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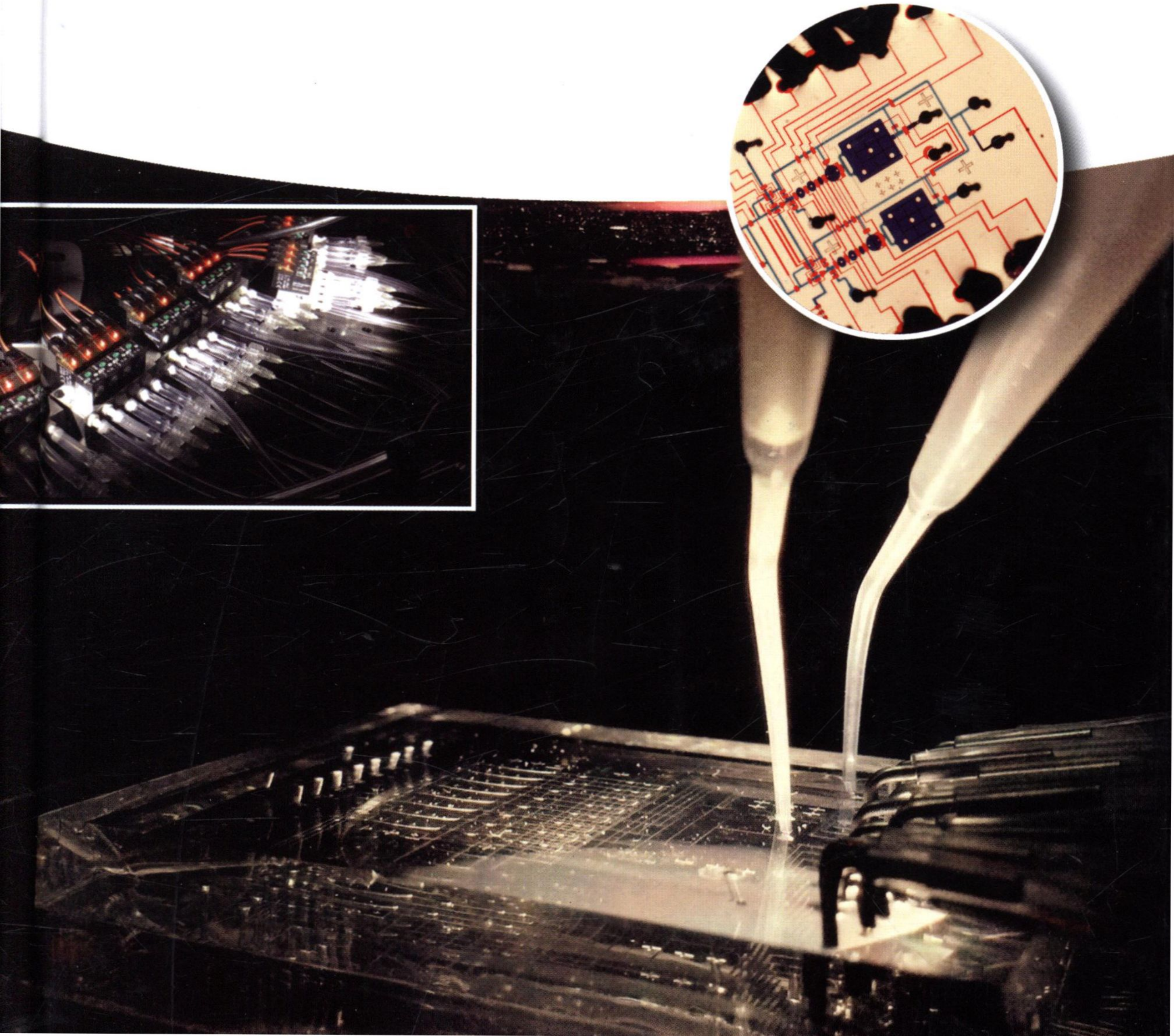
Edited by
Yujun Song, Daojian Cheng, and Liang Zhao

Microfluidics

Fundamentals, Devices, and Applications



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The first book offering a global overview of fundamental microfluidics and the wide range of possible applications, for example, in chemistry, biology, and biomedical science.

As such, it summarizes recent progress in microfluidics, including its origin and development, the theoretical fundamentals, and fabrication techniques for microfluidic devices. The book also comprehensively covers the fluid mechanics, physics and chemistry as well as applications in such different fields as detection and synthesis of inorganic and organic materials.

