Preface

Over the past four decades, there has been increased attention in the research of transport phenomena in porous media due to its importance in many engineering and industrial sectors. Major advances have been made in modeling fluid flow, heat, and mass transfer through a porous medium, including clarification of several important physical phenomena. For example, the non-Darcy effects on momentum, energy, and mass transport in porous media have been studied in depth for different geometrical configurations and boundary conditions. Much of the research in porous media for the past couple of decades has utilized what is now commonly known as the Brinkman–Forchheimer-extended Darcy or the generalized model.

Key topics that have received considerable interest include porosity variation, thermal dispersion, the effects of non-local thermal equilibrium between the fluid phase and the solid phase, partially filled porous configurations, geomechanical effects, and anisotropic porous media, among others. Advanced measurement techniques have also been developed, including more efficient measurement of effective thermal conductivity, flow and heat transfer measurement, and flow visualization. The main objective of this handbook is to compile and present the pertinent recent research information related to fluid flow, mechanics of the porous media skeleton, and heat and mass transfer, including practical applications for the analysis and design of engineering devices and systems involving porous media. The previous editions as well as the present edition of the *Handbook of Porous Media* are aimed at providing researchers with the most relevant and up-to-date advances in the modeling and analysis of flow, heat, and mass transfer in porous media. The third edition of the *Handbook of Porous Media*, which addresses a considerably different set of topics as compared to the first and second editions, includes recent studies related to current and future challenges and advances in fundamental aspects of porous media, forced and double diffusive convection in porous media, turbulent flow, heat transfer of nanofluids in porous media, geological applications, dynamic modeling of convective transport through porous media, and a number of other important topics.

It is essential to be aware that different models can be found in the literature and in the present handbook in the area of fluid flow, heat, and mass transfer in porous media. An in-depth analysis of these models is essential in resolving uncertainty in utilizing them (see Tien and Vafai, 1989; Hadim and Vafai, 2000; Vafai and Hadim, 2000). Additionally, competing models for multiphase transport models in porous media were analyzed in detail (see Vafai and Sözen, 1990). In that work, a critical analysis of various multiphase models including the phase change process was presented. These previous studies provide some clarification and insight for understanding several suitable aspects of modeling of transport phenomena in porous media utilized in the literature and this handbook.

In another study, a detailed analysis of variations among transport models for fluid flow and heat transfer in porous media was presented (see Alazmi and Vafai, 2000a). In this work, the essential models for fluid flow and heat transfer in porous media for four major categories were analyzed. An important aspect of modeling in porous media relates to interface conditions between a porous medium and a fluid layer. As such, the analysis of fluid flow and heat transfer in the neighborhood of an interface region for the current interfacial models was presented (see Alazmi and Vafai, 2000b). The determination of the appropriate thermal boundary conditions for the solid and fluid phases within a porous medium is also an important aspect of modeling in porous media. This type of modeling is necessary when the prescribed wall heat flux boundary conditions and local thermal nonequilibrium effects are present. As such, Alazmi and Vafai (2000c) presented and analyzed different pertinent forms of constant heat flux boundary conditions.

Developments in modeling transport phenomena in porous media have advanced several relevant areas, such as in biology (see Khaled and Vafai, 2003; Khanafer, and Vafai, 2006, 2007).

In these studies, various biological areas such as diffusion in brain tissues, diffusion during the 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 have been synthesized. Another area includes the applications of nanofluids in porous media. Most recently, nanofluids have received a great interest because of their role in the enhancement of thermal properties. For example, Khanafer et al. (2003) conducted one of the first studies related to natural convection of nanofluids in a differentially heated cavity. A critical synthesis of the variants within the thermophysical properties of nanofluids was presented by Khanafer and Vafai (2011). In this work, correlations for effective thermal conductivity and viscosity were synthesized and developed in terms of suitable physical parameters based on the reported experimental data.

Different turbulent models for transport through porous media were analyzed in detail by Vafai et al. (2005). In this work, various features, strengths, and weaknesses of the essential turbulent models for flow through porous media have been analyzed, and the formulation of a generalized model leading to a more promising model is established and discussed. Further advances in porous media include modeling of the free surface fluid flow and heat transfer through porous media. This topic is important in a number of engineering applications such as geophysics, die filling, metal processing, agricultural and industrial water distribution, oil recovery techniques, and injection molding. Accordingly, a comprehensive analysis of the free surface fluid flow and heat transfer through porous media is presented in a work by Alazmi and Vafai (2004).

