POROUS MEDIA TRANSPORT PHENOMENA

FARUK CIVAN

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Dedicated to my family with love and appreciation

CONTENTS

PREFACE

Many processes in the nature and engineering applications occur in porous media and materials. The mathematical description of such processes in porous materials is usually overwhelmingly complicated. Often, a compromising analysis approach is therefore necessary between complexity of modeling and effort required for the solution of problems of practical interest. This is usually accomplished by emphasizing an averaged representative description and neglecting the details of low-order influence.

This book has been designed to provide an understanding of the fundamentals of the relevant processes. The theory and modeling of the porous material, fluid, and species behavior in porous media are reviewed. The methods for prediction, analysis, and description of the commonly encountered porous media processes are discussed. Emphasis is placed upon practical understanding and implementation with straightforward mathematical treatment.

Transport in porous media is an interesting interdisciplinary subject, which attracted many researchers from various disciplines. This book covers the relevant materials with sufficient detail but without overwhelming the readers. This book can be used for understanding and description of the porous media problems. It may serve as a useful reference and text. This book provides knowledge of the theoretical and practical aspects of porous media transport for various purposes, including conducting laboratory and actual-size tests, model-assisted interpretation of test data, and prediction and simulation of various porous media processes.

Obviously, the abundance of literature available in this area is overwhelming because of the great interdisciplinary nature and the wide variety of potential approaches and applications in porous media. Numerous references have been used in the preparation of this book. However, an encyclopedic presentation of all approaches is not attempted for the purpose of this well-focused book. Rather, I have determined and limited the coverage of the relevant materials in this book to the essential critical bottom-line information required for the analyses and description of porous media processes. I believe this book will form an important basis for readers from which they can begin to explore innovative and creative approaches in dealing with applications in porous media.

This book is intended to provide an effective and comprehensive overview of the fundamentals and the experimental and theoretical approaches present in the area of the transport phenomena in porous media. The mechanisms of processes occurring in porous media are discussed. Various approaches used in the modeling of porous media single- and multiphase transport processes, with and without the thermal, species, and particulate processes, are presented systematically. The techniques available for the analysis and modeling of these processes with well-established approaches are described.

Porous media transport phenomena is an interdisciplinary issue of concern for petroleum, chemical, environmental, geological, geothermal, civil, and mechanical engineers, geologists, physicists, materials scientists, and mathematicians; it considers the simultaneous mass, momentum, and energy transport issues associated with porous matrices, pore fluids, and species; it includes a model-assisted analysis of experimental data and parameter determination issues; and incorporates the recent developments in porous media process analysis and modeling techniques.

This book is written in a concise and practical manner. Emphasis is placed upon the practical understanding, formulation, and application of the relevant processes, mechanisms, and methods without overwhelming with unnecessary details and mathematical complexities. The philosophy and theoretical and technical principles involved in the measurement and experimental techniques are explained. It presents an introductory background at the beginning of the chapters, followed by the relevant theoretical development, application problems for illustration and demonstration purposes, instructive questions and exercise problems for self-practice, and many references for further reading and details.

Most of the topics covered in this book are of common interest and interdisciplinary nature. This book is intended for use by researchers, practicing engineers, professionals, and engineering students involved in porous media applications. This book can be used as a textbook for senior undergraduate and early graduate-level engineering courses. The prerequisites are thermodynamics, fluid mechanics, heat transfer, engineering mathematics, basic computer programming, and basic properties of fluids and porous materials.

