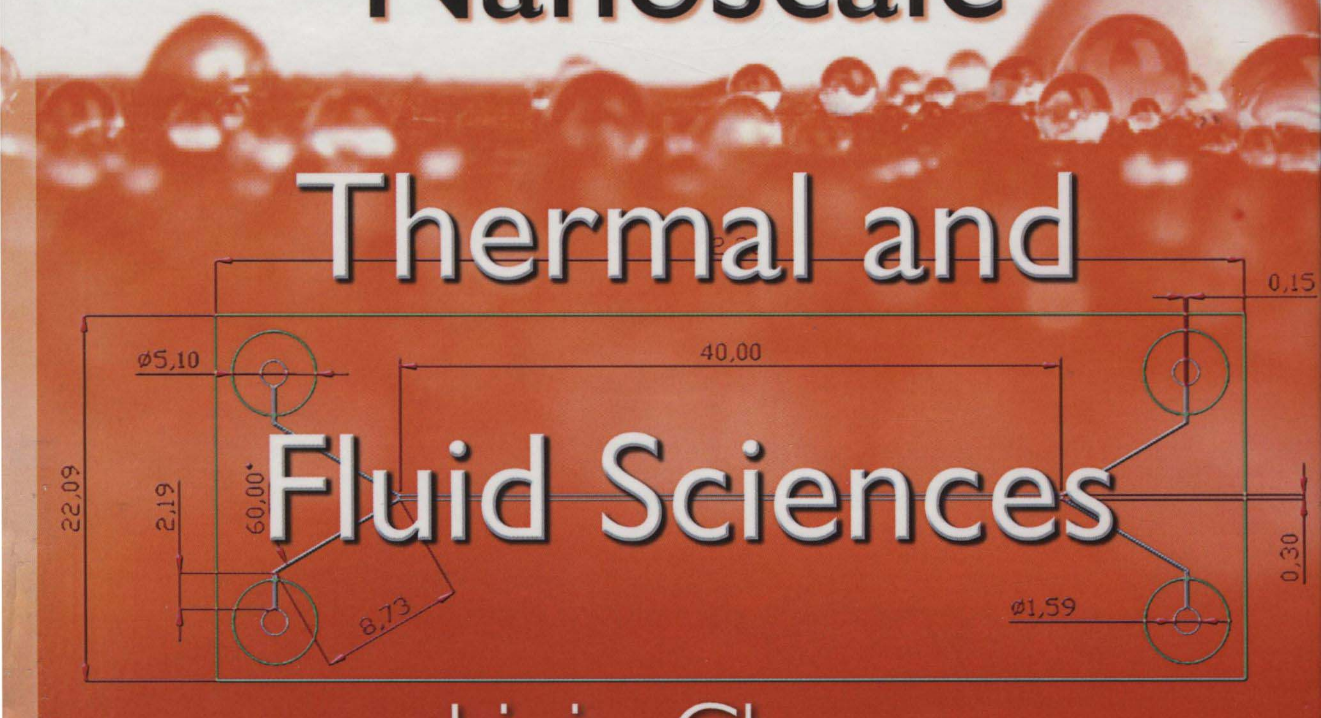
Mechanical Engineering Theory and Applications

Progress in Microscale and Nanoscale Thermal and Fluid Sciences



Lixin Cheng
Editor

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MECHANICAL ENGINEERING THEORY AND APPLICATIONS

PROGRESS IN MICROSCALE AND NANOSCALE THERMAL AND FLUID SCIENCES

LIXIN CHENG
EDITOR

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PREFACE

Applications of microscale and nanoscale thermal and fluid transport phenomena involved in traditional industries and highly specialized fields such as bioengineering, micro-fabricated fluidic systems, microelectronics, aerospace technology, micro heat pipes, chips cooling etc. have been becoming especially important since the late 20th century. However, microscale and nanoscale thermal and fluid transport phenomena are quite different from those of conventional scale or macroscale. Quite a few studies have been conducted to understand the very complex phenomena involved at microscale and nanoscale. New methods have been applied to measure the basic physical parameters at microscale and are continuously under development. New prediction methods have also been developed to cover both macroscale and microscale channels and are being continuously under investigation. New theories and mechanisms are also urgently needed for the fluid flow and heat transfer phenomena at microscale and nanoscale. There are many issues to be clarified from both theoretical and applied aspects in the microscale and nanoscale thermal and fluid transport phenomena. Furthermore, Interdisciplinary research areas are also rapidly under development. For example, as a new research frontier of nanotechnology, the research of nanofluid two-phase flow and thermal physics is rapidly growing, however, it has also posed new challenges as there are quite contradictory results in the available research.