A useful reference for non-specialists and a basic guideline for research scientists and technicians already active in this field or intending to work in microfluidics.

__Yujun Song__ is a professor in School of Mathematics and Physics at USTB in Beijing, China, focusing on synthesis, interface structure control and application of metal-based nanohybrids using microfluidic process and template-assisted growth process. Having obtained his PhD degrees in Materials Science and Engineering from Beijing University of Chemical Technology, he spent 5 years at Louisiana State University in microfluidics and bio-nanotechnology, 2 years working at Old Dominion University in surface plasmon resonance and biotechnology, 7 years working at Beihang University in microfluidic synthesis and template-assisted growth process. He also spent one year working at University of Toronto as a visiting professor working on fabrication of hybrid semiconductor nanowire thin films, before taking up his present appointment at USTB.

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ISBN 978-3-527-34106-1

9 783527 341061

www.wiley-vch.de

Song • Cheng • Zhao (Eds.)

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Cover
The material used on the cover was
kindly provided by the editors

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-527-34106-1
ePDF ISBN: 978-3-527-80062-9
ePub ISBN: 978-3-527-80065-0
Mobi ISBN: 978-3-527-80066-7
oBook ISBN: 978-3-527-80064-3

Cover Design Adam-Design, Weinheim, Germany
Typesetting SPi Global, Chennai, India
Printing and Binding C.O.S. Printers Pte Ltd Singapore

Printed on acid-free paper

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Preface

Confucius stated, "Learning without thought is labor lost, thought without learning is perilous." During the past decades, microfluidics has quickly become an important tool in several fields including new technologies and basic research. As both thinker and practitioner for Engineers and Scientists, it is time to summarize and build up the fundamental fluid mechanics, physics, and chemistry in microfluidics and the relationship with their amazing successful applications in consideration of the future development of this field.

Microfluidics deals with small volumes of fluids from 10^{-9} to 10^{-18} l using channels with dimensions from several to hundreds of micrometers, which can be expanded even to millimeters. Microfluidics is an intrinsically multidisciplinary field of science that embraces research in physics, chemistry, medicine, engineering, materials science, and biology (2–6). Since the first applications of microfluidic technologies in analysis appearing as capilliary format succeeded in 1992, great progresses in their applications have been achieved in chemical analysis, biomolecule detection, cell treatment, pharmaceutical screening, robust and portable point-of-care devices, controlled synthesis of materials, precise reaction control, and so on, due to their opportunities for the spatial and temporal control of matter and heat transfer. Lots of academic and industrial materials on microfluidics have been accumulated, including construction of microfluidic devices according to their unique application areas, fundamental theory in microfluidics, and success in academic or industrial applications. Now, microfluidics has been paved into one of the main stream of new technologies, which is important not just for this field but also for lots of multidisciplinary technologies struggling to be made great in time.

The purpose of this book is mainly to summarize and build up the fundamental fluid mechanics, physics, and chemistry in microfluidics and the relationship with their amazing successful applications. This book will then provide prospective insights for the blooming of microfluidics to open a new and smart era in analysis, sensing, probing, synthesis, and screening of matter. It will provide not only a fundamental tool for the current researchers and commercial users of microfluidics to find the related physics and chemistry theory and a manual for their future fantastic applications but also a useful and powerful reference for the newcomer to add their knowledge and enlighten their own strategies in the development of a new theory and application of microfluidics.

From Chapter 1 to Chapter 4, the basic principles related to microfluidics will be discussed, including the history and current status of microfluidics, the fundamental physics of fluidic mechanism, the design/fabrication/materials of microfluidic devices, the related surface and interface effect in microfluidics unique from bulk reactors, and the fluidic simulation in microfluidics. In Chapter 5, the recently developed microfluidic devices, including smart microfluidic devices (e.g., digital microfluidics) and the robust and portable point-of-care microfluidic devices and their potential applications will be discussed. Then the rapidly developed applications of microfluidics in chemical/biological analysis (i.e., Micro Total Analysis Systems (μ-TAS)) and biological medical engineering (e.g., gene express, high-throughput disease diagnosis) will be summarized in Chapters 6–10 to analyze their advantages and marvelous progress by considering their unique features. And then the related materials synthesis via varieties of microfluidic devices including lab-on-chip and microtubing-based systems will be elucidated in Chapters 11–16 to show their potentials that sometimes cannot be successful in bulk reactors, including the synthesis of organics, polymers, metals, inorganics, composites, or hybrids. Finally, we will discuss the most recent progress (e.g., opto-microfluidics and other field coupled microfluidics and their future amazing applications) and some issues in microfluidics in Chapter 17, giving the readers a full and wide vision of this attractive technology.