This handbook is targeted at researchers and practicing engineers, as well as 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 yet complementary way with a common format. Nomenclature common to various sections was used as much as possible.

This third edition of the *Handbook of Porous Media* is divided into six sections with a total of 26 chapters. The subject matter in Section I covers general characteristics and modeling of porous media such as multiscale modeling of porous media, two-phase flow, compressible porous media, and dispersion in porous media. Section II covers fundamental topics of transport in porous media, including theoretical models of transport, membrane transport phenomena, modeling transport properties, and transport in biomedical applications. Section III covers several important aspects of turbulence in porous media, including advances in modeling turbulence phenomena in heterogeneous porous media. Heat transfer of nanofluids in porous media is presented in Section IV. Section V covers thermal transport in porous media, including forced convection, double diffusive convection, high-heat flux applications, and thermal behavior of poroelastic media. Finally, Section VI covers geological applications in porous media, including modeling and experimental challenges related to oil fields, CO_2 migration, groundwater flows, and velocity measurements.

Over the past several decades, computational models for simulating subsurface flow problems have provided an impressive, ever-expanding ability to represent processes at a high resolution. Chapter 1 provides the thermodynamically constrained averaging theory (TCAT) approach to multi-scale modeling of porous medium systems that includes systematic averaging of conservation equations, thermodynamics, and phase and interface kinematics. By developing the definitions of all larger-scale variables in terms of smaller-scale precursors, the TCAT approach overcomes the limitations of rational thermodynamics approaches, which neglect smaller-scale thermodynamics and kinematics. Because the TCAT model yields general forms of closure relations defined in terms of averaged forms of precisely defined microscale quantities, both microscale experimental and simulation approaches provide a means to fully close the model and verify critical aspects of the macroscale theory. Lattice Boltzmann simulations and microfluidic experiments are used to validate critical aspects of the theory and inform the closure processes.

Chapter 2 provides a unifying approach to the theory of capillarity based on rational thermodynamics. Theoretical, experimental, and computational results have shown that the difference in fluid pressures is a function of the boundary conditions and dynamic properties of the system, such as flow rate or dynamic viscosities. Capillary pressure can be seen as an intrinsic property of the fluid-solid system and independent of the dynamics of the system. Therefore, specific interfacial area (area of fluid–fluid interfaces per unit volume of the porous medium) as a new state variable is introduced in this chapter to account for the fact that capillary pressure is an interfacial phenomenon and not a volumetric one. Most recently, the problem of disposal of radioactive wastes has become a critical problem of national and international concern. Geological formations are considered as an acceptable storage area for radioactive nuclear wastes, as their permeability is typically low. Many of such formations are, however, highly fractured, even several hundred meters below the surface. Groundwater that flows through the fractures at such depths would be the carrier of any nuclear waste and contaminants that might leak out of the storage area and enter the flow system. Therefore, the characterization and modeling of fractures and fracture networks are discussed in Chapter 3.

Chapter 4 aims to illustrate why thin porous media are different from traditional porous media and identify the generic problems. This is performed through the consideration of a variety of selected examples extracted from studies on fuel cells, particle filtration, drying and salt efflorescence formation. A brief review of other situations involving thin porous media is also proposed in this chapter. Magnetically stabilized and fluidized beds have been the subject of moderate research and applications for several decades. More recently, this technique is being rediscovered and applied to important areas of research, for example, environmental technologies, especially biotechnology and biomedical applications. Chapter 5 presents a review of the applications of magnetically stabilized beds, including a description of its main principles and background theory. In Chapter 6, a comprehensive review of the recent studies on the lift generation in soft porous media is provided and includes four specific sections: the motion of red blood cells over the endothelial glycocalyx layer and its implications to soft porous lubrication, lift generation in highly compressible porous media under rapid compression, lift mechanics of skiing or snowboarding, and, finally, from red blood cells to skiing to soft porous lubrication. Chapter 7 reviews models for scalar transport in saturated porous media with nonlinear bulk and surface sources and sinks. Single- and multi-equation models for both equilibrium and nonequilibrium, integro-differential descriptions of time nonlocality, and hybrid approaches that couple partial differential equations acting at different scales are presented. As an example, this chapter shows how effective parameters can be calculated directly over a three-dimensional image of a bead-packing obtained using x-ray computed microtomograph.

