Preface

Theoretical and applied research in flow, heat, and mass transfer in porous media has received increased attention during the past three decades. This is due to the importance of this research area in many engineering applications. Significant 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 various geometrical configurations and boundary conditions. Many of the research works in porous media for the past couple of decades utilize what is now commonly known as the Brinkman–Forchheimer-extended Darcy or the generalized model.

Important topics that have received significant interest include porosity variation, thermal dispersion, the effects of local thermal equilibrium between the fluid phase and the solid phase, partially filled porous configurations, 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 heat and mass transfer including practical applications for analysis and the design of engineering devices and systems involving porous media. Both the first and the present editions of the *Handbook of Porous Media* are aimed at providing researchers with the most pertinent and up-to-date advances in modeling and analysis of flow, heat, and mass transfer in porous media. The second edition of the *Handbook of Porous Media,* which addresses a substantially different set of topics compared to the first edition includes recent studies related to current and future challenges and advances in fundamental aspects of porous media, viscous dissipation, forced and double diffusive convection in porous media, turbulent flow, dispersion, particle migration and deposition in porous media, dynamic modeling of convective transport through porous media, and a number of other important topics.

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 uncertainty in utilizing them (see Tien, C.L. and Vafai, K., 1989, Convective and radiative heat transfer in porous media, *Adv. Appl. Mech.,* 27, 225–282; Hadim, H. and Vafai, K., Overview of current computational studies of heat transfer in porous media and their applications — forced convection and multiphase transport, in W. J. Minkowycz and E. M. Sparrow, eds, *Advances in Numerical Heat Transfer*, Taylor and Francis, Vol. 2, Chap. 9, pp. 291–330, Taylor & Francis, New York (2000); Vafai, K. and Hadim, H., Overview of current computational studies of heat transfer in porous media and their applications — natural convection and mixed convection, in W. J. Minkowycz and E. M. Sparrow, eds, *Advances in Numerical Heat Transfer*, Taylor and Francis, Vol. 2, Chap. 10, pp. 331–371, Taylor & Francis, New York (2000)). Additionally, 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, *Annu. Rev. Heat Transfer*, 3, 145–162). 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 pertinent aspects of modeling of transport phenomena in porous media utilized in the literature and this handbook.

In another study, detailed analysis of variations among transport models for fluid flow and heat transfer in porous media was presented (see Alazmi, B. and Vafai, K., 2000, Analysis of variants within the porous media transport models, *ASME J. Heat Transfer*, 122, 303–326). In this 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 Alazmi and Vafai (Alazmi, B. and Vafai, K., 2000, Analysis of fluid flow and heat transfer interfacial conditions between a porous medium and a fluid layer, *Int. J. Heat Mass Transfer*, 44, 1735–1749). 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 prescribed wall heat flux boundary conditions and local thermal nonequilibrium effects are present. As such, Alazmi and Vafai (2000) presented and analyzed different pertinent forms of constant heat flux boundary conditions (see Alazmi, B. and Vafai, K., 2000, Constant wall heat flux boundary conditions in porous media under local thermal non-equilibrium conditions, *Int. J. Heat Mass Transfer*, 45, 3071–3087).

Developments in modeling transport phenomena in porous media have advanced several pertinent areas, such as biology (see Khaled, A. –R. A. and Vafai, K., 2003, The role of porous media in modeling flow and heat transfer in biological tissues, *Int. J. Heat Mass Transfer*, 46, 4989–5003). In this work, various biological areas such as diffusion in brain tissues, diffusion 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. Different turbulent models for transport through porous media were analyzed in detail by

Vafai et al. (Vafai et al., 2005, Synthesis of models for turbulent transport through porous media, in W. J. Minkowycz and E. M. Sparrow, eds, *Handbook of Numerical Heat Transfer*, John Wiley & Sons, New York). In this work, various features, strengths, and weaknesses of the pertinent turbulent models for flow through porous media have been analyzed and the formulation of a generalized model leading to a more promising model has been 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 recent work by Alazmi and Vafai (see Alazmi, B. and Vafai, K., 2004, Analysis of variable porosity, thermal dispersion and local thermal non-equilibrium effects on free surface flows through porous media, *J. Heat Transfer*, 126, 389–399).

