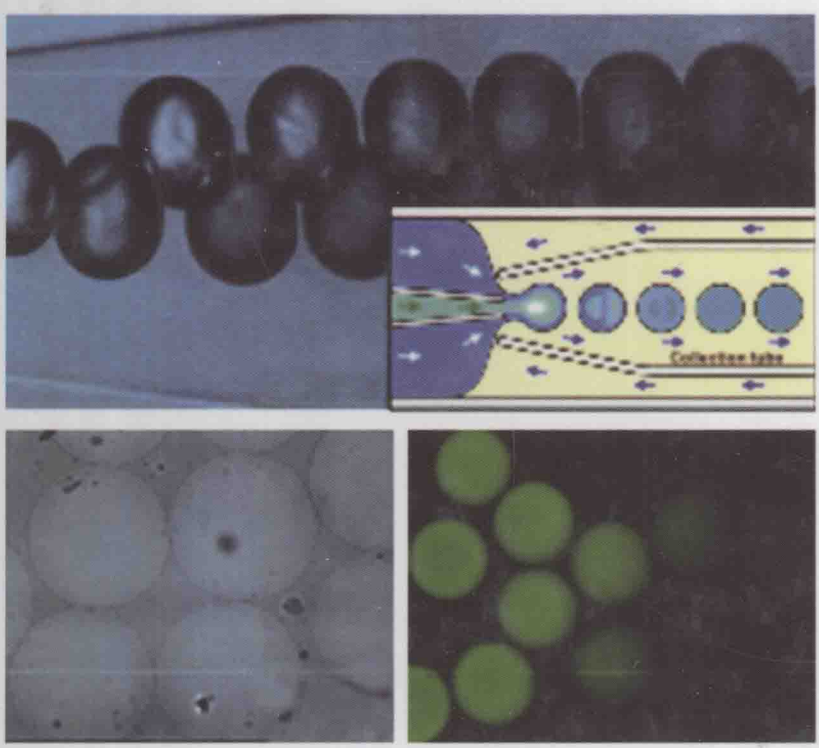
Edited by
Challa S. Kumar

Microfluidic Devices in Nanotechnology

Fundamental Concepts



WILEY

ftp://
SITE AVAILABLE

MICROFLUIDIC DEVICES IN NANOTECHNOLOGY

Fundamental Concepts

Edited by

CHALLA S. KUMAR

WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Microfluidic devices in nanotechnology. Fundamental concepts / edited by
Challa S. Kumar.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-47227-9 (cloth)
1. Microfluidic devices. 2. Nanofluids. 3. Nanotechnology. 4. Fluidic devices. I. Kumar, C. S. S. R. (Challa S. S. R.)
TJ853.4.M53M533 2010
620.1'06–dc22 2009051008

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

MICROFLUIDIC DEVICES IN NANOTECHNOLOGY

PREFACE

In the past two decades, the field of microfluidics has seen a phenomenal growth with increasing applications in several disciplines ranging from basic sciences such as chemistry, physics, and biology to most engineering disciplines. With the emergence of the field of nanotechnology, embracing literally every industry and application, it is not surprising that the field of microfluidics is also undergoing dramatic changes thanks to the influence of nanotechnology. The most obvious impact is the emergence of the field of nanofluidics, where the main difference with microfluidics is primarily a matter of scale, as defined by the volume of fluids handled in the system. However, the developments in microfluidics coupled with nanotechnology are paving the way for growing number of investigations to replace, in the future, conventional synthesis of nanomaterials and nanomaterials-based analytical methods by lab-on-a-chip systems combining microfluidic devices with nanotechnology. Surprisingly, there are no books published to date that capture these latest developments. It is indeed my pleasure to introduce you to the two-volume book series entitled *Microfluidic Devices in Nanotechnology*, covering fundamental concepts in the first volume and applications in the second volume. These books are the first ever to be published that focus on synergy between microfluidics and nanotechnology.

