Preface

Fundamental and applied research in flow, heat, and mass transfer in porous media has received increased attention during the past several decades. This is due to the importance of this research area in many engineering applications, which can be modeled or approximated as transport through porous media such as thermal insulation, packed bed heat exchangers, drying technology, catalytic reactors, petroleum industries, geothermal systems, and electronic cooling. Other examples include computational biology, tissue replacement production, biofilms, drug delivery, advanced medical imaging, porous scaffolds for tissue engineering and effective tissue replacement to alleviate organ shortages, and transport in biological tissues. Another important application of porous media can be the diffusion process in the extracellular space (ECS), which is important for investigating central nervous system physiology. Significant advances have been made in modeling fluid flow, heat, and mass transfer through a porous medium including clarification of several important physical phenomena.

Despite some short treatises, this book, to the best of our knowledge, is the first to address, focus, and offer a comprehensive coverage of applications of porous media theory to biomedical and biological sciences. It covers various transport processes as well as mechanical behavior and material properties of biological tissues from a porous media point of view. This book will be of substantial help to researchers of various fields including but not limited to engineering, biophysics, biology, and medicine. Only the most outstanding contributors for each category in the field were selected and involved in the production of this book.

It is important to place this book in proper perspective relative to the first and second editions of *Handbook of Porous Media*. The material presented in these handbooks will enhance our understanding of what is presented here. As such, it is beneficial to briefly discuss the coverage within these two handbooks, as they may get referred to directly or indirectly during material discussion in this book. Both the first and the second editions of the *Handbook of Porous Media* were aimed at providing researchers with the most pertinent and up-to-date advances in modeling and analysis of flow, heat, and mass transfer. The first *Handbook of Porous Media* was arranged into 8 sections with a total of 19 chapters: section one covered fundamental topics of transport, which included theoretical models of fluid flow and the local volume averaging technique, capillary and viscous effects in porous media, and application of fractal and percolation concepts in characterizing porous materials; section two discussed basic aspects of conduction; in section three, various aspects of forced convection including numerical modeling were covered; section four concentrated on natural convection, thermal stability, and double diffusive convection; in section five, mixed convection was presented; section six was dedicated to the discussion of radiative transfer; and section seven was about turbulence; finally, the last section of the handbook covered several important applications of transport, which included packed bed chemical reactors, environmental applications (e.g., soil remediation), and drying and liquid composite molding (e.g., RTM and SRIM), which had received significant recent interest. Earlier chapters included other applications, such as forced convection heat transfer enhancement, which were covered along with other material.

The second edition of the *Handbook of Porous Media* addressed a substantially different set of topics as compared to the first edition. It included recent studies related to current and future challenges and advances in fundamental aspects of porous media, viscous dissipation, forced and double diffusive convection, turbulent flow, dispersion, particle migration and deposition, dynamic modeling of convective transport, and a number of other important topics related to porous media. This second edition handbook was arranged into seven parts with a total of 17 chapters: Part I covered fundamental topics of transport in porous media including theoretical models of fluid flow, the local volume averaging technique and viscous and dynamic modeling of convective heat transfer, and dispersion in porous media; Part II discussed various aspects of forced convection including numerical modeling, thermally developing flows and three-dimensional flow, and heat transfer within highly anisotropic medium; natural convection, double diffusive convection, and flows induced by both natural convection and vibrations were presented in Part III; Part IV looked at the effects of viscous dissipation for natural, mixed, and forced convection applications; Part V covered turbulence and in Part VI particle migration and deposition were discussed; finally, Part VII concentrated on several important applications including geothermal systems, liquid composite molding, combustion in inert porous media, and bioconvection applications. This final part also included the application of genetic algorithms (GAs) for identification of the hydraulic properties of porous materials in the context of petroleum, civil, and mining engineering. Whenever applicable, each of these handbooks discussed pertinent aspects of experimental works and techniques.

