Preface

Fundamental and applied research in heat and mass transfer in porous media has generated increasing interest over the past three decades because of the importance of porous media in many engineering applications. Consequently, a large amount of literature has been generated on this subject. Significant advances have been made in modeling fluid flow and heat transfer in porous media including several important physical phenomena. The non-Darcy effects of inertia and solid boundaries on momentum and energy transport in porous media have been studied extensively for various geometrical configurations and boundary conditions, and most of the studies used what is now commonly known as the Brinkman-Forchheimer-extended Darcy or the generalized model.

Other important topics that have received significant attention include porosity variation, thermal dispersion, the effects of local thermal equilibrium between the fluid phase and the solid phase, partially porous configurations, and anisotropic porous media. Advanced measurement techniques have been developed, for example, 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 all the important up-to-date research information related to heat transfer in porous media, including practical applications for analysis and design of engineering devices and systems involving porous media. It also describes recent studies related to current and future challenges for further advances in fundamental as well as applied research in porous media including random porous media (e.g., fractured media), multiphase flow and heat transfer, turbulent flow and heat transfer, improved measurement and flow visualization techniques, and improved design correlations.

It is important to recognize 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 any confusion in utilizing them (see Tien, C. L., and Vafai, K. 1989. Convective and radiative heat transfer in porous media. *Advances in Applied Mechanics*, **27**: 225–282). In a recent study, analysis of variants within the transport models for fluid flow and heat transfer in porous media is presented in an article by Alazmi and Vafai (see Alazmi, B. and Vafai, K. 2000. Analysis of variants within the porous media transport models. *Journal of Heat Transfer*, **122**, In Press). In that work, the pertinent models for fluid flow and heat transfer in porous media for four major categories were analyzed. Another important aspect of modeling in porous media relates to interface conditions between a porous medium and a fluid layer. As such, analysis of fluid flow and heat transfer in the neighborhood of an interface region for the pertinent interfacial models is presented in another article by Alazmi and Vafai (see Alazmi, B. and Vafai, K. 2000. Analysis of fluid flow and heat transfer interfacial conditions between a porous medium and a fluid layer, to appear in *International Journal of Heat and Mass Transfer*). Finally, competing models for multiphase transport models in porous media were analyzed in detail in Vafai and Sozen (Vafai, K. and Sozen, M. 1990. A comparative analysis of multiphase transport models in porous media. *Annual Review of Heat Transfer*, **3**, 145–162). In that work, a critical analysis of various heat and mass transfer models including the phase change process was presented. These three studies provide some clarification and insight for understanding several pertinent aspects of modeling of transport phenomena in porous media utilized in the literature and this handbook.

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, homogeneous yet complementary way with common format. Nomenclature common to various sections was used as much as possible.

The handbook is arranged into eight sections with a total of 19 chapters. The material in Part I covers fundamental topics of transport in porous media, including 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. Part II covers basic aspects of conduction in porous media. In Part III, various aspects of forced convection in porous media including numerical modeling are explored. Natural convection, thermal stability, and double diffusive convection in porous media are reviewed in Part IV. Part V presents mixed convection in porous media. Part VI discusses radiative transfer in porous media, and Part VII covers turbulence in porous media. The final part covers several important applications of transport in porous media, including packed bed chemical reactors, environmental applications (e.g., soil remediation), and drying and liquid composite molding (e.g., RTM and SRIM), which has received significant recent interest. Other applications, such as forced convection heat transfer enhancement, are reviewed along with other material presented in earlier chapters.

Chapter 1 deals with the basic governing equations describing conductive and convective heat transfer for flow in rigid porous media. Both homogeneous and heterogeneous thermal sources are considered in the analysis, which leads to Darcy-scale, or volume-averaged, transport equations for the temperature and velocity. Closure problems are developed that can be used to predict the values of the effective transport coefficients. The problem of local thermal equilibrium is considered in detail, and the constraints associated with this condition are developed. The one-equation model that is associated with local thermal equilibrium is derived, and predicted values of the longitudinal thermal dispersion coefficient are compared with experimental values. When the constraints associated with local thermal equilibrium are not valid, a two-equation model is required to accurately describe the heat transfer process. This two-equation model is also developed in this chapter.

In Chapter 2, displacement of a fluid by another immiscible fluid under quasi-static conditions and in low Reynolds number flow is considered. The microscopic aspects are analyzed in terms of capillary models, and, whenever feasible, the macroscopic phenomenological displacement relationships are either derived from or interpreted in terms of the capillary models. Particular importance is attached to waterflooding of oil and to mobilization of trapped oil blobs by the mechanism of spreading oil on water in the presence of an inert gas. Steady, concurrent two-phase flow is discussed, with particular emphasis on the effects of contact angle, interfacial tension, and viscosities on the relative permeabilities and on the widely debated issue of viscous coupling.

