ADVANCES IN
NUMERICAL HEAT TRANSFER

# NANOPARTICLE HEAT TRANSFER AND FLUID FLOW

*Edited by*

W. J. Minkowycz

E. M. Sparrow

J. P. Abraham

CRC Press
Taylor & Francis Group

Volume IV

ADVANCES IN
NUMERICAL HEAT TRANSFER

Volume 4

# NANOPARTICLE HEAT TRANSFER AND FLUID FLOW

Edited by

**W. J. Minkowycz**
*Mechanical and Industrial Engineering*
*University of Illinois at Chicago*
*Chicago, Illinois*

**E. M. Sparrow**
*Mechanical Engineering*
*University of Minnesota, Twin Cities*
*Minneapolis, Minnesota*

**J. P. Abraham**
*School of Engineering*
*University of St. Thomas*
*St. Paul, Minnesota*



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742



Printed in the United States of America on acid-free paper
Version Date: 2012924

International Standard Book Number: 978-1-4398-6192-9 (Hardback)



**Visit the Taylor & Francis Web site at**
**http://www.taylorandfrancis.com**

**and the CRC Press Web site at**
**http://www.crcpress.com**

# ADVANCES IN NUMERICAL HEAT TRANSFER

Volume 4

# Series in Computational and Physical Processes in Mechanics and Thermal Sciences

**Series Editors**

W. J. Minkowycz

*Mechanical and Industrial Engineering*
*University of Illinois at Chicago*
*Chicago, Illinois*

E. M. Sparrow

*Mechanical Engineering*
*University of Minnesota*
*Minneapolis, Minnesota*

Nanoparticle Heat Transfer and Fluid Flow, *edited by W. J. Minkowycz, E. M. Sparrow, and J. P. Abraham*

Advances in Numerical Heat Transfer, Volume 3, *edited by W. J. Minkowycz, and E. M. Sparrow*

Advances in Numerical Heat Transfer, Volume 2, *edited by W. J. Minkowycz, and E. M. Sparrow*

Advances in Numerical Heat Transfer, Volume 1, *edited by W. J. Minkowycz*

# Preface

The day of nanoparticles and nanofluids has arrived, and the applications of these media are legion. Here, attention is focused on such disparate applications as biomedical, energy conversion, material properties, and fluid flow and heat transfer. The common denominator of the chapters that set forth these applications here is numerical quantification, modeling, simulation, and presentation.

The first chapter of this volume conveys a broad overview of nanofluid applications, while the second chapter presents a critical synthesis of the variants within the thermophysical properties of nanofluids and then narrows the focus to the applications of nanoparticles in the biomedical field. Chapters 3 and 4 deepen the biomedical emphasis. Equally reflective of current technological and societal themes is energy conversion from dispersed forms to more concentrated and utilizable forms, and these issues are treated in Chapters 5 and 6.

Basic to the numerical modeling and simulation of any thermofluid process are material properties. Nanofluid properties have been shown to be less predictable and less repeatable than are those of other media that participate in fluid flow and heat transfer. Property issues for nanofluids are set forth in Chapters 6 and 7.

The last three chapters each focus on a specific topic in nanofluid flow and heat transfer. Chapter 8 deals with filtration. Microchannel heat transfer has been identified as the preferred means for the thermal management of electronic equipment, and the role of nanofluids as a coolant is discussed in Chapter 9. Natural convection is conventionally regarded as a low heat-transfer coefficient form of convective heat transfer. Potential enhancement of natural convection due to nanoparticles is the focus of Chapter 10.

# Editors

**W. J. Minkowycz** is the James P. Hartnett Professor of Mechanical Engineering at the University of Illinois at Chicago. He joined the faculty at UIC in 1966. His primary research interests lie in the numerical modeling of fluid flow and heat transfer problems. Professor Minkowycz is currently the editor-in-chief of the *International Journal of Heat and Mass Transfer*, *Numerical Heat Transfer*, and *International Communications in Heat and Mass Transfer*. He has won numerous awards for his excellence in teaching, research, and service to the heat transfer community.

**E. M. Sparrow** is a professor of mechanical engineering at the University of Minnesota. He has taught and performed research there since 1955. He is a member of the National Academy of Engineering, a Max Jakob awardee, and is a Morse Alumni Distinguished Teaching Professor and Institute Professor. He has published over 600 peer-reviewed articles on a wide variety of topics in heat transfer and fluid flow.

**J. P. Abraham** has worked in the area of thermal sciences for approximately 20 years. His research areas include nanoscale thermal processes, energy production and distribution, climate monitoring, and medical device development. He has about 150 journal publications, conference presentations, book chapters, and patents. He teaches courses in the undergraduate and graduate mechanical engineering programs at the University of St. Thomas, St. Paul, Minnesota.