The first volume, *Microfluidic Devices in Nanotechnology: Fundamental Concepts*, in its combined form provides readers up-to-date knowledge about fluid and particle kinetics, spatiotemporal control, fluid dynamics, residence time distribution (RTD), and nanoparticle focusing within microfluidics. The fundamental concepts discussed here are invaluable for both nanotechnology and microfluidic practitioners. The first volume is a must for those who would like to take advantage of the combined power of microfluidics and nanotechnology. Before I go ahead giving you details of individual chapters in the first volume, I would like to take this opportunity to thank each and every author who made this exciting project a reality. I would also like to convey my thanks to each and every person (unfortunately due to lack of space I am unable to mention all the names) with whom I had the privilege of interacting and who have helped me directly or indirectly during the course of the publication of the two volumes. I would like to express my gratitude to my employer and colleagues at Center for Advanced Microstructures and Devices, family and friends, and Anita Lekhwani and Rebekah Amos at John Wiley & Sons, Inc., for their support and assistance. I do hope that this series will help enhance the knowledge of readers in this particular field. Finally, my special thanks to you, the readers, for ensuring that the knowledge base provided in this book series will be a building block for further understanding of synergism between microfluidics and nanoscience. I do realize that there is a lot of scope for improvement and I hope that I will be able to, with your comments and suggestions, take this series to a new level in the near future.

The book has a total of nine chapters. Chapter 1 by Professor Samuel K. Sia and coworkers provides a comprehensive discussion on physics, modeling, technological components, and fabrication of microfluidics. Chapter 2 by Michael D. Genualdi and David H. Gracias enlightens the readers on future directions and probable techniques and applications that will drive the cutting-edge research in microfluidics such as reconfigurable microfluidics with spatial and temporal control. Keeping in tune with recent advances in utilizing microfluidic devices as enabling technologies for kinetic studies in chemistry, the three most important components—microfluidic platform, rapid mixing apparatus, and integrated detection technologies—are reviewed by Professor Derek J. Wilson in Chapter 3. Chapter 4 by Professor Dimitris Drikakis et al. provides a description of recent advances in computational modeling for micro- and nanofluid dynamics. This chapter focuses on multiscale and metamodeling approaches that have recently experienced an explosion of work and are expected to become the dominant computational tools for processes at these scales in the future. Nanofluidic devices and their potential applications are reviewed by Dr. Patrick Abgrall et al. in Chapter 5. This chapter covers not only geometry-based fabrication techniques for nanofluidic networks but also the electrokinetic effects and hydrodynamics within the nanochannel.

The remaining part of the book stimulates conversations on microfluidic devices as enabling technologies for studying particle transport, electrokinetic effects, and magnetic control of particle transport. Chapter 6 by Professor E. P. Furlani provides an overview of the transport of magnetic particles in magnetophoretic microsystems. Chapter 7 by Professor Adrienne R. Minerick discusses relevant issues on the behavior of particles in microfluidic systems and presents fundamental aspects of synthesis and manipulation of particles in microfluidic systems. Chapter 8 by Professor Jie Wu covers various methods for particle manipulation such as electrofluidic and DC and AC electrokinetic methods, highlighting the importance of a preconcentration strategy. As residence time distribution is one of the most relevant aspects in the synthesis of nanomaterials within microfluidics, Chapter 9 by G. Alexander Groß and Professor J. Michael Köhler analyzes the RTD for the formation of different types of nanoparticles.

The second volume, *Microfluidic Devices in Nanotechnology: Applications*, is a unique source of information that judiciously combines elements of microfluidics and nanotechnology and shows a way forward for exciting applications in various fields such as chemistry, biology, molecular and cell biology, neuroscience, catalysis, and nanomaterials synthesis. It is hoped that both the volumes will prove useful for practitioners of microfluidics and nanotechnology, as well as interdisciplinary researchers seeking to take advantage of synergism between these two fields for potential problem solving in their own areas, be it energy, medicine, or environment.