To foster the research development of numerous evolving research topics, technologies and applications based on microscale and nanoscale thermal and fluid transport phenomena, I formed a new journal-*International Journal of Microscale and Nanoscale Thermal Fluid and Transport Phenomena (IJMNTFTP)* in 2010, which provides a high-quality forum specially for a wide range of papers dealing with original research results, technical notes and state-of-the-art reviews pertaining to thermal and fluid transport phenomena at microscale and nanoscale. It is aimed at meeting such urgent needs and to bring these important frontier research works together worldwide. It covers a wide range of topics on fundamentals and applications of micro-scale and nano-scale transfer processes of mass, momentum and energy such as micro-scale and nanoscale heat transfer and fluid flow, nanofluid flow and heat transfer, microfluidcs, nanofludics and technologies based on these transport processes such as various micro-scale and nano-scale thermal and fluid devices, micro and nano energy systems, micro-cooling technology in the computer and electronics industries and information technologies etc., MEMS, NEMS and the interdisciplinary research related to micro-scale and nano-scale thermal and fluid transport phenomena in bio-engineering, medical engineering and life engineering etc. Over the past five years, the new journal is going well and has provided an excellent platform for researchers and readers to exchange their research results.

It is my great pleasure to present this preface to this new edited book which includes selected research papers from volume 4 of the ***IJMNTFTP***. It is my greatest wish that the book can provide advanced knowledge in microscale and nanoscale thermal and fluid sciences and thus further promote research in the microscale and nanoscale thermal and fluid transport phenomena in our community.

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ABOUT THE EDITOR

Professor Lixin Cheng is the founder and Editor-in-Chief of the *International Journal of Microscale and Nanoscale Thermal and Fluid Transport Phenomena (IJMNTFTP)* and is the editor of the new book series "Microscale and Nanoscale Thermal and Fluid Sciences" (*MNTFS*) in 2015. He is the Editor-in-Chief of e-book series *Advances in Multiphase Flow and Heat Transfer*, and editor of *SpringerBriefs on "Multiphase Flow" and Book series "Frontiers and Progress in Multiphase Flow"* by Springer Verlag in Germany. He is an associate professor at Aarhus University, Denmark since July 2013. He received his Ph.D. in Thermal Energy Engineering at the State Key Laboratory of Multiphase Flow at Xi'an Jiaotong University, China, in 1998. He was a senior lecturer and course leader in Petroleum Engineering at the University of Portsmouth, UK in 2011-2013, and was a lecturer in Chemical Engineering at the University of Aberdeen, UK in 2009 – 2011. He was a scientific collaborator of the Laboratory of Heat and Mass Transfer (LTCM) at the Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland in 2006 - 2009. He was awarded an Alexander von Humboldt Research Fellowship and worked at the Institute of Process Engineering at the Leibniz University of Hanover, Germany in 2004 - 2006. He was a senior research fellow at London South Bank University in 2001 - 2003, and a post-doctoral research fellow at Eindhoven University of Technology, the Netherlands in 2000 - 2001. His research interests include multiphase flow and heat transfer, enhanced heat transfer, micro-scale heat transfer, nanofluid two-phase flow and heat transfer, compact and micro-heat exchangers and thermal systems. He has published more than 100 papers in journals and conferences, 8 book chapters and edited 10 books.

