing in flow



(a) (b) (c)

Figure 4. (a) 3D modeling results of capturing cells released from the left side of the square well. (b)-(c) Capturing breast cancer cells in flow moving from left to right. (b) After 5 seconds. (c) After 30 seconds.

Conclusions: Alignment and movement of multiple particles under DEP are simulated using particle tracing module in COMSOL 4.4 with particle-particle interaction taken into consideration. All our simulation results exhibit very good agreement with experimental observations, confirming the validity of our new approach to advance the DEP theory.

References:

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