Note: Additional color versions of selected figures are available on ftp://ftp.wiley.com/public/sci_tech_med/microfluidic_devices_applications

Baton Rouge, LA, USA
November 15, 2009

CHALLA S. S. R. KUMAR

CONTRIBUTORS

Patrick Abgrall, Biomedical Diagnostics Institute, Dublin, Ireland

Kweku A. Addae-Mensah, Department of Biomedical Engineering, Columbia University, New York, NY, USA

Nikolaos Asproulis, Fluid Mechanics and Computational Science Group, Aerospace Sciences Department, Cranfield University, Cranfield, Bedfordshire, UK

Aurélien Bancaud, LAAS-CNRS, Toulouse, France

Matyas Benke, Fluid Mechanics and Computational Science Group, Aerospace Sciences Department, Cranfield University, Cranfield, Bedfordshire, UK

Sau Y. Chin, Department of Biomedical Engineering, Columbia University, New York, NY, USA

Dimitris Drikakis, Fluid Mechanics and Computational Science Group, Aerospace Sciences Department, Cranfield University, Cranfield, Bedfordshire, UK

Edward P. Furlani, Institute for Lasers, Photonics and Biophotonics, University at Buffalo (SUNY), Buffalo, NY, USA

Michael D. Genualdi, Department of Chemical and Biomolecular Engineering, The Johns Hopkins University, Baltimore, MD, USA

David H. Gracias, Department of Chemical and Biomolecular Engineering, The Johns Hopkins University, Baltimore, MD, USA

Gregor Alexander Groß, Department of Physical Chemistry and Microreaction Technology, Institute of Micro- and Nanotechnologies, Ilmenau University of Technology, Ilmenau, Germany

Pierre Joseph, LAAS-CNRS, Toulouse, France

Johann Michael Köhler, Department of Physical Chemistry and Microreaction Technology, Institute of Micro- and Nanotechnologies, Ilmenau University of Technology, Ilmenau, Germany

Tassaneewan Laksanasopin, Department of Biomedical Engineering, Columbia University, New York, NY, USA

Adrienne R. Minerick, Dave C. Swalm School of Chemical Engineering, Mississippi State University, Mississippi State, MS, USA

Hesam Parsa, Department of Biomedical Engineering, Columbia University, New York, NY, USA

Evgeniy Shapiro, Fluid Mechanics and Computational Science Group, Aerospace Sciences Department, Cranfield University, Cranfield, Bedfordshire, UK

Samuel K. Sia, Department of Biomedical Engineering, Columbia University, New York, NY, USA

Zuankai Wang, Department of Biomedical Engineering, Columbia University, New York, NY, USA

Derek J. Wilson, Department of Chemistry, York University, Toronto, Ontario, Canada

Jie Wu, Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, TN, USA

CONTENTS

1

FUNDAMENTALS OF MICROFLUIDICS DEVICES

Kweku A. Addae-Mensah, Zuankai Wang, Hesam Parsa, Sau Y. Chin, Tassaneewan Laksanasopin, and Samuel K. Sia

Department of Biomedical Engineering, Columbia University, New York, NY, USA

1.1 INTRODUCTION

Microfluidics is a term that describes the research discipline dealing with transport phenomena at microscopic length scales (typically 1–500 μm) and components and techniques used to control and actuate the fluids.

The science of miniaturization was initially fueled by the microelectronics industry during the development of miniature silicon-based electronic devices. Techniques for silicon microfabrication and miniaturization were then extended to the fabrication of mechanical devices that became known as microelectromechanical systems (MEMS).[1] A later trend in MEMS technology was the development of devices for applications in medical and life science areas. The term biological microelectromechanical systems (BioMEMS) was coined to describe such devices and systems, although subsequently they did not all necessarily have the components normally found in traditional MEMS devices. Hence, a broad definition of BioMEMS would include some devices and applications made using the modern implementation of microfluidics, which was developed by Manz and coworkers[2,3] in the early 1990s.

With the emergence of the field of nanotechnology (roughly defined as the understanding and control of matter at dimensions of 1–100 nm), the field of

Microfluidic Devices in Nanotechnology: Fundamental Concepts, Edited by Challa S. Kumar

nanofluidics has recently emerged. The main difference between microfluidics and nanofluidics is primarily a matter of scale, as defined by the volume of fluids handled in the system.