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

The Handbook of Porous Media, Second Edition, is arranged into seven sections with a total of 17 chapters. The material in Part I covers 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 covers various aspects of forced convection in porous media including numerical modeling, thermally developing flows and three-dimensional flow, and heat transfer within highly anisotropic porous media. Natural convection, double diffusive convection and flows induced by both natural convection and vibrations in porous media are presented in Part III. Part IV presents the effects of viscous dissipation in porous media for natural, mixed, and forced convection applications. Part V covers turbulence in porous media. Particle migration and deposition in porous media — composed of two parts — are discussed in Part VI. The final part, VII, covers several important applications of transport in porous media, including geothermal systems, liquid composite molding, combustion in inert porous media, and bioconvection applications in porous media. Also, the final part includes the application of Genetic Algorithms (GAs) for identification of the hydraulic properties of porous materials in the context of petroleum, civil, and mining engineering.

Chapter 1 examines the general problem of coupled, nonlinear mass transfer with heterogeneous reaction in porous media. This situation occurs whenever the mole fraction of the diffusing species is not small compared to one. Under these conditions, the flux depends on both the mole fractions and the mole fraction gradients of all other species that are present. For most processes of diffusion and reaction in porous media, the governing equations can be linearized over the averaging volume and this allows for the method of volume averaging to be applied in the traditional manner. The main conclusion of this work is that a single tortuosity tensor describes the influence of the porous medium on the diffusion process of all species present in the system.

In Chapter 2, macroscopic descriptions of flows and convective heat transfer in porous media are obtained by averaging the microscopic Navier–Stokes and energy equations volumetrically over fluid and solid phases, respectively. This averaging procedure leads to the closure problem where new unknowns require modeling to relate the unknowns to the averaged flow quantities. Dynamic closure modeling for incompressible flows was constructed based on the first principle of microscopic heat convection over the solids. The coefficients in the closure relations, which depend only on the microstructure of solids, are evaluated experimentally and/or numerically for some special micro-geometries, such as the periodic media in two and three dimensions. The analogies of the flows and heat transfer in porous media to those of Hele-Shaw cells that represent laminated parallel-plates are examined. The characteristics of macroscopic convective heat transfer in porous media are demonstrated with the steady forced convections and the enhanced heat transfer by oscillating flows past a heated circular cylinder in Hele-Shaw cells.

Chapter 3 starts with the general volume-averaged transport equations: fluid flow momentum equation, energy balance equation, and mass balance equation. In these equations, there is a common term that is absent for flow through a system where the porous matrix is not present, namely, the dispersion. Mathematically, the origin of the dispersion is due to the microscopic spatial velocity variation (special fluctuation). Physically, dispersion occurs because of constant joining and splitting of flow streams when the fluid is traversing through the porous structure. Discussion of the dispersion and its effect on single fluid (and multiple fluids) flow, heat transfer, and mass transfer is presented. Dispersion models are evaluated in this chapter.

Chapter 4 deals with recent analytical studies of forced convection in channels or ducts. The studies fall under two headings, namely thermal development and transverse (cross-channel) heterogeneity. The extension to the case of local thermal nonequilibrium is also studied. Further, the extension to the case where axial conduction and viscous dissipation are not negligible is analyzed. In this chapter, the effect of transverse heterogeneity with respect to permeability or thermal conductivity (or both) is also discussed for the case of fully developed forced convection in a parallel-plate channel and a circular duct, with walls at uniform temperature or uniform heat flux.

Chapter 5 presents a review of recent studies on the hydrodynamics and heat transfer effects of variable (with temperature) viscosity flows in a liquid saturated porous media channel. The Hydrodynamics section discusses in detail the fundamental modifications necessary to correct existing models, leading to the newly proposed Modified-HDD model. Influence of variable viscosity on the Nusselt number, the pump power, and other aspects related to heat-transfer enhancements, are reviewed in the Heat Transfer section. A Perturbation Models section reviews alternative efforts to address the thermohydraulic problem analytically. Before concluding, a brief section is devoted on the experimental validation of the proposed models.