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Chapter 1

COUPLED ELECTROHYDRODYNAMIC-DIELECTROPHORETIC MICROPUMPING OF COLLOIDAL SUSPENSIONS IN A MICROCHANNEL

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ABSTRACT

Effective and versatile microfluidic pumps can be produced by utilizing various electrokinetic effects, such as electrohydrodynamics (EHD), induced-charge electroosmosis (ICEO) and dielectrophoresis (DEP). Among these, traveling-wave EHD (twEHD) has emerged as a powerful pumping mechanism due to its potential for miniaturization and the ability to pump a variety of liquids. However, when twEHD is used to deliver colloidal suspensions, the simultaneous presence of EHD effect may favorably or adversely influence the overall pumping performance, or vice versa. The net flow depends on the particle-fluid combination and the frequency range of the applied electric field. In this paper, the coupled EHD-twDEP flow was studied numerically in a microchannel with a three-phase interdigitated microelectrode array fabricated at the bottom surface. The results show that, depending on the frequency range of the traveling-wave electric field and the applied thermal boundary condition, the EHD-induced flow can significantly enhance or weaken the twDEP-induced flow.

Keywords: Electrohydrodynamics, dielectrophoresis, traveling-wave, micropump

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NOMENCLATURE

A Particle radius, μm
D Electrical diffusivity, m^2/s
E Electric field, kV/m
F Force, N
H Height of microchannel, μm
J Current density, A/m^2
K Thermal conductivity, W/(m K)
L Characteristic length, μm
T Temperature, K
U Charateristic velocity, μm/s
d Width or spacing, μ m
f Frequency, Hz
p Dipole moment, C m*t* Time, s
u Velocity, μm/s

Greek symbols

α Thermal diffusivity, m^2/s
ε Electrical permittivity, F/m
Λ Wavelength, μm
μ Viscosity, N s/m^2
ρ Density, kg/m^3
ρ_q Charge density, C/m^3
σ Electrical conductivity, S/m
ϕ Electric potential, V
Ω Angular frequency, rad/s

Subscripts

b Body
e External
f Fluid
m Medium
p Particle
r Relative

1. INTRODUCTION

The ability to generate and control fluid flow in small amounts with high precision is critical to the continued growth of microfluidic technology, which is now widely applied in drug delivery [1], chemical synthesis [2], biological diagnostics [3] and electronics cooling [4]. Conventional pumping methods driven by mechanical means are unsuitable for microfluidic applications due to their limits in miniaturization and lack of precision and flexibility in controlling low flow rates [5, 6]. Among the alternative solutions, a particularly attractive scheme is to exploit the AC electrokinetic effects, i.e., to generate the flow by inducing electrical forces in the fluid with an applied traveling-wave electric field. Based on the origin of the electrical forces, electrokinetic micropumps can be classified as the induced-charge electroosmotic (ICEO) micropump [7,8], dielectrophoretic (DEP) micropump, and electrohydrodynamic (EHD) micropump [10-12], etc.

In ICEO micropumps, the electrical double layer (EDL) is formed by the normal component of the traveling-wave field at the interface between the electrode and the electrolyte solution. The tangential component of the electric field acts on the mobile charges accumulated in the EDL, giving rise to a force that pulls the fluid along the direction of the traveling wave. The EHD micropumps are also generated through the interaction of an electric field with induced charges (ions), but the charge induction usually occurs in the bulk fluid due to the presence of a temperature gradient produced by anisotropic heating. The induced ions can be attracted or repelled by the traveling-wave field, depending on the direction of the temperature gradient, so that the fluid moves together with the ions owing to viscous drag. Although both ICEO and EHD micropumps involve a traveling-wave field, they can be discerned without ambiguity because they operate at very different frequency range [9, 13]. For instance, the maximum effect of EHD occurs near the charge relaxation frequency $f_c = \sigma_m/(2\pi\varepsilon_m)$ [14], while the optimal frequency of ICEO is around $f_{ICEO} = [\sigma_m/(2\pi\varepsilon_m)]/(\lambda_D/L)$, where λ_D is the Debye length and L is the characteristic length of the system, and f_{ICEO} is several orders of magnitude smaller than f_c.