Understanding the physical, chemical, and biological processes governing an organism is important in biomedical engineering and physiology. Interactions involving mechanics, fluid mechanics, heat transfer, and mass transport in biology and medicine are crucial in understanding the causes of disease and in the development of new prophylactic, diagnostic, and therapeutic procedures for improving human health. Nearly all of the human tissues and organs can be categorized as porous media. Thus, this theory has found outstanding applications in biological and biomedical sciences, including but not limited to tissue engineering, biomaterials, biomechanics, biotransport phenomena, and biomedical imaging. Advances in numerical simulations and emergence of sophisticated porous models have significantly improved the study and analysis of biological systems. For instance, the most accurate description of initiation and growth of atherosclerosis is obtained via modeling the arterial wall as a multilayer porous medium. Another example is the application of porous scaffolds in tissue engineering. Developments in modeling transport phenomena in porous media have advanced the field of biology (see Khaled, A. -R. A. and Vafai, K., 2003, The Role of Porous Media in Modeling Flow and Heat Transfer in Biological Tissues, *International Journal of Heat Mass Transfer*, **46**, 4989–5003 and Khanafer, K., and Vafai, K., 2006, The Role of Porous Media in Biomedical Engineering as Related to Magnetic Resonance Imaging and Drug Delivery, *Heat and Mass Transfer*, **42**, 939–953). In these works, various biological areas such as diffusion in brain tissues and, during tissue-generation process, the use of magnetic resonance imaging (MRI) to characterize tissue properties, blood perfusion in human tissues, blood flow in tumors, bioheat transfer in tissues, and bioconvection that utilize different transport models in porous media have been synthesized. Pertinent works associated with MRI and drug delivery were reviewed to demonstrate the role of transport theory in advancing the progress in biomedical applications. Diffusion process is considered significant in many therapies such as delivering drugs to the brain. As such, progress in development of the diffusion equation using local volume averaging technique and evaluation of the applications associated with the diffusion equation was analyzed. Tortuosity and porosity have an impact on the diffusion transport. As such, different relevant models of tortuosity were presented and mathematical modeling of drug release from biodegradable delivery systems was analyzed. New models for the kinetics of drug release from porous biodegradable polymeric microspheres under bulk erosion and surface erosion of the polymer matrix were presented and diffusion of the dissolved drug, dissolution from the solid phase, and erosion of the polymer matrix were found to play a central role in controlling the overall drug release process. These studies paved the road for the researchers to develop comprehensive models based on porous media theory utilizing fewer assumptions as compared to other approaches.

Several pertinent areas of interest in which the porous media modeling is crucial are macromolecular transport in arterial walls, biofilms, tissue engineering, biodegradable porous drug delivery systems, diffusion-weighted magnetic resonance imaging (DW-MRI), and modeling and understanding heat transport and temperature variations within biological tissues and body organs, which are key issues in medical thermal therapeutic applications such as hyperthermia cancer treatment. In what follows, these cited areas are elaborated on. Macromolecular transport in arterial walls can affect the arteries of the brain, heart, kidneys, and the arms and legs. It is caused by the slow buildup of fatty substances, cholesterol, cellular waste products, calcium, and other substances found in the blood within the arterial walls. This buildup is called plaque. The transport of the low-density lipoprotein (LDL) from the blood into the arterial wall and its accumulation within the wall play an important role in the process of atherogenesis. This transport process is termed "arterial mass transport" and is influenced by blood flow in the lumen and transmural flow in the arterial wall. Four-layer model based on porous media can be used for the description of the mass transport in the arterial wall coupled with the mass transport in the arterial lumen. The endothelium, intima, internal elastic lamina (IEL), and media layers can all be treated as macroscopically homogeneous porous media and mathematically modeled using proper types of volume averaged porous media equations with the Staverman filtration and osmotic reflection coefficients employed to account for selective permeability of each porous layer to certain solutes (see Yang, N., and Vafai, K., 2006, Modeling of Low-Density Lipoprotein (LDL) Transport in the Artery-Effects of Hypertension, *International Journal of Heat and Mass Transfer*, **49**, 850–867; Ai, L., and Vafai, K., 2006, A Coupling Model for Macromolecule Transport in a Stenosed Arterial Wall, *International Journal of Heat and Mass Transfer*, **49**, 1568–1591; Khakpour, M., and Vafai, K., 2008, Critical Assessment of Arterial Transport Models, *International Journal of Heat and Mass Transfer*, **51**, 807–822; Yang, N., and Vafai, K., 2008 Low density Lipoprotein (LDL) Transport in an Artery-A Simplified Analytical Solution, *International Journal of Heat and Mass Transfer*, **51**, 497–505; Khakpour, M., and Vafai, K., 2008, A Comprehensive Analytical Solution for Macromolecular Transport within an Artery, *International Journal of Heat and Mass Transfer*, **51**, 2905–2913 and Khakpour, M., and Vafai, K., 2008, Effects of Gender-Related Geometrical Characteristics of Aorta-Iliac Bifurcation on Hemodynamics and Macromolecule Concentration Distribution, *International Journal of Heat and Mass Transfer*, **51**, 5542–5551).

