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Cell transport and suspension in high conductivity electrothermal flow with negative dielectrophoresis by immersed boundary-lattice Boltzmann method

Qinlong Ren [a,*], Fanlong Meng [b], Cho Lik Chan [c]

[a] Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[b] Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
[c] Department of Aerospace and Mechanical Engineering, The University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

The cell transport and suspension using AC electrokinetics is essential for cell patterning and other biomedical applications in microfluidics. To avoid the undue cellular stress and irreversible damage to cells caused by low conductivity media, direct manipulations of cells in physiological solution of high electrical conductivity without dilution becomes significant. The driving mechanism of alternating current electrothermal (ACET) flow makes it attractive for pumping the physiological conductivity solution and transporting cells through the electrohydrodynamic (EHD) force. In addition, negative dielectrophoresis (nDEP) force is induced on a cell when its electrical conductivity is lower than that of solution media. In this paper, the effectiveness of ACET flow and negative DEP force in high conductivity solution is novelly used simultaneously to achieve a successful long-range cell transport and suspension in the microfluidic chamber. An immersed boundary-lattice Boltzmann method (IB-LBM) is developed to investigate the cell transport and suspension mechanism with respect to AC voltage magnitude, electrical conductivities of cell and solution, cell initial position, and cell size. It is found that a sufficient DEP force is indispensable for stabilizing the cell transport process and anchoring cells by overcoming the cell-cell interaction. Based on this, the design of a lab-on-a-chip device to generate a large DEP force is essential for future research to realize an efficient AC electrokinetic-based cell transport and suspension in physiological fluids.

1. Introduction

Microfluidics has been developed as an innovative technology for several biomedical applications such as cell manipulation, bacteria trapping, drug delivery, analyte mixing, protein immunoassay and so on due to the progress of microfabrication techniques [1]. Due to the requirement of a fast, precise, and low-damaged technique to manipulate or separate cells for the organ regeneration in the tissue engineering, several technologies have been developed by researches in this field during recent years. AC electrokinetics which include dielectrophoresis (DEP), AC electroosmosis (ACEO), and AC electrothermal (ACET) is one of the efficient approaches used in several biomedical devices for manipulating the bioparticles and fluid flow [2]. The DEP phenomenon refers to the motion of an electrically polarizable particle under the existence of non-uniform AC electric field, and it has been used to control different bioparticles such as cells, bacteria, and DNA molecules [3]. When AC voltage with frequency ranging from 100 Hz to 100 kHz is applied in an aqueous solution, due to the interaction between the tangential electric field and the induced charges in the electrical double layer (EDL), the fluid flow is activated termed as the ACEO flow [4]. However, when the electrical conductivity of aqueous solution (above 0.002 S/m) or the AC voltage frequency (above 100 kHz) is high, the ACEO flow is negligible due to the compression of EDL. Under this situation, the ACET flow which is caused by the gradients of permittivity and conductivity through local heating becomes dominant, and it serves as an efficient technique for pumping high conductivity solutions in microfluidic chambers [5]. Dielectrophoresis-based cell manipulation or patterning which aims at the capability of locating the cells on a desired location using DEP force has been developed as an important tool in the cellular microenvironment [6,7]. Ho et al. designed the concentric-ring array electrodes combined with stellate tips which could enhance the spatial electric field gradient

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* Corresponding author.
E-mail address: qinlongren@xjtu.edu.cn (Q. Ren).