Traveling-wave DEP (twDEP) is the sustained motion of dielectric particles in a fluid medium when exposed to a multi-phase (> 2 phases) traveling-wave field [15]. The driving force for particle motion originates from the interaction of the applied field with the induced electric dipole in the particles. When the moving particles drag the surrounding fluid together with them, an appreciable net flow, i.e., the twDEP micropumping effect, is generated [15]. The maximum twDEP is expected to take place near the Maxwell-Wagner relaxation frequency, $f_{M\text{-}W}$,

$$f_{M-W} = \frac{1}{2\pi}\left(\frac{\sigma_p + 2\sigma_m}{\varepsilon_p + 2\varepsilon_m}\right) \tag{1}$$

This frequency is of the same order of magnitude of the charge relaxation frequency of EHD (f_c) at which the maximum EHD pumping occurs. In fact, $f_{M\text{-}W}$ and f_c can coincide for certain particle-fluid combinations, for instance, if $\sigma_p << 2\sigma_m$ and $\varepsilon_p << \varepsilon_m$, $f_{M\text{-}W}$ will reduce to f_c. Furthermore, the velocity fields produced by twDEP micropumping and EHD micropumping are typically comparable in magnitude, while the flow directions may be totally opposite (as will be discussed below). Consequently, when a traveling-wave electric field is applied to transport colloidal suspensions, where the subject of interest can be either the particles or the carrier liquid, twDEP-induced flow and EHD-induced flow are simultaneously present, and the two pumping mechanisms may cooperate or compete with each other, depending on their relative flow directions with respect to the applied field. Thus, it is important to analyze the EHD-twDEP coupled flow and its potential variations in order to ensure satisfactory liquid/particle delivery capability of a microfluidic system that employs the AC electrokinetic effects [9, 16-18].

In this paper, the coupled EHD- and twDEP electrokinetic flow was studied numerically in a microchannel with an interdigitated microelectrode array fabricated at the bottom surface. The temperature gradient for EHD flow was induced by Joule heating in the electrolyte solution, and both the repulsion-type and the attraction-type EHD were considered. The flow field due to twDEP was solved using an equivalent mixture approach. The results show that, depending on the frequency range of the traveling-wave field and the thermal boundary condition, the EHD effect and the twDEP effect can work either synergistically or competitively to strengthen or weaken the net flow generated.

2. Theory and Analysis

2.1. Electrohydrodynamics

EHD flow arises as the result of the interaction of an electric field with free charges induced in a fluid medium. The charge induction occurs when a temperature gradient ∇T exists in the bulk of the liquid, which brings about gradients in the temperature-dependent electrical conductivity and permittivity. Upon the application of an electric field, the electrical force drives the free charges into motion, thereby producing the bulk fluid flow. EHD pumping due to preexisting temperature gradient, e.g., a temperature difference imposed across the boundaries of the fluid, has been studied extensively for heat transfer enhancement applications [14, 19-21]. Under a difference circumstance where the fluid medium has a non-negligible electrical conductivity, the electric field used in electrokinetics studies is usually high enough to generate appreciable Joule heating, which can produce a substantial temperature gradient in the bulk liquid [22]. EHD originating from Joule heating is also termed the electrothermal effect [23], and is considered in this work. The steady-state energy equation for the fluid is given as

$$\rho c_p\left(\vec{u}\cdot\nabla T\right)=k\nabla^2 T+\sigma E^2 \tag{2}$$

where the heat generation source term σE^2 is due to Joule heating.

The electrical force due to EHD is given by [24]

$$\vec{f}_e=\rho_q\vec{E}-\frac{1}{2}E^2\nabla\varepsilon 2 \tag{3}$$

where ρ_q is the free charge density, and $\vec{E}$ is the electric field. The two terms at the right hand side (RHS) of Eq. (3) represent the Coulomb and dielectric forces, respectively. The free charge density is related to the electric field by Gauss's law

$$\rho_q = \nabla \cdot \left(\varepsilon \vec{E}\right) \tag{4}$$

and the charge conservation equation is

$$\frac{\partial \rho_q}{\partial t} + \nabla \cdot \vec{J} = 0 \tag{5}$$

where the current density $\vec{J}$ consists of the convection current, the conduction current and the diffusion current, and is given by

$$\vec{J} = \rho_q \vec{u} + \sigma \vec{E} - D \nabla \rho_q \tag{6}$$

where D is the electrical diffusivity. The convection and diffusion currents can be neglected in this work since they are much smaller than the conduction current [23, 25].