A porous medium approach based on the volume averaging theory can be used to investigate solute diffusion and ultrafiltration processes associated with hemodialysis using a hollow fiber membrane dialyzer. An appropriate set of the governing equations based on the three-concentration model (i.e., the blood, dialysate, and membrane phases) has been derived using a porous media concept and is presented in Chapter 8. Available experimental data are found to agree well with the presented analytical estimates generated from the porous media theory. Furthermore, three-dimensional numerical models are proposed in this chapter for possible optimization of hollow fiber systems, such as dialyzers and desalination modules.

The prediction of effective transport properties of porous media is very important not only to the analysis and optimization of material performance, but also to new material designs. Chapter 9 first examines the difficulties in predicting porous media characteristics by summarizing and critiquing the existing major analytical approaches dealing with effective property modeling. The focus then shifts to recent advances in numerical modeling that are able to predict more accurately and efficiently the effective properties of porous materials with complex internal microstructures. A random generation-growth algorithm is highlighted in Chapter 9 for reproducing porous microstructures, statistically equivalent to the actual ones, based on the geometrical and morphological information obtained from measurements and experimental estimations. Chapter 10 presents a review of the outstanding approaches presented in the literature and several improved approaches developed for the formulation of effective transport through porous media under nonequilibrium relaxation conditions. Typical applications of these approaches are presented for different processes occurring in porous media. These include the separation of dissolved gas from oil and water, displacement of immiscible fluid phases in porous media, transport of dispersed wetting/nonwetting phases through porous media, permeability impairment in porous media by precipitate deposition, and the modification of the popular gradient laws such as the Darcy, Fourier, and Fick laws for porous media flow, heat conduction, and diffusion, respectively, under unsteady-state conditions. The improvements and developments introduced are shown to describe the nonequilibrium dynamics of the porous media processes better than the previous approaches presented in the literature.

In Chapter 11, a deterministic model is suggested that describes the collective behavior of a microorganism population with a general form of stimuli gradient-based taxis in porous media. This population has a mass density slightly heavier than the density of water and forms a suspension. The suspended cells are active in motion with a thermotaxis behavior (temperature gradient follower). The model is basically comprised of the Darcy equation for the fluid motion in porous media, the equation of cell conservation for the microorganism population, and the equation of conservation for the considered stimuli. To take into account the density effects, Boussinesq's approximation is used. Linear stability analysis shows that temperature has interesting effects on the bioconvection pattern of the thermotactic microorganisms. The last part of the chapter discusses different potential applications of this model in porous media in the fields of life sciences and engineering, as well as for various natural biological systems. The topic of using feedback control to promote or suppress the transition to chaos in porous media convection is reviewed in Chapter 12. The feedback control is used to provide a comparison between an analytical expression for the transition point to chaos and numerical results. In addition, it is shown that such a feedback control can be applied as a practical means for controlling (suppressing or promoting) chaos by using a Magyari transformation. The latter shows that the main effect the feedback control has on the solution is equivalent to altering the initial conditions. The theoretical and practical significance of such equivalent alteration of the initial conditions is presented and discussed in this chapter. Chapter 13 provides an overview of recent development in modeling and simulating turbulent reactive flow in porous media, and the advantages of having a combustion process inside an inert porous matrix are well documented. In Chapter 14, the effects of nanofluids on convection in porous media are presented. Property variations that are the consequence of the fact that nanofluids are suspensions and the processes that occur due to the smallness of the nanoparticles are discussed in this chapter. The applications to forced convection, natural convection, and mixed convection in various geometries are then reviewed.

Chapter 15 reviews the controversial results for nanofluids and provides an explanation that settles the conflict between the apparent enhancement of the effective thermal conductivity in some experiments and the lack of enhancement in other experiments. Theoretical results combined with experimental data are reviewed in this chapter to conclude that while there is no improvement in the effective thermal conductivity of nanofluids beyond Maxwell's effective medium theory (Maxwell, 1891), there is substantial heat transfer augmentation via nanofilms.

