Chapter 1
Introduction

Fluid and flow problems in porous media have attracted the attention of industrialists, engineers and scientists from varying disciplines, such as chemical, environmental and mechanical engineering, geothermal physics and food science. Porous medium domains, in which fluid phase mass, phase component mass, momentum, energy, electric charge, and other extensive quantities are being transported while undergoing transformations, are encountered in a variety of disciplines: Civil Engineering (concrete is a porous medium, and soil is a deformable porous medium), Hydrology (aquifers), Environmental Engineering (groundwater pollution by toxic liquids and hazardous wastes), Chemical Engineering (reactors, but the subsurface also behaves like a large chemical reactor in which chemical and biological transformations of contaminants take place), Petroleum Engineering (oil and gas production from reservoirs), Agricultural Engineering (drainage and irrigation), Biomedical Engineering (lungs, kidneys), and Geothermal Engineering (geothermal reservoirs), to mention but a few.

It is widely accepted that most materials are to some extent porous, in the sense that it is quite difficult to find or compose an extremely dense (non-porous) medium. It is evident that the physical and chemical properties of these materials are dependent on their pore structure. For instance, the control of porosity is of great industrial importance in the design of catalysts, industrial adsorbents, membranes and ceramics, as it influences the chemical reactivity of solids and the physical interaction of solids with gases and liquids. The complexity and variety of porous materials has therefore led to a diverse variety of studies on the transport processes occurring there.

1.1 Why Porous Materials?

What is a porous material? The term “porous” is used to describe a complex structure consisting of a compact phase (usually solid) and some void space, where their analogy defines the most significant property of a porous material, its

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"porosity". Generally speaking, any solid material which contains cavities, channels or interstices may be regarded as porous, although in a particular context a more restrictive definition may be appropriate. Thus, in describing a porous solid, care must be exercised in the choice of terminology in order to avoid ambiguity. More precisely, all these "pores", "cavities" etc. must be carefully defined. Chapter 2 of this book presents a detailed discussion of these terms and their use. For the moment, the following definition sounds accurate enough for the reader: *A porous medium is a region in space comprising of at least two homogeneous material constituents, presenting identifiable interfaces between them in a resolution level, with at least one of the constituent remaining fixed or slightly de-formable* [1].

Why are porous materials interesting? Besides the wide spectrum of applications they have attained during the last centuries, they are not transparent, thus it is necessary to describe any processes occurring within them without local observation, and based only on macroscopic data regarding the inlet and outlet of the domain. The complexity of porous structures allows for assuming very complex local-scale phenomena, which should be integrated to normal macroscopic ones. For instance, even very low volumetric flow-rate would lead to extremely high local velocity and Reynolds number, when the porous structure contains very thin (capillary) throats locally.

The term "porous" is often used instead of the term "dense", which is the most suitable fundamental consideration for the continuum in physics and applied sciences in general. What is important is that dense materials do not actually exist. Even the most compact artificially developed material is of small porosity and must be treated as porous. As a consequence, the study of flow and transport in porous media is applicable to a very wide range of fields, with practical applications in modern industry and environmental areas. In all these disciplines, transport phenomena and transformation occur in porous media domains at a wide range of scales, from the microscopic to the field scale. Understanding these transport phenomena, modeling them at different scales, coping with the uncertainties inherent in such models, and solving the models in order to provide data for management and decision making is the subject of this book.

1.2 Aims and Scopes

This book examines the transport processes that take place in the pore structure of porous materials. Models of pore structure are presented with a discussion of how such models can be used to predict macroscopic quantities that are useful for practical applications. The book is in principal devoted to interpretations of experimental results and simulation predictions in this area, giving directions for future research. Practical applications are given where applicable.

As a first step towards the study of transport processes in porous media, several techniques for artificial representation (modeling) of porous media are discussed. Single phase flows in simplistic and complex porous structures are described in terms of macroscopic and microscopic equations as well as their analytical and numerical solutions. Furthermore, macroscopic quantities such as permeability are introduced and discussed. Mass transport processes in porous media are also discussed and further strengthened by experimental validation and specific technological applications.

The special features of this book are (a) the use of state-of-the-art techniques for modeling transport processes in porous structures, (b) the consideration of realistic sorption mechanisms, (c) the application of advanced mathematical techniques for up-scaling major quantities, and (d) experimental investigation and application, namely, experimental methods for the measurement of relevant transport properties.

1.3 Book Contents and Structure

This book contains seven chapters about transport processes in porous media, organized as follows:

- Initially, Chap. 2 introduces the reader to the *Fundamentals of Porous Structures* by presenting some methods for the description of porous structures. These methods correspond to analytical descriptions (cell models) and numerical ones, either deterministic (digital reconstruction) or probabilistic (stochastic modeling).
- Chapter 3 presents the *Flow in Porous Media*, which is necessary for the adequate estimation of any other transport process. More precisely, this chapter presents the analytical expressions derived in cell models when single phase flow is considered. This is then further exploited to more realistic granular structures.
- *Transport Phenomena in Porous Structures* are presented in Chap. 4, where details of basic phenomena (diffusion and dispersion) are discussed, while a selected application (Dispersion in Packed Beds Flowing by Non-Newtonian Fluids) has been used as an abundant exemplar.
- Chapter 5 deals with the *Modeling of Transport Processes in Porous Materials*, presenting single phase transport in the selected geometries specified in Chap. 3 (cells, granular structures) as well as a novel scale-up technique to obtain macroscopic quantities from microscopic measures/calculations ("Macroscopic quantities for single phase transport").
- The theoretical results of Chap. 5 are further strengthened by the *Experimental Investigation of Transport in Porous Media*, presented in Chap. 6. These experiments contain measurements of molecular diffusion and axial and radial dispersion coefficients, calculation of the solubility of organic compounds at

different temperatures, as well as estimation of tortuosity in porous media. Finally, an application of mass transfer around active solids is presented.

- Five applications of all the above theoretical concepts and experimental results are discussed in Chap. 7 (*Applications and Examples*). These particular applications are: (a) Contaminant Plume Sizes Associated to Different Active Solids, (b) Rising Damp in Building Walls, (c) Bubbles and Drops in Porous Structures, (d) Transport Processes in Solid Oxide Fuel Cells (SOFCs), and (e) Multi Phase Transport in Porous Media.

Each chapter is systematically detailed to be easily understood by a reader with basic knowledge of fluid mechanics, heat and mass transfer, and computational and experimental methods. Although much of the subject matter contained here is available in research literature, journals and conference proceedings, this book presents an overview of the most interesting developments over a wide variety of the most important topics in transport phenomena in porous media. The fundamental concept for this book was to present the complete story of transport processes in porous structures, and for this reason the chapters are self-contained, citing separate references, and presenting their own mathematics, explanations and terminology.

Reference

1. Lage, J.L., Narasimhan, A.: Porous media enhanced forced convection fundamentals and applications. In: Vafai, K. (ed.) Handbook of Porous Media. Marcel Dekker, New York (2000)