Assuming small variations in the permittivity and electrical conductivity, the electric field can be written as the sum of the applied component $\vec{E}_0$ and the perturbation component $\vec{E}_1$, where $\vec{E} = \vec{E}_0 + \vec{E}_1$ and $\left|\vec{E}_0\right| \gg \left|\vec{E}_1\right|$. The electrical force becomes

$$\vec{f}_e = \left(\nabla \varepsilon \cdot \vec{E}_0 + \varepsilon \nabla \cdot \vec{E}_1\right)\vec{E}_0 - \frac{1}{2} E_0^{\,2} \nabla \varepsilon \tag{7}$$

Equations (4) and (5) can be combined as

$$\nabla \sigma \cdot \vec{E}_0 + \sigma \nabla \cdot \vec{E}_1 + \frac{\partial}{\partial t}\left(\nabla \varepsilon \cdot \vec{E}_0 + \varepsilon \nabla \cdot \vec{E}_1\right) = 0 \tag{8}$$

In an applied AC field of angular frequency ω, $\vec{E}_0(t) = \mathrm{Re}\left(\vec{E}_0 e^{i\omega t}\right)$ and $\partial / \partial t = i\omega$, where Re(…) is the real part of a complex quantity. From Eq. (8), it follows

$$\nabla \cdot \vec{E}_1 = \frac{-\left(\nabla \sigma + i\omega \nabla \varepsilon\right) \cdot \sigma + i\omega \nabla \varepsilon}{\sigma + i\omega \varepsilon} \tag{9}$$

Putting Eqs. (7) and (9) together, the time-averaged electrical force can be written as

$$\langle \vec{f}_e \rangle = \frac{1}{2}\mathrm{Re}\left\{\left[\frac{(\sigma\nabla\varepsilon - \varepsilon\nabla\sigma)\cdot\vec{E}_0}{\sigma + i\omega\varepsilon}\right]\vec{E}_0^{*} - \frac{1}{2}E_0^{\,2}\nabla\varepsilon\right\} \tag{10}$$

where * denotes the complex conjugate. The variations in permittivity and conductivity are related to the temperature gradient as

$$\frac{\nabla\sigma}{\sigma} = \frac{1}{\sigma}\left(\frac{\partial\sigma}{\partial T}\right)\nabla T \tag{11}$$

and

$$\frac{\nabla\varepsilon}{\varepsilon} = \frac{1}{\varepsilon}\left(\frac{\partial\varepsilon}{\partial T}\right)\nabla T \tag{12}$$

The EHD-induced flow field can be described by the Navier-Stokes equations for an incompressible fluid

$$\rho\left(\frac{\partial\vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \vec{f}_b + \vec{f}_e \tag{13}$$

and the continuity equation

$$\nabla\cdot\vec{u} = 0 \tag{14}$$

where $\vec{f}_b$ is other body forces if present. Considering the small velocity involved in most microfluidic studies, the inertia term can be omitted from Eq. (13) since the Reynolds number is usually less than unity ($\mathrm{Re} = \rho u L / \mu \leq 1$). Further neglecting the body force, Eq.(13) reduces to the Stokes equation

$$0 = -\nabla p + \mu\nabla^2\vec{u} + \vec{f}_e \tag{15}$$

2.2. Dielectrophoresis

Dielectrophoresis (DEP) is the motion of dielectric particles in colloidal suspensions when exposed to non-uniform electric fields [15]. When an electric field is applied, the re-distribution of electrical charges in the particle gives rise to an induced dipole across the particle.

The induced dipole tends to align with the applied field. The induced dipole moment, $\vec{p}$, and the dielectrophoretic force, $\vec{F}$, are given by