1.1.1 State-of-the-Art Commercial and Scientific Aspects

The fields of MEMS and microfluidics have extended beyond the traditional area of development of inkjet head and pressure sensors to areas such as drug delivery, chemical synthesis, protein crystallization,[4] cell culture,[5] point-of-care diagnositics,[6] genetic sequencing, drug discovery, genomics, and proteomics. Microfluidics has the potential to dramatically change the way in which the pharmaceutical industry screens for drugs and targets with a significant increase in performance due to the ability to do fast, high-throughput, parallel experiments with very little reagents on a single chip. This capability is not possible with current benchtop techniques.

Microfluidics has also found much use in the scientific community. It is now a common tool for chemists, physicists, biologists, and most engineering disciplines and has thus become a multidisciplinary platform advancing many frontiers in science and engineering. It has helped to advance understanding the theory and modeling of fluid dynamics, including the transition from continuum-based theory to discretized models. Life scientists are using microfluidics to explore phenomena at the single-cell level and in confined well-defined environments. Chemists and biophysicists are able to grow and analyze protein crystals and sequence DNA in a reagent and time efficient manner. The overall influence of microfluidics in the scientific community is evidenced by a large and sustained growth in the number of publications in journals and conferences from the mid-1990s to today.

1.1.2 Organization of the Chapter

The remaining chapter is divided into five sections, each of which is outlined as follows:

- Section 1.2 discusses aspects of the physics and modeling of microfluidics. We examine continuum and molecular-level models, and also introduce some of the dimensionless numbers relevant in the physics of microfluidics; since our discussion is not an exhaustive treatment, we direct readers to other publications with more in-depth analysis.[7]
- Section 1.3 deals with technological components used in microfluidics. The section is divided into subsections that deal with fluid switching, fluid flow and actuation, and fluid mixing. This section also includes a section on droplet microfluidics.
- Section 1.4 discusses aspects of fabrication of microfluidic devices. This section is divided into four subsections that examine techniques (based primarily on the nature of the material) for fabricating a microfluidic system.
- Section 1.5 discusses applications of microfluidics.

- Section 1.6 discusses future directions and probable techniques and applications that will drive the cutting edge of research in microfluidics.

1.2 PHYSICS AND MODELING

Attempts toward understanding the physics behind fluid flow at the microscale have been made to account for a different dominant type of force at microscale dimensions. At larger dimensions, inertial forces play a dominant role, whereas as the dimensions decrease surface forces become increasingly important. The Reynolds dimensionless number is used to compare the body forces and surface viscous forces. Moreover, surface area relative to volume increases as the characteristic dimension decreases.[8]

As the size scale decreases, the assumption of continuity is increasingly challenged. In general, approaches for modeling fluids can be divided into the two major categories of continuum models and molecular-level models.[9] In continuum models (the most common of which are formulated using Navier–Stokes equations), the discontinuity that exists among discrete molecules is discarded. This assumption is valid when the dimensions of the system are much larger than molecular dimensions, but the assumption breaks down when the dimensions of the system become comparable to molecular dimensions. For simulating systems with small dimensions, molecular-based models can be deterministic (e.g., some forms of molecular dynamics simulations), statistical (e.g. Monte Carlo), or a hybrid. A dimensionless number, the Knudsen number, can be used to evaluate whether the continuum flow or discrete molecular model is more appropriate.

1.2.1 Dimensionless Numbers

The above two examples hint at the importance of dimensionless numbers in microfluidics. Since it is the interplay of different phenomena that lead to specific flow patterns at the microscale, dimensionless numbers are defined to compare the relative importance of each of these phenomena. Some important dimensionless numbers in microfluidics are described briefly below:

- *Reynolds Number (Re)*: As the characteristic length in microfluidic devices is decreased, inertial forces (which are dominant in macroscale systems) decrease significantly compared to viscous forces. Since inertial terms are the cause for creating turbulence, flow regimes tend toward laminar flow at small dimensions. The Reynolds number ($\rho UL/\eta$) compares the relative magnitudes of inertial force ($\rho U^2/L$) and viscous force ($\eta U/L^2$). In microfluidics, Re is typically less than 1.
- For $Re \ll 1$, nonlinear terms (such as convective acceleration) can be neglected, such that fluid flow switches to the Stokes regime.
- *Knudsen Number (Kn)*: The validity of continuum model is normally assessed using the measure of free path length, as embodied by the Kn, which is the ratio of the mean free path length to the characteristic dimension. The assumption of

continuum model is valid as long as the *Kn* number is small ($Kn \ll 1$). On the basis of various magnitudes of Knudsen numbers, flow regimes change from continuous flow to slip flow, and finally free-molecule flow regime.[10]

- *Pèclet Number (Pe)*: When Reynolds number is small (which is generally the case in microfluidic systems), flow is not turbulent, and hence fluid mixing by convection is not significant. In such cases, mixing through diffusion becomes important. To define a measure of diffusive versus convective transport, the Pèclet number (Uh/D) is defined as the ratio of convective transport (Uh) to diffusive transport (D).[7]
- *Damköhler Number (Da)*: Extensive development of microfluidic applications has led to the incorporation of chemical reactions on surfaces. For instance, in immunoassay diagnostic devices, functionalized surface of the microchannel serves as a reacting surface, and the relative speed of reaction versus diffusion is one of the key factors in determining efficiency of the assay. The Damköhler number ($k_{on}Ch/D$) compares the relative speed of diffusive transport (D) and surface reaction ($k_{on}Ch$).
- *Capillary Number (Ca)*: In a microscale environment, surface effects are extremely important due to the high surface area-to-volume ratio. As such, surface tension plays a significant role in many microfluidic applications, including droplet formation. The relative magnitude of surface tension (γ) with respect to viscous effects (ηU) is compared by defining the dimensionless capillary number ($\eta U/\gamma$). One use of *Ca* is to make droplets with different dimensions (by choosing appropriate capillary numbers) to study chemical reaction kinetics.[11]
- *Mach Number (Ma)*: The Mach number is defined as the ratio of flow velocity to the velocity of sound in that medium; this number serves as a measure of fluid compressibility. For Ma less than 0.3, the fluid can be considered incompressible.

1.2.2 Modeling Approaches

Continuum models are defined in terms of independent variables (velocity, pressure, and density) that are solved for all fluid element nodes at each time step. For finite element simulations, smaller elements provide better accuracy at the expense of higher computational effort. Thus, the conservation of mass and momentum could be written as

$$\frac{\partial p}{\partial t} + \nabla, (\rho u) = 0$$

$$\rho\left(\frac{\partial u}{\partial t} + u, \nabla u\right) = -\nabla p + \nabla T + f$$

Where ρ and u are fluid density and velocity, respectively, p is pressure, T is surface force, and f is body force. In the case of viscous flow, the Navier–Stokes equation is a second-order partial differential equation that requires two boundary conditions. First, the normal component of velocity is normally set to zero at the impermeable boundaries. Additional tangential boundary conditions are required to solve the Navier–Stokes equation in the region of interest. For continuum flow, the no-slip boundary condition is a second boundary condition, although this assumption breaks down for higher Knudsen numbers ($Kn > 0.1$).

1.2.3 Particle Imaging Velocimetry

Fluid flow models can be verified with particle imaging velocimetry (PIV). Methods for qualitative visualization of fluid flow are insightful but are not sufficient for determining the flow structures in microchannels. Traditionally, intrusive methods using pressure tubes or hot-wire anemometer, and nonintrusive methods such as laser Doppler velocimetry, have been used to determine single-point velocities in the fluid, but are ill-suited to determine the velocity field across all fluid elements.[12] In particle imaging velocimetry, tracer particles are added to the fluid, and a single cross-sectional plane of the fluid is visualized. A CCD camera is used to record a sequence of images (with the frequency of the recording determined in part by fluid velocity), and postprocessing algorithms help determine the velocity field. PIV has proven to be a powerful method in the visualization fluid flow in microfluidic devices.[13]

1.3 COMPONENTS OF MICROFLUIDICS

Since around 1990, when the modern implementation of microfluidic systems originated,[3] researchers have developed a diverse range of microfluidic components, ranging from micropumps to micromixers. Such components allow precise control and manipulation of fluids. The design and operation of these components are based on the volume of fluids handled, the type of fluids, and the particular application.