A numerical model for a three-dimensional heat and fluid flow through a bank of infinitely long cylinders in yaw has been proposed in Chapter 6 to investigate complex flow and heat-transfer characteristics associated with man made anisotropic porous media, such as extended fins and plate fins in heat-transfer equipment. Upon exploiting the periodicity of the structure, one structural unit is found to represent the calculation domain. An economical quasi-three-dimensional calculation procedure has been proposed in this chapter to replace exhaustive three-dimensional numerical manipulations. Extensive numerical calculations were carried out in this chapter for various sets of the porosity, degree of anisotropy, Reynolds number, and macroscopic flow direction in a three-dimensional space. Upon examining the numerical data, a useful set of explicit expressions are established for the permeability tensor and directional interfacial heat-transfer coefficient to characterize flow and heat transfer through a bank of cylinders. The systematic modeling procedure proposed in this study can be utilized to conduct subscale modelings of manmade structures needed in the possible applications of a volume-averaging theory to investigate flow and heat transfer within complex heat and fluid flow equipment consisting of small elements.

Chapter 7 contains substantially revised material on double-diffusive convection from the first version of the *Handbook of Porous Media*. Also, new updated material is included as well as new results concerning the Soret effect in double-diffusive convection in porous media.

Chapter 8 presents a linear and weakly nonlinear stability analysis (analytical and numerical study) of the thermal diffusive regime under the action of mechanical harmonic vibrations. In this chapter, the influence of high frequencies and small amplitude vibrations on the onset of convection in an infinite horizontal porous layer and in rectangular cavity filled with a saturated porous medium is studied. The influence of the direction of vibration is also studied when the equilibrium or quasi-equilibrium solution exists. In this chapter, the so-called time-averaged formulation is utilized. The two horizontal walls, of the cell, are kept at different but uniform temperatures, while vertical walls are subject to adiabatic conditions.

Chapter 9 reviews recent research progress related to the effect of viscous dissipation on steady free, forced, and mixed convection flows over a vertical plane surface embedded in a fluid saturated porous medium. The presence of viscous dissipation breaks the usual equivalence between the upward free convection flow from a heated vertical flat plate and from its downward cooled counterpart. In the latter case the opposing effect of the buoyancy forces due to heat release by viscous dissipation can give rise to a parallel flow. In the case of forced and mixed convection flows, the usual thermal asymptotic condition contradicts the energy equation when the viscous dissipation is taken into account. The asymptotic conditions that need to be substituted in order to achieve consistency with the energy equation are set forth. It is shown that any local disturbance of the static equilibrium of a (resting) fluid leads to a local heat release due to viscous dissipation and in turn, owing to gravity, to a self-sustaining buoyant flow, even if the plate is kept at the constant ambient temperature of the fluid. With the aid of a uniform lateral suction of the fluid, this self-sustaining buoyant flow is shown to behave as a steady jet-like momentum and thermal boundary layer. This turns out to be a universal flow in the sense that its characteristics do not depend on the thermophysical properties of the fluid and the solid skeleton. These kinds of flows are discussed in detail in this chapter.

In Chapter 10, the double-decomposition concept (Pedras, M.H.J. and de Lemos, M.J.S., *IJHMT*, 44(6), 1081–1093, 2001) is presented and thoroughly discussed prior to the derivation of macroscopic governing equations. Equations for turbulent momentum transport in porous media are listed showing detailed derivation for the mean and turbulent field quantities. The statistical k–ε model for clear domains, used to model macroscopic turbulence effects, serves also as the basis for turbulent heat transport modeling. Also, this chapter discusses applications in Hybrid Media covering flow over wavy porous layers in channels and in cavities partially filled with porous material.

A microscopic phenomenological model and its simulation and experimental validation for fine particle migration and deposition in porous media is presented in Chapter 11. The mathematical model of Gruesbeck and Collins (Gruesbeck, C. and Collins, R.E., 1982, Entrainment and deposition of fine particles in porous media, *SPEJ*, 22(6), 847–856) with the modifications and improvements proposed by Civan (Civan, F., 2000, *Reservoir Formation Damage — Fundamentals, Modeling, Assessment, and Mitigation*, Gulf Pub. Co. Houston, TX, and Butterworth-Heinemann, Woburn, MA) is utilized in this work. A bundle of plugging and nonplugging parallel capillary pathways is developed in order to represent the particle and fluid transfer processes associated with flow of a particle–fluid suspension through porous media. This model allows for particle transfer between the plugging (highly tortuous flow paths) and nonplugging (smoother flow paths) pathways by means of crossflow, and attempts to simulate the porosity and permeability reduction, and the evolution of plugging and nonplugging pathways by particle deposition in porous media.