We hope that this book will contribute to the research and teaching of this field and also attract more readers to pay attention. We also know that it is impossible to include all progresses and aspects of this rapidly blooming and exciting field. Therefore, we will feel gratified if only this book can give readers some clues on this interesting field and promote its scientific and technological development.

Finally, I dedicated this book to my lovely daughter: Xinran Song, who is full of curious about details of tiny things and creatures and dreaming to be a famous Biologist.

Beiing, China *Yujun Song*
July 16, 2017

Acknowledgments

This work was supported by National S&T Major Project (pre-approved No. SQ2018ZX100301), NSFC (Grant No. 51371018 & 81372425) and the Fundamental Research Funds for the Central University of China (FRF-BR-14-001B).

Abbreviations

$\vec{J}_i$	flux of component i
$\partial T/\partial x$	temperature gradient along x-direction, K/m
$\overline{B}$	magnetic field strength
$^{\partial u}/_{\partial y}$	local shear velocity
$\sim\lambda_{\mathrm{D}}$	ionic screening cloud of width
$\times$	cross product
∇	vector differential operator
a	speed of sound
A	cross-section area of the flow
A_1	cross-section areas A_1
A_2	cross-section areas A_2
AIP	American Institute of Physics
Ar	Archimedes number
At	Atwood number
Bi	Biot number
B_o	Bond number
Br	Brinkman number
c	total molar concentration (equation (2.19))
C	concentration of the species (equation (2.9))
c	light speed (equation (2.97))
Ca	capillary number
C_e	centrifuge number
Cfr	friction coefficient
c_i	molar concentration of component i
C_P	constant pressure heat capacity
C_V	constant volume heat capacity
d	collision diameter of molecules
D	diffusion coefficient (cm^2/s) (equation (2.14))
D	diffusion coefficient of the species (equation (2.92))
$\mathrm{D_{AB}}$	diffusivity of A in B
D_e	diffusion coefficient in gas or liquid filling the pore (equation (2.16))
D_e	Dean number
$\mathrm{D_h}$	hydraulic diameter

D_i	diffusivity of the ions
D_{ij}	Maxwell–Stefan diffusivity
DRIE	deep reactive ion etching
$\bar{E} = -\nabla\phi e$	local applied electrical filed strength
$E_{//}$	local electric strength
E	bulk modulus elasticity (N/m^2 (Pa))
$\bar{E}$	electric field
E	spacing distance (x) dependent electric field strength (equation (2.82))
Ec	Eckert number
EDL	electrical double-layer
Ek	Ekman number
E_o	Eötvös number
Eu	Euler number
F	magnitude of this force
FEP	fluorinated ethylene propylene
F_{mix}	extent efficiency of mixing two fluids next to each other accomplished only through diffusion
Fo	Fourier number
Fr	Froude number
Fr_R	rotating Froude number
Fs	shear force
g	acceleration of gravity
Ga	Galileo number
Gr	Grashof number
Gz	Graetz number
h	fluid depth (equation (2.30))
h(r)	displacement of the interface
h	height
Hg	Hagen number
I	beam intensity
I_0	intensity of the incident light
ICEK	induced-charge electrokinetic
ICEO	induced-charge electro-osmosis
IOP	Institute of Physics
J_0	zero-th order Bessel function
Ja	Jakob number
Jx	net flux
k	wavenumber of the laser beam
Kn	Knudsen number
k_rCL/D	Damköhler number
L	characteristic length
L	separation between electrodes (equation (2.94))
La	Laplace number
LC	liquid crystal
Le	Lewis number
LLCP	linear liquid crystal polymer