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Nomenclature

A	cell surface area
A^*	dimensionless cell surface area
c	lattice speed
c_s	sound speed
D_x	horizontal distance between cells
D_y	vertical distance between cells
d_h	function defined in Eq. (26)
$d_{i,j}$	distance between the centers of ith cell and jth cell
d_i	distance between the centers of ith cell and imaginary cell
$\boldsymbol{E_{rms}}$	root mean square of AC electric field
$\boldsymbol{E^*_{rms}}$	dimensionless root mean square of AC electric field
$\boldsymbol{e}_i$	discrete lattice velocity in direction$i$
$\boldsymbol{F_b}$	fluid-cell interactive momentum force
$\boldsymbol{F^*_b}$	dimensionless fluid-cell interactive momentum force
$\boldsymbol{F_{DEP}}$	dielectrophoresis force
$\boldsymbol{F^*_{DEP}}$	dimensionless dielectrophoresis force
$\boldsymbol{F_e}$	AC electrothermal force
$\boldsymbol{F^*_e}$	dimensionless AC electrothermal force
$\boldsymbol{F}_s$	‘momentum force’ on the Lagrangian grids
F_i	discrete body force in direction$i$
$\boldsymbol{F^p_{i,j}}$	repulsive force between cells
$\boldsymbol{F^W_i}$	repulsive force between cell and wall
$\boldsymbol{F'_i}$	total repulsive force
$\boldsymbol{f}$	body force
$\tilde{f}_{CM}$	Clausius-Mossotti factor
f_i	density distribution function in direction i
f_i^{eq}	equilibrium distribution function of density in direction$i$
$\boldsymbol{g}$	gravitational acceleration
L_c	characteristic length
I_f	parameter defined as $I_f = 0.5\rho_f\pi R_p^4$
I_p	mass momentum inertia of cell $I_p = 0.5\rho_p\pi R_p^4$
JH	Joule heating term
k	thermal conductivity
M_f	mass of solution with the cell size volume $M_f = \rho_f\pi R_p^2$
M_p	mass of 2D circular cell $M_p = \rho_p\pi R_p^2$
N	number of cells
n	normal direction of boundary surfaces
p	pressure
p^*	dimensionless pressure
Re	Reynolds number defined as $Re = \frac{\rho_f U_c L_c}{\mu}$
$Re\left(\tilde{f}_{CM}\right)$	real part of Clausius-Mossotti factor
R_p	cell radius
R_{pi}	ith cell radius
R_{pj}	jth cell radius
$\lvert r\rvert$	distance between the Cartesian grid and Lagrangian grid
s	Lagrangian coordinate
T	temperature
T^*	dimensionless temperature
T_r	reference room temperature $T_r = 298K$
t	time
t^*	dimensionless time
U_c	characteristic velocity defined as $U_c = \sqrt{\frac{\varepsilon_{fr}\delta_\sigma \Delta T V_c^2}{\rho_f L_c^2}}$
$\boldsymbol{U_p}$	cell translational velocity vector
$\boldsymbol{U^*_p}$	dimensionless cell translational velocity vector
$\boldsymbol{U}^d$	desired velocity on the Lagrangian grids
$\boldsymbol{U}^t$	temporary velocity vector on the Lagrangian grids
$\boldsymbol{u}$	velocity vector
$\boldsymbol{u}^*$	dimensionless velocity vector
$\boldsymbol{u}^t$	temporary velocity on the Cartesian grids

V_c	characteristic AC voltage applied on the electrodes
V_{rms}	root mean square value of AC electric potential
V^*_{rms}	dimensionless root mean square value of AC electric potential
$\boldsymbol{X}(s)$	vector of location on the Lagrangian grids
$\boldsymbol{X_c}$	location vector of the cell center
$\boldsymbol{X^*_c}$	dimensionless location vector of the cell
$\boldsymbol{X_i}$	location vector of the ith cell center
$\boldsymbol{X_j}$	location vector of the jth cell center
$\boldsymbol{X'_i}$	location vector of the nearest imaginary cell center on the wall
$\boldsymbol{X_w}$	location vector of points at the cell surface
$\boldsymbol{X^*_w}$	dimensionless location vector of points at the cell surface
$\boldsymbol{x}$	vector of location on the Cartesian grids
x	coordinate in horizontal direction
x^*	dimensionless coordinate in horizontal direction
y	coordinate in vertical direction
y^*	dimensionless coordinate in vertical direction

Greek symbols

ρ	criterion parameter used in the repulsive force
ρ_e	charge density
ρ_f	solution density
ρ_p	cell density
ρ_r	density ratio between cell and solution
μ	dynamic viscosity
σ_f	electrical conductivity of solution
σ_{fr}	reference electrical conductivity of solution at T_r
σ_p	electrical conductivity of cell
ε_f	electrical permittivity of solution
ε_{fr}	reference electrical permittivity of solution at T_r
$\tilde{\varepsilon}_f$	complex permittivity of solution
ε_p	electrical permittivity of cell
$\tilde{\varepsilon}_p$	complex permittivity of cell
ϵ_p	parameter used in the repulsive force between cells
ϵ'_p	parameter used in the repulsive force between cells
ϵ_W	parameter used in the repulsive force between cell and wall
ϵ'_W	parameter used in the repulsive force between cell and wall
α	parameter defined as $\alpha = \frac{\delta_\sigma}{\delta_\varepsilon}$
δ_h	Dirac’s delta unction
δ_s	arch length of the segment on the Lagrangian grids
δ_x	lattice space
δ_σ	parameter defined as $\delta_\sigma = \frac{1}{\sigma_f}\frac{d\sigma_f}{dT}$
δ_ε	parameter defined as $\delta_\varepsilon = \frac{1}{\varepsilon_f}\frac{d\varepsilon_f}{dT}$
β_T	thermal expansion coefficient of fluid
ΔT	characteristic temperature defined as $\Delta T = \frac{\sigma_{fr}V_c^2}{k}$
Δt	time step
Δx	lattice space in x direction
Δy	lattice space in y direction
τ	the charge relaxation time of AC signal
τ_f	dimensionless relaxation time of density
ω	AC voltage frequency
ω_i	weight coefficient in direction i
Ω_s	cell surface curve
$\boldsymbol{\Omega_p}$	cell angular velocity
$\boldsymbol{\Omega^*_p}$	dimensionless cell angular velocity