Another area of focus is related to biofilms. A biofilm is a complex aggregation of microorganisms growing on a solid substrate. Structural heterogeneity, genetic diversity, complex community interactions, and an extracellular matrix of polymeric substances characterize biofilms. Biofilms are common in nature as bacteria possess mechanisms by which they can adhere to surfaces and to each other. Each year, microbial biofilm deposits on surfaces cost the global economy billions of dollars in equipment damage, product contamination, energy losses, and medical infections. In industrial environments, biofilms can develop on the interiors of pipes and lead to clogging and corrosion. Thus, it is important to develop new strategies on the basis of a better understanding of bacterial attachment, growth, and detachment as it is needed by many industries (see Shafahi, M., and Vafai, K., 2009, Biofilm Affected Characteristics of Porous Structures, *International Journal of Heat and Mass Transfer*, **52**, 574–581 and Shafahi, M., and Vafai, K., 2010, Synthesis of Biofilm Resistance Characteristics Against Antibiotics, *International Journal of Heat and Mass Transfer*, **53**, 2943–2950). Another area of focus is related to porous scaffolds for tissue engineering and its effective replacement to alleviate organ shortages. Tissue engineering is an emerging field bringing together chemical and material engineering, biology, and medicine. The major aim of this multidisciplinary field is to develop biological substitutes for the repair and regeneration of tissue or organ function. Examples of tissue-engineered substitutes that are currently being investigated throughout the world include skin, cartilage, bone, vascular, heart, breast, and liver. Porous scaffolds for tissue engineering serve to provide anatomical shape to the implant/repair, attach cells, direct cell growth/differentiation, and finally provide an environment for tissue formation. The success of tissue regeneration depends upon various factors of the functional design of the scaffold. This requires the scaffold to have optimum porosity and interconnectivity so as to accelerate the growth of tissues (see Khaled, A. –R. A. and Vafai, K., 2003, The Role of Porous Media in Modeling Flow and Heat Transfer in Biological Tissues, *International Journal of Heat Mass Transfer*, **46**, 4989–5003 and Khanafer, K., and Vafai, K., 2006. The Role of Porous Media in Biomedical Engineering as Related to Magnetic Resonance Imaging and Drug Delivery, *Heat and Mass Transfer*, **42**, 939–953).

Another application of a porous medium is it being used along with advanced fabrication techniques and materials to develop new technologies and computer models to enhance the performance of biodegradable porous drug-delivery devices. Controllably releasing a pharmacological agent to the site of action at a designed rate has numerous advantages over the conventional dosage forms. This interest stems from its importance in reducing dosing frequency, adverse side effects, and achieving enhanced pharmacological activity as well as maintaining constant and prolonged therapeutic effects. The basic formulation of a controlled release of a drug consists of an active agent and a carrier, which is usually made of polymeric materials. Biodegradable polymers have received considerable attention over the last decade, for controlling the drug delivery in the human body without the need to remove them after treatment. The biodegradable polymers can be used as either matrix devices or reservoirs. In matrix systems, the drug is dispersed or dissolved in the polymer and the release rate of the drug decreases as the time advances. While in reservoir, the drug is encapsulated in a biodegradable membrane. As such, the drug is released by diffusion through the membrane at a constant rate. The popularity of this technique has been improved by favorable intrinsic delivery properties of the microspheres (see Khanafer, K., and Vafai, K., 2006 The Role of Porous Media in Biomedical Engineering as Related to Magnetic Resonance Imaging and Drug Delivery, *Heat and Mass Transfer*, **42**, 939–953).