m	mass of molecule
M	molecular weight (equation (2.8))
M	molar mass (g/mol) (equation (2.14))
Ma	Marangoni number
M_B	molar mass of solvent B
Mo	Morton number
n	the number of components
N	Avogardro number
ñ	outward unit normal on surface
n_0	bulk concentration of ions
n1	refractive index
Nu	Nusselt number
P	static pressure (equation (2.32))
P	difference in pressure inside (P_i) and outside (P_o) of the bubble (equation (2.68))
p	pressure (atm)
∇_{P}	pressure gradient
P↑	beam power threshold
Pe	Péclet Number
PEEK	polyaryl etheretherketone
Pr	Prandtl number
Q	volumetric flow rate
q''_x	heat density along x-direction, W/m^2
R	gas constant (equation (2.1))
R and T	normal incidence for weak deformations with linearized curvatures (equation (2.99))
$\mathrm{R}(\theta_2, \theta_1)$	classical reflection
r	internal radius (equation (2.33))
r	average distance of the liquid (equation (2.79))
r	distance from the center to the laser beam
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
R_o	Rossby number
R_x and R_y	radii of curvature in all axes parallel to the surface
Sc	Schmidt number
Sh	Sherwood number
SH	source or a sink of heat
St	Strouhal number
Sta	Stanton number
Ste	Stefan number
Stk	Stokes number
$\mathrm{T}(\theta_2, \theta_1) = 1 - \mathrm{R}(\theta_2, \theta_1)$	transmission Fresnel coefficients in electromagnetic energy
T	absolute temperature
T_0	reference temperature (K)
T_1	absolute temperature

T_2	absolute temperature
Ta	Taylor Number
TMAs	tubular microactuators
u/y	rate of shear deformation or shear velocity
$\bar{u}$	average molecule velocity
$\bar{u}$	velocity vector
u_1	effective velocity of the fluid flow through and A_1 (equation (2.31))
u_2	effective velocity of the fluid flow through and A_2.
$\bar{u}_{ep}$	electrophoretic velocity of the species
U_{th}	largest interfacial tension
V_A	molecular volume of solute A under the boiling point, cm^3/mol.
w	half width of the light beam
We	Weber Number
W_{SLV}	work to form a kind of contact
x	heat transfer direction (equation (2.27))
x	distance from the channel wall (equation (2.90))
α	activity (equation (2.19))
α	thermal diffusivity (equation (2.28))
α	Womersley number
β	volumetric thermal expansion coefficient
β_T	isothermal compressibility
γ	relative magnitude of surface tension
γ_{SL}, γ_{LV} and γ_{SV}	interfacial tensions between solid and liquid, liquid and vapor, and solid and vapor, respectively
δ	constrictivity
Δp	characteristic pressure difference of flow
ΔP	pressure jump (equation (2.72))
ΔP	Laplace pressure (equation (2.67))
ΔT	characteristic temperature difference
ε	coefficient of thermal expansion
ε_t	porosity available for transport (dimensionless)
ε_w	dielectric constant
$\zeta_i \approx E_{0r}$	potential drop of field
ζ_i	local induced zeta potential
θ	contact angle
θ_1 and θ_2	transmission angles
κ	heat conductivity
λ	mean free path
λ_D	screening lengths
$\Lambda_{o,i}$	thermal conductivities (the subscripts i, o denote the fluids inside and outside)
μ	dynamic viscosity (equation (2.3))
μ	viscosity of liquid (equation (2.89))
$\mu\nabla^2 h$	laplace force
μ_0	reference viscosity

μ_a	pure viscosity of component a
μ_b	pure viscosity of component b
μ_i	chemical potential
μ_l	dynamic viscosity of liquid (Pa·s)
$\mu_\mathrm{o,i}$	shear viscosity
μ_r	relative viscosity (dimensionless)
μ_s	dynamic viscosity of slurry
μ_{T1}	dynamic viscosity of solvent at T_1
μ_{T2}	dynamic viscosity of solvent at T_2
v	ratio of inertial forces to viscous forces
$\Pi_\mathrm{Rad(r)}$	balance between radiation pressure
Π_Rad	light pressure
ρ	density of liquid
$\rho 1$	density
ρC_P	volumetric heat capacity (J/(m^3·K))
ρgh	gravity
ρ_q	local net charge density
ρ_tot	sum of two densities
σ	excess free energy of a drop on a solid surface (equation (2.69))
σ	surface tension (N/m)
$\sigma_\mathrm{A,B} = (\sigma_1 + \sigma_2)/2$	average collision diameter (Å)
σ_d	interfacial free energy of highest energy level
σ_f	interfacial free energy of final status
$-\sigma\hat{\mathrm{H}}$ (r)	laplace pressure
σ_i	interfacial free energy of initial status
τ	shear stress
$\overline{v}$	particle's velocity
$\overline{v}i$ "	diffusion velocity of the component
Φ	associated parameter of the solvent
χ	mole fraction
χ_a	mole fraction of component *a*
n	mole fraction of component *b*
Ω	temperature-dependent collision integral (usually of order 1)(dimensionless).
ω^*	characteristic frequency of interfacial wave
ω	circular frequency
ω	angular velocity of disc (equation (2.79))
ω_i	angular velocity of inner cylinder