Finishing the first part is Chapter 3. It begins with a consideration of field-scale porous media that are highly heterogeneous at many length scales, ranging from microscopic to macroscopic and megascopic. Modeling flow and transport in such porous media depend critically on their correct characterization and modeling, which have been hampered, however, by an insufficient amount of data, variations in the data, and their great uncertainty. Since about a decade ago, it has become increasingly clear that the distributions of the heterogeneities of field-scale porous media follow fractal stochastic processes. An important consequence of this is that the heterogeneities contain long-range correlations whose extent may be as large as the linear size of the system. In addition, it has been firmly established that for highly heterogeneous porous media, percolation theory provides a realistic description of the media and of the flow and transport processes that take place there. Percolation theory quantifies the effect of the connectivity of various zones or regions of a system on its large-scale properties. This chapter attempts to summarize the progress that has been made in applying such concepts and ideas to characterization and modeling of field-scale porous media and flow and transport processes.

In Chapter 4, conduction in porous media is considered. Heat conduction in materials consisting of substances with different thermal properties is encountered frequently in many engineering applications. However, the traditional treatment of heat conduction is still based largely on the lumped mixture model under the local thermal equilibrium assumption. With these assumptions, the issue becomes the determination of effective thermal conductivity. This chapter extends the scope of validity in treating the transient heat conduction in porous materials saturated with fluids to the domain of local thermal non-equilibrium with a two-equation model. The conditions for the validity of the local thermal equilibrium assumption are assessed by exercising the two-equation model for one-dimensional heat conduction in a porous slab subjected to a sudden change of boundary condition. The deviation from local thermal equilibrium in the two phases is discussed based on the parameters such as interfacial transfer, thermal conduction ratio, heat capacity ratio and porosity. It is noted that the treatment can be extended easily to a multicomponent porous medium.

The section on forced convection begins with Chapter 5. This chapter presents a review of forced convective heat transfer in porous media for boundary-layer flows over a flat plate embedded in a fluid-saturated, porous medium and internal forced convection through parallel-plate channels, circular pipes, and annular ducts filled or partially filled with porous media. Models for the momentum and energy transport that have recently been applied are examined. Variable porosity and thermal dispersion effects, as well as departure from local thermal equilibrium, are discussed. Forced convection in porous-filled ducts saturated with non-Newtonian fluids is also documented at the end of the chapter.

Chapter 6 concentrates on the analytical study of fully developed steady laminar forced convection flow in a number of classical composite configurations. Both Poiseuille flow and Couette flow in composite parallel-plate channels are considered. Poiseuille flow is investigated in four composite configurations: (1) a channel with a fluid core, (2) a channel with a porous core, (3) a channel heated from the fluid side, and (4) a channel heated from the porous side. Couette flow is investigated in two composite configurations. It is assumed that momentum flow in the porous region can be described by the Brinkman-Forchheimer-extended Darcy equation. Utilizing the boundary-layer technique, analytical solutions are obtained for the velocity and temperature distributions, as well as for the Nusselt number. These new analytical solutions make it possible to investigate possibilities for heat transfer enhancement in composite channels. These new solutions are also valuable for gaining deeper insight into and understanding of the transport processes at the porous/fluid interface and of ways for testing numerical codes.

Chapter 7 provides the basic concepts and fundamentals of convective boundary layers in porous media for external flows. The governing equations, along with their important simplifications, are presented so as to include the dimensionless parameters that arise and the basic nature of the transport processes. Free and mixed convection over vertical and horizontal surfaces embedded in a porous medium are discussed in detail, and the resulting heat transfer expressions are presented. The case of free convection boundary layer near the forward stagnation point of a cylindrical surface in a porous medium has also been considered. Emphasis is placed on the modern developments in this field, including numerical and analytical techniques, and a considerable number of recent references are also included.

A post-1993 review of publications related to the application of porous media for enhancing incompressible forced-convection heat transfer is presented in Chapter 8. A brief introduction to the fundamentals of convection heat transfer through porous media is followed by the description of enhancing designs for particular applications grouped into five main categories: (1) porous inserts and cavities, (2) microsintering, porous coatings, and porous fins, (3) microchannels, (4) permeable fences and perforated baffles, and (5) cylinder arrays.

The flow and thermal convection in rotating porous media is developed and a systematic classification and identification of the relevant problems in such a configuration is introduced in Chapter 9. An initial distinction between rotating flows in isothermal heterogeneous porous systems and free convection in homogeneous non-isothermal porous systems provides the two major classes of problems to be considered in this chapter. Examples of solutions to selected problems are presented, highlighting the significant impact of rotation on the flow in porous media.

Chapter 10 presents the recent development of numerical analyses of thermofluid behavior in fluid-saturated porous media based on a structural model. A regular array of obstacles is used to describe microscopic porous structures. The idea of microscopic numerical simulations at pore scale to determine macroscopic flow and heat transfer characteristics is elucidated, and a series of numerical results are examined. The permeability and thermal dispersion coefficients, determined purely from the theoretical basis without any empiricism, agree quite well with available experimental data.