1.3.1 Fluid Actuation

In this section, we examine methods and techniques that are used to drive fluids through the microfluidic system. We discuss only systems where the pumping is done by components on-chip, although syringe pumps (which are external to the chip) are often used. We discuss traditional mechanical pumps as well as two pumping schemes that have been enabled by the microscale. Important parameters that are considered in design and fabrication of pumps include the maximum flow rates that can be achieved, power consumption, efficiency, and back pressures that can be sustained while maintaining appreciable pumping.

1.3.1.1 Mechanical Displacement Pumps

Most pumps in this category use a diaphragm or a flexible membrane. Displacement of the diaphragm applies a force to the fluid, thus causing it to be displaced. In the reciprocating pumps, the deflection is done in a periodic manner. Materials for the

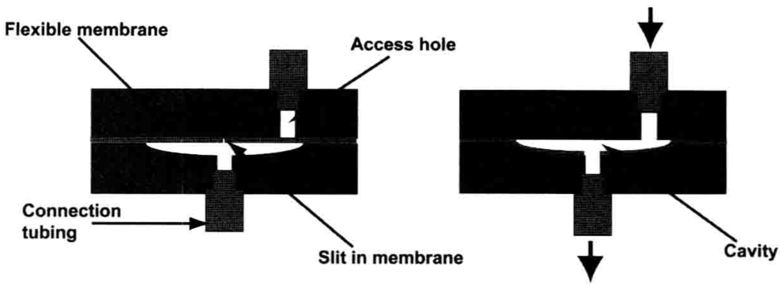


FIGURE 1.1 Schematic showing the mode of operation of a passive membrane type valve.

diaphragms include thin silicon, glass films, elastomeric polymers such as thin layers of silicone or polydimethylsiloxane (PDMS), and thin films of other polymers such as polyimide and parylene C. Such pumps normally have passive check valves (Section 1.3.2.2) that regulate the flow of fluid into and out of the pump chambers. During a single pump cycle, movement of the diaphragm first increases the volume of the pump chamber (during the suction or expansion stroke), thereby drawing fluid into the chamber. A subsequent decrease in the volume of the pump chamber during the alternate stroke of the diaphragm (during the contraction or discharge stroke) forces the fluid out (Figure 1.1). In some cases, more than one pumping chamber is connected in series to form a peristaltic pump.[14–16]

Alternatively, electrostatically driven micropumps can be driven by both AC and DC current. Materials include parylene (multilayer peristaltic pump)[17] and a combination of glass, silicon, and polysilicon with gold electrodes.[18]

The use of piezoelectrics to drive microfluidic micropumps was initially demonstrated in inkjet printer heads in the early 1980s.[19] Piezoelectrically driven micropumps have become more common because they are relatively inexpensive to fabricate especially when the diaphragm or flexible membrane is made with cheap elastomeric materials like PDMS instead of thin glass or silicon membranes. The literature on piezoelectric-driven micropumps is extensive, with many recent designs reported in the literature.[20–24]

Electromagnetically driven micropumps use Lorentz forces generated by interaction of electromagnetic fields (when an electric current is passed through a coil that surrounds a permanent magnet). The electromagnet is designed with a movable part that deflects an attached membrane upon turning on the electromagnet. The advantage of this actuation mechanism over others (such as electrostatic) is a lower requirement of voltage. Furthermore, by incorporating the coils and permanent magnet directly into the device, electromagnetically driven micropumps have been fabricated with improved diaphragm deflection and reduced sizes.[25,26] Modifications to this technique include the use of composite diaphragms in which magnetic material is incorporated into the diaphragm material such as PDMS.[27]

Thermally actuated micropumps depend on expansion of materials or changes in stress due to applied heat for actuation. Common thermal techniques include the use of thermopneumatic (e.g., indium tin oxide (ITO) coated on glass with a PDMS