Yet another important area is the development of more effective imaging techniques such as DW-MRI for brain injuries, based on porous media modeling. Diffusion plays a crucial role in brain function: the spaces between cells can be likened to a foam and many substances move within this complicated region; besides delivering glucose and oxygen from the vascular system to brain cells, diffusion also moves informational substances between cells. Diffusion-weighted imaging, which is based on the molecular diffusion coefficient *in vivo*, is sensitive to cerebral ischemia within minutes of the onset of stroke. This technique shows superior capabilities in the early prediction of the brain stroke, compared to the conventional imaging techniques. In the neuroscience context, the ECS constitutes the microenvironment for brain cells. It is a conduit for cellular metabolites, a channel for chemical signaling mediated by volume transmission and a route for drug delivery. Therefore, the extracellular space represents a significant communication channel between neurons and glial cells. From a physical perspective, the extracellular space of the brain resembles that of a porous medium. Thus, theoretical approaches utilizing classical diffusion theory and porous media concepts can be used to measure diffusion properties in very small volumes of highly structured but delicate material (see Khanafer, K., Vafai, K. and A., Kangarlu, 2003, Water Diffusion in Biomedical Systems as Related to Magnetic Resonance Imaging *Magnetic Resonance Imaging Journal*, **21**, 17–31 and Khanafer, K., Vafai, K. and Kangarlu, A., 2003, Computational Modeling of Cerebral Diffusion-Application to Stroke Imaging, *Magnetic Resonance Imaging Journal*, **21**, 651–661).

The last cited focus area deals with an accurate description of the thermal interaction between vasculature and tissues, which is essential for the advancement of medical technology in treating fatal diseases such as tumors and breast cancer. Mathematical models have been used in the analysis of hyperthermia in treating tumors, cryosurgery, laser eye surgery, fetal-placental studies, and other applications. Thermal treatment has been demonstrated to be effective as a cancer therapy in recent years. The success of these types of treatments strongly depends on the knowledge of the heat-transfer processes in blood-perfused tissues. Thermal transport within living organisms and bioheat transfer is an important biological and therapeutic issue, which involves new aspects in thermal therapies, cryobiology, burn injury, disease diagnostics, and thermal comfort analysis. Understanding heat-transfer processes and temperature distributions within biological media are key issues in thermal therapy techniques such as in cancer treatment. The biological media can be treated as a blood saturated tissue represented by a porous matrix. Thermal side effects of various treatments are important issues in bioheat investigations such as bone drilling operations, frictional heating, and ophthalmology. Human eye is one of the most sensitive parts of the body when exposed to a thermal heat flux. Since there is no barrier (such as skin) to protect the eye against the absorption of an external thermal wave, the external flux can readily interact with cornea. The crucial role of blood-tissue in the eye thermal interactions subject to extreme thermal conditions has been established (see Shafahi, M., Vafai, K. Human Eye Response to Thermal Disturbances, to appear in *ASME Journal of Heat Transfer*). A principal issue in medical thermal therapeutic applications is modeling and understanding the heat transport and temperature variation within biological tissues and body organs. Thermal treatment also improves the efficiency of other cancer therapies such as chemotherapy and radiotherapy (see Mahjoob, S., and Vafai, K., 2009, Analytical Characterization of Heat Transport through Biological Media Incorporating Hyperthermia Treatment, *International Journal of Heat and Mass Transfer*, **52**, 1608–1618; Mahjoob, S., and Vafai, K., 2010, Analysis of Bioheat Transport Through a Dual Layer Biological Media, *ASME Journal of Heat Transfer*, **132**, 031101 pp. 1–14; Khanafer, K., and Vafai, K., 2009, Synthesis of Mathematical