Starting the fourth part, on natural and double diffusive convection in porous media, is Chapter 11. This chapter is concerned with buoyancy-driven flows in saturated, porous, media-filled (or partially filled) enclosures. The discussion begins with a consideration of vertical, inclined, and horizontal rectangular enclosures. The governing equations are presented and various solutions are discussed. Equations for the Nusselt number are given. The flow in non-rectangular, porous, media-filled enclosures is then considered, emphasis being placed on flow in annular enclosures. Attention is then given to enclosures that are partly filled with a saturated porous medium. The flow in enclosures filled with anisotropic porous media, maximum density effects, double-diffusive flows, and non-Darcy effects are discussed briefly. The chapter is intended to provide a broad introduction to the subject.

In Chapter 12, an attempt has been made to give a comprehensive account of the state of the art of research into the Darcy–Bénard problem. Some attention has been paid to analytical techniques used in determining the stability of convective flows, and detailed descriptions of how flow changes occur are presented. The manner in which the Darcy–Bénard problem is altered by the inclusion of extra terms is discussed. The discussion includes, but is not limited to, various effects such as form drag, internal heating, local thermal nonequilibrium, and modified boundary conditions. A detailed list of references is provided to enable the new researcher to gain a good overview of the subject.

The objective of Chapter 13 is to investigate natural convection driven by two buoyancy sources, such as heat and mass, in a porous medium saturated with Newtonian fluids. A comprehensive review of the literature concerning double-diffusive convection in fluid-saturated, porous media, the Soret effect and the thermogravitational diffusion in multicomponent systems is presented. This chapter mainly reports analytical, numerical, and scale analysis studies of the onset of a double-diffusive convective regime in a tilted rectangular cavity filled with a porous medium saturated with a binary fluid. The instabilities that can occur when two walls are maintained at different uniform temperature and concentration while the two other walls are impervious and adiabatic are investigated.

Research on mixed convection in saturated porous media conducted over the last 20 years is reviewed in Chapter 14. Although emphasis has been placed on the Darcy flow regime, non-Darcy effects are included whenever the need for a complete understanding of the subject is called for. The results are classified into general categories: external and internal flows. In each category, works are reviewed according to their geometry and thermal boundary condition. The effects of variable properties are included for a complete discussion. Heat transfer correlations are provided for engineering applications. Finally, the direction and challenge of future research are suggested.

Chapter 15, on radiative transfer in porous media, provides recent information on the contemporary understanding of the importance of dependent scattering in porous media. It is pointed out that even very high porosity beds are subject to dependent scattering effects, which were not included in earlier analyses of radiative transfer in these systems. Thus, early methods for predicting radiative properties and for treating radiation in packed and porous materials are suspect. Guidance is provided on determining the importance of dependent scattering.

Chapter 16 reviews the weak turbulence regime associated with porous media non-steady and non-periodic convection in models allowing temporal irregular (i.e., chaotic) solutions, and the conditions for the regime's validity are specified. The rich dynamics linked to the transition from steady convection to chaos is demonstrated and explained analytically as well as computationally.

The final part, on applications, begins with Chapter 17. Over the past 25 years, modeling of the drying process has evolved from the solution of the mass diffusion equation to the solution of the balance equations for the gas and liquid phases, the various constituents of the gas and liquid phases, and the energy equation. This chapter summarizes the development of a drying model based on three dependent variables—moisture content, temperature, and gas phase pressure—from the general balance equations. For many practical drying problems this complex set of nonlinear partial differential equations can be greatly simplified using scale analysis. Scale analysis is utilized to illustrate the relative importance of the various transport phenomena for the thermal transient, constant drying rate, and low- and high-intensity drying regimes.

Chapter 18 briefly describes several technologies for remediation of soils contaminated with hydrocarbons. Mathematical models for hydrodynamic, thermal, and mass transfer processes that take place during removal of multispecies contaminants by soil venting and steam injection are discussed in detail. The models have been shown to describe, in general, the behavior observed in laboratory experiments. A detailed validation of the models in a typical field site is lacking. However, soil venting with preheating of the incoming air and steam injection have been shown to be very effective technologies for remediation of soil contaminated with volatile and semi-volatile hydrocarbons.

Finally, Chapter 19 focuses on non-isothermal mold filling during the liquid composite manufacturing (LCM) process. The LCM processes such as resin transfer molding (RTM), vacuum resin transfer molding (VARTM), and structural reaction injection molding (SRIM) are modeled using Darcy's law. In such processes, a viscous resin (about 100 to 1000 times more viscous than water) is injected to saturate the fiber preform (which is considered as a stationary porous media) placed inside a hot mold cavity. To predict the flow front, one needs only the average Darcian velocity. To predict the temperature distribution, however, one must account for micro-convection due to the interstitial local microvelocity. Important issues related to composite processing are highlighted and future outlook is discussed.

In each of these chapters, whenever applicable, pertinent aspects of experimental work and techniques are discussed. Experts in the field rigorously reviewed each chapter. Overall, many reviewers were involved. The authors and I are very thankful for the valuable and constructive comments that were received.

Kambiz Vafai