# Contributors

**Ronald J. Adrian**
Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, Arizona

**Corinne S. Baresich**
Department of Mechanical and Aerospace Engineering
Rutgers, The State University of New Jersey
Piscataway, New Jersey

**John C. Bischof**
Department of Mechanical Engineering
and
Department of Biomedical Engineering
and
Department of Urologic Surgery
University of Minnesota
Minneapolis, Minnesota

**Anna S. Cherkasova**
Department of Mechanical and Aerospace Engineering
Rutgers, The State University of New Jersey
Piscataway, New Jersey

**Massimo Corcione**
Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica
Sapienza Università di Roma
Rome, Italy

**Omar De Leon**
Department of Mechanical and Aerospace Engineering
University of Miami
Coral Gables, Florida

**Richard E. DeVor (Deceased)**
Department of Mechanical Science and Engineering
University of Illinois
Urbana, Illinios

**Michael L. Etheridge**
Department of Mechanical Engineering
and
Department of Biomedical Engineering
University of Minnesota
Minneapolis, Minnesota

**Yu Feng**
Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh, North Carolina

**Rhonda R. Franklin**
Department of Electrical and Computer Engineering
University of Minnesota
Minneapolis, Minnesota

**Shiv G. Kapoor**
Department of Mechanical Science and Engineering
University of Illinois
Urbana, Illinois

**Khalil M. Khanafer**
Department of Biomedical Engineering
University of Michigan
Ann Arbor, Michigan

**Clement Kleinstreuer**
Department of Mechanical and Aerospace Engineering
and
Department of Biomedical Engineering
North Carolina State University
Raleigh, North Carolina

**Jie Li**
Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh, North Carolina

**Chen Lin**
Department of Mechanical and Aerospace Engineering
Rutgers, The State University of New Jersey
Piscataway, New Jersey

**Ronghui Ma**
Department of Mechanical Engineering
University of Maryland Baltimore County
Baltimore, Maryland

**Navid Manuchehrabadi**
Department of Mechanical Engineering
University of Maryland Baltimore County
Baltimore, Maryland

**Todd P. Otanicar**
Department of Mechanical Engineering
University of Tulsa
Tulsa, Oklahoma

**Patrick E. Phelan**
Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, Arizona

**Ravi S. Prasher**
Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, Arizona

**Jerry W. Shan**
Department of Mechanical and Aerospace Engineering
Rutgers, The State University of New Jersey
Piscataway, New Jersey

**Di Su**
Department of Mechanical Engineering
University of Maryland Baltimore County
Baltimore, Maryland

**Robert Taylor**
School of Mechanical and Manufacturing Engineering
and
School of Photovoltaic and Renewable Energy Engineering
University of New South Wales
Sydney, Australia

**Kambiz Vafai**
Department of Mechanical Engineering
University of California
Riverside, California

**John E. Wentz**
School of Engineering
University of St. Thomas
St. Paul, Minnesota

**Kaufui V. Wong**
Department of Mechanical and Aerospace Engineering
University of Miami
Coral Gables, Florida

**Zhuomin M. Zhang**
G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia

**Liang Zhu**
Department of Mechanical Engineering
University of Maryland Baltimore County
Baltimore, Maryland

**Qunzhi Zhu**
School of Energy and Environment Engineering
Shanghai University of Electric Power
Shanghai, China

# Contents

# 1 Review of Nanofluid Applications

*Kaufui V. Wong and Omar De Leon*

## CONTENTS



## 1.1 INTRODUCTION

Nanofluids are dilute liquid suspensions of nanoparticles with at least one of their principal dimensions smaller than 100 nm. From the literature, nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat-transfer coefficients compared with those of base fluids like oil or water [1–6].

From this review, it will be seen that nanofluids clearly display enhanced thermal conductivity, which goes up with increasing volumetric fraction of nanoparticles. The current review does concentrate on this relatively new class of fluids and not on colloids, which are nanofluids because the latter have been used for a long time. Review of experimental studies clearly showed a lack of consistency in the reported results of different research groups regarding thermal properties [7,8]. The effects of several important factors such as particle size and shapes, clustering of particles, temperature of the fluid, and relationship between the surfactant and effective thermal conductivity of nanofluids have not been studied adequately. It is important to conduct more research so as to ascertain the effects of these factors on the thermal conductivity of wide range of nanofluids.

Classical models have not been successful in explaining the observed enhanced thermal conductivity of nanofluids. Recently developed models only include one or two postulated mechanisms of nanofluids heat transfer. For instance, there has not been much fundamental work reported on the determination of the effective thermal diffusivity of nanofluids nor heat-transfer coefficients for nanofluids in natural convection [9].

There is a growth in the use of colloids, which are nanofluids in the biomedical industry for sensing and imaging purposes. This is directly related to the ability to design novel materials at the nanoscale level alongside recent innovations in analytical and imaging technologies for measuring and manipulating nanomaterials. This has led to the fast development of commercial applications, which use a wide variety of manufactured nanoparticles. The production, use, and disposal of manufactured nanoparticles will lead to discharges of nanoparticles to the air, soils, and water systems. Negative effects are likely and quantification and minimization of these effects on environmental health is obligatory. Actual knowledge of concentrations and physico-chemical properties of manufactured nanoparticles under realistic conditions is important to predicting their fate, behavior, and toxicity in the natural aquatic environment. The aquatic colloid and atmospheric ultrafine particle literature both offer evidence as to the presumptive behavior and impacts of manufactured nanoparticles [10], and there is no pretense that a review duplicating similar literature about the use of colloids which are also nanofluids is attempted in the current review, which is an update of Ref. [11].

As they have enhanced properties such as for thermal transfer, nanofluids can be used in a wide range of engineering applications from the automotive industry to the medical arena to applications in power plant cooling systems as well as computers.

## 1.2 HEAT-TRANSFER APPLICATIONS

### 1.2.1 Industrial Cooling Applications

Routbort et al. [12] started a project in 2008 that employed nanofluids for industrial cooling that could result in great energy savings and resulting emissions reductions. For U.S. industry, the replacement of cooling and heating water with nanofluids has the potential to conserve 1 trillion Btu of energy. For the U.S. electric power industry,