Models Representing Bioheat Transport to appear in *Advances in Numerical Heat Transfer*, CRC Press, chapter 1, pp 1–28; Mahjoob, S., and Vafai, K., 2009, Analytical Characterization and Production of an Isothermal Surface for Biological and Electronic Applications, *ASME Journal of Heat Transfer*, **131**, 052604 pp. 1–12 and Mahjoob, S., Vafai, K., and Beer, N. R., 2008, Rapid Microfluidic Thermal Cycler for Polymerase Chain Reaction Nucleic Acid Amplification, *International Journal of Heat and Mass Transfer*, **51**, 2109–2122).

The core objective of this book is to explore innovative approaches and to discover ways to more effectively apply existing technologies to biomedical applications, which will be central to the vision and operation of the discussed research works. This book is targeted at researchers, practicing engineers, clinicians, as well as seasoned beginners in this field. A leading expert in the related subject area presents each topic. An attempt has been made to present the topics in a cohesive, concise, and yet complementary way with a common format. Nomenclature common to various sections was used as much as possible. This book will combine the efforts of world-class scientists and engineers to collaborate and respond to the problems of significance, along with providing porous media researchers with opportunities to pursue an exciting work related to biological systems.

The main goal here is to present the state-of-the-art research advancements related to the applications of porous media in biological systems and biotechnology. This book is arranged into 14 chapters and the subject matters presented in it are arranged as follows.

Chapter 1 takes a look at the general set of bioheat transfer equations for blood flows and its surrounding biological tissue using a volume averaging theory of porous media. This is a rigorous mathematical development, based on the volume averaging theory, so as to arrive at a set of the volume averaged governing equations for bioheat transfer and blood flow. A two-energy equation model for the blood and tissue temperatures is established for the case of isolated blood vessels and the surrounding tissue. Subsequently, the two-energy equation model is extended to the three-energy equation model, to account for the effect of countercurrent heat transfer between closely spaced arteries and veins in the blood circulatory system. In this model, three distinctive energy equations are derived for the arterial blood phase, venous blood phase, and tissue phase with three individual temperatures.

Chapter 2 presents electroporation, which is the use of electrical pulses to increase the cell membrane's permeability and is an important *in vivo* tool for clinical applications. The membrane plays a vital role in the life of a cell, and changing its properties may have far-reaching consequences on the cell itself, the tissue in which it is found, and in fact, on the entire body. A mass transfer model that associates some microscale phenomena on the cellular level with the macroscale conditions at the tissue level is introduced to help in explaining the process of drug uptake by cell.

Chapter 3 deals with hydrodynamics in porous media with applications to tissue engineering. Basic knowledge in biological processes is summarized from the cell's viewpoint and tissue growth with emphasis on the interactions between mechanical stimuli, nutrient transport, cell, and biomaterials. Moreover, different theoretical approaches that enable the modeling of the functional development of tissue-engineered material is presented in detail.

Chapter 4 focuses on interrelationship between the structure of microbial biofilms, with emphasis on porosity and their resistance to common modalities of antibiotic treatments. This resistance is currently a major problem in medicine, culminating in growing numbers of hospitalizations, amputations, sepsis, and death.

Chapter 5 centers on the influence of biofilms on porous media hydrodynamics. Microbial biofilms are formed in natural and engineered systems and can significantly affect the hydrodynamic properties of porous media. Biofilm growth influences porosity, permeability, dispersion, diffusion, and mass transport of reactive and nonreactive solutes. Understanding and controlling biofilm formation in porous media will maximize the potential benefit and minimize the detrimental effects of porous media biofilms.

Chapter 6 explores the application of porous media theory to the modeling of flow changes in cerebral aneurysms treated by endovascular coils. Conventional fluid mechanics modeling is not suitable for this setting because of the difficulty in describing the geometry of the random-shaped endovascular coil when solving the Navier–Stokes equations. Even if the geometry of the coils could be determined, the density and total number of nodal points required to capture the characteristics of the flow would represent a major limitation.