In Chapter 12, rectilinear and radial macroscopic phenomenological models along with analytical solutions and applications for impairment of porous media by migration and deposition of fine particles are presented. The mechanism and kinetics of the fine-particle deposition in porous media for two different models are described. The two models are compared and a phenomenological approach is taken to represent the depositional source/sink term and to provide constitutive relationships. For these models, the coupled set of nonlinear equations are expressed in normalized variables and solved analytically by means of the method of characteristics for both rectilinear and radial flows in porous media. Analytical solutions are provided for both constant and variable deposition rates. The analysis in this chapter compares the solutions and results of the two models with an eye toward the interpretation and representation of experimental data.

Chapter 13 describes the mathematical modeling process applied to physical systems where fluids move within heated porous ground structures. The parameters that are needed to describe the thermodynamic properties of the fluid and solid phases are listed and explained. Techniques for solving the nonlinear system of differential equations, which result from the formal modeling process are described, and some recent developments and foci of research in this area are discussed.

Chapter 14 deals with Liquid Composite Molding (LCM) processes such as Resin Transfer Molding (RTM), Vacuum Assisted Resin Transfer Molding (VARTM), CoInjection Resin Transfer Molding (CIRTM), and Structuring Reaction Injection Molding (SRIM). These processes are used for manufacturing advanced polymer composites. In such processes, the fiber preform is placed inside the mold cavity and a thermoset resin is injected into the mold to wet the fiber preform. The resin cures and cross-links to form a solid composite material. To understand the impregnation and the curing process during manufacturing of composites, research has been conducted to model the heat and flow phenomena in the LCM processes. The transport theories in porous media and the chemical reaction equations have been used to model the thermal and fluid behavior.

Chapter 15 of this handbook discusses premixed combustion of gaseous fuels and air, which react in porous inert media (PIM) that serve as "flame holders" for the burners. The intimate coupling of local chemical energy release during the reaction and heat transfer by conduction, convection, and radiation in the solid matrix results in recirculation of part of the heat of reaction and affects the flame speed, flame stability, the peak flame temperature, and pollutant emissions. The design, theory, modeling, and characteristics of selected combustion systems in which the reactants are preheated using heat recycled from beyond the flame zone, without mixing the two streams, are discussed in this chapter. Applications of devices that have the potential for high efficiencies, low pollutant emissions, and possibility of burning low calorific value gaseous fuels and combustion of lean hydrogen/air mixtures are discussed here.

Chapter 16 deals with bioconvection in porous media. This is an area that is related to a number of pertinent biological applications. One of the applications of porous media is in control and suppression of bioconvection. This problem is of importance, for example, in separation between living and dead cells in suspensions of upswimming mobile microorganisms. Since living microorganisms are heavier than water, their upswimming results in an increase in the density of the upper fluid layer. This leads to convection instability that induces convective motion in the fluid layer. This convective motion, called bioconvection, moves the dead cells from the lower part of the fluid layer and transports them to the upper part of the fluid layer, causing mixing between living and dead cells. By utilizing porous substrates it is possible to control or even completely suppress bioconvection. A large portion of the chapter is devoted to derivation of the stability criteria for bioconvection in porous media. The effect of cell deposition and declogging as well as the effect of fouling of porous media on the critical permeability are investigated. Finally, this chapter also presents a theory of a bioconvection plume in a suspension of oxytactic bacteria in a deep chamber filled with a fluid saturated porous medium.

The last chapter in the handbook addresses the inverse problem of the identification of the hydraulic properties of porous materials in the context of petroleum, civil, and mining engineering. The application of GAs, which attempts to imitate the principles of biological evolution in the construction of optimization strategies and has led to the development of a powerful and efficient optimization tool, is investigated for such purposes. In this chapter, an inversion technique is formulated in order to retrieve homogeneous or spacewise dependent material property coefficients. Surface measurements by means of simulated ports along the sealed boundaries of the materials serve as information to the GA optimization procedure, thus enabling a modified least squares functional to minimize the difference between the observed and the numerically predicted boundary pressure and/or average hydraulic flux measurements under current hydraulic conductivity tensor and specific storage estimates. Composite anisotropic materials, that is, incorporating faults, are also investigated. Parameter identification in inverse problems is numerically investigated and the results are found to provide an accurate means of recovering the required material properties. A comparison on the performance of the inversion highlights the advantages of the GA optimization approach against a traditional gradient-based optimization procedure.

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

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