Chapter 16 is concerned with heat transfer in closed- and open-cell foams at any temperature level. Porous cellular materials are of great interest since they present an unequalled combination of physical, mechanical, electrical, and thermal properties and find numerous applications in aerospace, chemical, mechanical, and energy engineering. The account is restricted to materials with a random structure and with submillimeter and/or larger mean pore (cell) diameters. The solid and fluid are assumed to be inert, and there are no chemical reactions in the fluid and is no phase change. In this chapter, the most recent literature related to the phenomena using the volume-averaged transport equations employing phenomenological closure coefficients is discussed. Chapter 17 gives an introduction to the flow and convection of Bingham fluids in a porous medium. For such yield-stress, fluids flow arises when the local body force, such as an externally imposed pressure gradient or buoyancy force, exceeds the threshold. Network models are derived and solved and plausible macroscopic Darcy–Bingham laws are given. Nonlinear convection is computed, and the resulting patterns are found to depend on the underlying microstructure of the medium. Recent advances in distributed (and modulated) wick structures, which have resulted in increased critical heat flux (CHF) and decreased superheat are reviewed in Chapter 18. Heat sinks use liquid-vapor, phase change in wicks submerged in liquid (pool boiling) or in phase separation (single-pipe, loop heat pipes, and vapor chambers) for high heat flux applications with exceptional mechanical reliability and minimal power consumption. The maximum heat transfer rate, that is, CHF, and the related superheat are associated with the thermal-hydraulic bottlenecks within or near the wicks. The hydrodynamic instability, capillary-viscous flow, and wick thermal resistance limits are discussed in this chapter.

Jet impingement of a cold fluid is an efficient method for the cooling of a heated surface. This is one of the techniques employed in heat transfer enhancement technologies. Chapter 19 discusses impinging jets in porous media. The main contributions on the impinging jet in a porous medium are summarized in this chapter with some information on jet geometry, thermal conditions on the target plate, flow regime, and local thermal equilibrium (LTE) and nonequilibrium (LTNE). The classical problem in geomechanics dealing with the stress-induced isothermal flow of a fluid through a deformable porous medium, usually referred to as the process of soil consolidation, is a cornerstone in the development of the subject of *soil mechanics* and is generally regarded as the start of multiphasic treatment of the mechanics of porous media. Chapter 20 considers the thermo-hydro-mechanical behavior of poroelastic media. Chapter 21 determines the effect of conducting bounding plates on the stability properties of a horizontal porous layer saturated by a binary fluid. As such, this provides a better approximation of how experiments are set up in the laboratory compared to the usual fixed temperature or heat flux boundary conditions. Recently, mechanical vibrations are also used to control thermoconvective or thermosolutal flows in incompressible fluids in order to optimize heat and mass transfer processes. An overview of the digital imaging workflow with an emphasis on x-ray computed tomography (CT) is presented in Chapter 22. This is followed by a discussion of the various elements of the digital petrophysics workflow that includes imaging, image processing, and the modeling of transport properties. A review of experimental approaches to image dynamic multiphase interactions at the microscopic level during drainage and imbibition follows. Finally, some of the difficulties involved in relating studies done at the pore scale to the phenomena observed at the macroscopic reservoir scale are addressed in this chapter.

In Chapter 23, the difficulties associated with modeling the flow and transport processes associated with CO_2 injection into subsurface formations, more specifically into deep saline aquifers (DSA), are reviewed. The progress made in recent years in addressing these challenges and the resulting analytical and numerical models for CO_2 migration in geologic sequestration in scenarios are outlined. Chapter 24 reviews groundwater flows and their measurement techniques, as tested and reported in the literature. Groundwater constitutes more than 99% of the whole volume of nonsalty liquid phase water present on Earth, and it is considered the most important source of water for living beings. At the start of this chapter, the basic aspects of groundwater hydrology and Darcy's law are discussed. Some of the unique concepts of aquifer properties, that is, hydraulic conductivity, transmissivity, and storativity, are introduced in connection with well tests. The remainder of the chapter focuses on groundwater velocity measurement techniques at both large and small scales, since velocity is the most important property that determines subsurface transport processes. One particular problem in modeling large-scale porous media, such as oil, gas, and geothermal reservoirs, and the simulation of fluid flow therein is the identification of the flow paths that consist of interwell zones with significant permeabilities. Chapter 25 discusses the geostatistical simulation and reconstruction of porous media. Finally, Chapter 26 aims to describe the major pore-scale processes associated with microbially induced carbonate precipitation (MICP), placing these in the context of porous media reactive transport modeling approaches. First, MICP is divided into biological, physical, and geochemical sub processes. Next, their interactions are discussed at the pore scale, and finally it is determined how these processes and interactions affect local and system-wide reactive transport. This chapter as a whole is intended to serve as an overview of the current knowledge within the MICP field in regards to pore-scale processes. The processes are represented in equation form where possible to provide mathematical relationships that are useful for modeling.

In each of these chapters, whenever applicable, relevant 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 who were involved. As such, the authors and I are very thankful for the valuable and constructive comments that were received.

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