Chapter 7 deals with recent advances in Lagrangian particles methods and their applications for micro(pore)scale modeling of multiphase flow, biomass growth, and mineral precipitation in porous media. Contrary to Darcy-scale models that require phenomenological description of interactions between multiple phases, the pore-scale models are based on fundamental conservation laws and are able to provide an accurate description of complex nonlinear processes involved in biogeochemical transformations. A hybrid model for a multiscale representation of biochemical processes in porous media is also described. With the hybrid model a range of applications of (otherwise very computationally expensive) microscale models can be significantly extended.

Chapter 8 discusses passive mass transport processes in cellular membranes and their biophysical implications. Physical mechanisms of water and solute transport across biological and artificial membranes have been studied since the 1930s and yet they are not completely understood. This is partially due to a limited understanding of the structure of a membrane, which differs significantly from any bulk phase.

Chapter 9 is concerned with modeling and treatment of mass transport through biological tissues, especially that of the skin. The treatment of the skin as a porous media is addressed. A review of experimental findings and observations regarding the electrically induced creation of local transport regions (LTRs) is presented. Moreover, a description of various methods used to describe electroporation of the skin (both empirical and mechanistic) is then provided.

Chapter 10 highlights the biological applications of porous media in marine systems. The focus of this study is on demonstrating the importance and applicability of porous media theories in the emerging field of marine microbiology. Owing to the complex geometries that appear in such applications, a Lattice Boltzmann method approach has been developed and adopted to different applications. The examples include but are not limited to sinking marine aggregates, bioirrigation of macrozoobenthos larvae, oscillating flows near seabed topographies, tortuosity of marine sediments, and devices for generating uniform bottom shear stresses.

Chapter 11 deals with the transport of large biological molecules in deforming tissues and is an example of porous media theory applied to understand tissue homeostasis and repair. Specifically, the movement of growth factors and the synthesis and transport of extracellular matrix molecules through a cyclically loaded articular cartilage is described by combining reactive transport theory with poroelasticity within the framework of porous media theory. Through a series of models of increasing complexity, the interplay between cyclic deformation, interstitial fluid flow, reaction kinetics with cell receptors and a range of matrix molecules, and the mechanical- and chemical-induced biosynthesis is investigated. The outcome provides a framework for understanding the mechanical and chemical environment of a cartilage cell and some of the factors leading to a healthy cartilage or the optimal growth of new cartilage in tissue-engineered constructs.

Chapter 12 is devoted to a review of applications of magnetic stabilized beds as applied to the areas of biotechnology and biomedicine, with emphasis on its current status, historical, and future developments. This includes a description of the main principles and of the background theory.

Chapter 13 summarizes the potential *in situ* characterization techniques for studying porous media and conductive membranes, especially for investigations in solutions. Some of the techniques include spectroscopic imaging ellipsometry (SIE), quartz crystal microbalance (QCM), X-ray diffraction and reflection (XRD and XRR), and laser scanning confocal microscopy (LSCM), in combination with electrochemical techniques. These techniques are either surface or bulk sensitive, or both; and they can provide either spatial or temporal information simultaneously or separately to reveal the dynamic nature of the processes involved in the biofuel cell or the electrode and membrane. Combining the information obtained from these *in situ* techniques can intelligently encompass a wide spectrum of understanding of the cell behavior.

Chapter 14 is concentrated on the development of bioconvection patterns generated by populations of gravitactic microorganisms in porous media. A continuum model consisting of a coupled system of fluid flow and diffusion–convection equations describes the interactions between the microorganisms and the surrounding fluid.

Whenever applicable in each of these chapters, pertinent aspects of experimental work or numerical techniques are discussed. The experts in the field have reviewed each chapter of this handbook. Overall, there were many reviewers involved. As such, the authors and I are very thankful for the valuable and constructive comments received and, particularly, we would like to thank reviewers who performed multiple reviews.

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