This book can be used by many disciplines and professionals for instructional and reference purposes because of its interdisciplinary nature. The material presented in this book has been tested in the courses taught by Dr. Civan at the University of Oklahoma over a period of 30 years. Parts of the materials presented in this book were tested by Dr. Civan in his industry short courses presented at various institutions. The materials presented in this book originate from Dr. Civan's key papers, and relevant literatures listed in the references as well as the relevant parts taken from Dr. Civan's course notes prepared for teaching the following courses:

Graduate courses

- Fluid Flow through Porous Media
- Transport Phenomena in Porous Media
- Waterflooding
- Advanced Reservoir Engineering
- Enhanced Oil Recovery
- Process Analysis and Simulation
- Numerical Simulation by Digital Computation

Undergraduate courses

- Oil Reservoir Engineering
- Natural Gas Engineering
- Applied Reservoir Engineering

This book can be used in the following related courses in petroleum, chemical, environmental, civil, and mechanical engineering:

- Transport Phenomena in Porous Media
- Fluid Flow through Porous Media
- Mass, Momentum, and Energy Transfer in Porous Media

Writing this book was an overwhelming accomplishment, which required the effort and dedication of the author for more than 10 years. Analyzing and condensing the vast amount of information available on this subject to the bottom-line critical presentation in this book was a tedious and laborious task. Some topics were more emphasized than others in the literature. Special undertaking was necessary to tie the loose ends. My dedication and motivation in taking such a responsibility was to make my lifelong learning, teaching, development, and expertise on this topic available for the readers of the book. Like any other information available, the readers should critically examine, test, and apply the information provided in this book in view of the particular conditions and requirements of problems of their interest.

I gratefully acknowledge the following organizations and companies for granting permissions to use various materials included in this book: American Chemical Society, American Geophysical Union, American Institute of Chemical Engineers, American Institute of Physics, American Society of Civil Engineers, American Society of Mechanical Engineers, Begell House Inc. Publishers, Chemical Engineering Education, Elsevier, John Wiley & Sons, Oklahoma Academy of Science, Society of Petroleum Engineers, Society of Petrophysicists and Well Log Analysts, and Springer.

Any comments, corrections, and suggestions by the readers to improve this book are welcome. After all, the overall objective of this book is to serve the readers by providing quality information in this one source.

I am indebted to the team at John Wiley & Sons Publishing Company for their support in the preparation and realization of this book.

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Faruk Civan is an M.G. Miller Professor in the Mewbourne School of Petroleum and Geological Engineering at the University of Oklahoma in Norman. Previously, he worked at the Technical University of Istanbul, Turkey. He formerly held the Brian and Sandra O'Brien Presidential and Alumni Professorships. He published a book, *Reservoir Formation Damage—Fundamentals, Modeling, Assessment, and Mitigation*, from Elsevier Publishing Company, and more than 270 technical articles published in journals, edited books, handbooks, encyclopedia, and conference proceedings, and presented more than 100 invited seminars and/or lectures at various technical meetings, companies, and universities. He holds an advanced degree in engineering from the Technical University of Istanbul, Turkey, a master of science degree from the University of Texas at Austin, and a doctor of philosophy degree from the University of Oklahoma. Civan has served on numerous American Institute of Chemical Engineers and Society of Petroleum Engineers technical committees. He is a member of the American Institute of Chemical Engineers, the Society of Petroleum Engineers, and the editorial boards of several journals. Civan has received 20 honors and awards, including five distinguished lectureship awards and the 2003 SPE Distinguished Achievement Award for Petroleum Engineering Faculty. He teaches short courses on topics of practical importance concerning the various aspects of in situ energy resource development and utilization.

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CHAPTER 1

OVERVIEW

1.1 INTRODUCTION

Processes occurring in porous media and materials are encountered frequently in various engineering applications. The mathematical description of these processes is complicated because of the intricate flow paths, proximity of the pore wall, and mutual interactions of the fluids, particulates, and porous media. Often, a compromising analysis approach is essential in order to circumvent the complexity of modeling in view of the effort required for the solution of problems of practical interest. We can realistically accomplish this task by emphasizing an averaged description capturing the dominant features and neglecting the low order of magnitude details.

Porous Media Transport Phenomena is a comprehensive review and treatise of the fundamental concepts, theoretical background, and modeling approaches required for applications involved in mass, momentum, energy, and species transport processes occurring in porous media. This general inter- and multidisciplinary book provides a comprehensive material and background concerning the description of the behavior of fluids in porous materials.

An updated, concise, practical, convenient, and innovative treatment and presentation of the critical relevant bottom-line issues of transport in porous media is presented, from which all disciplines dealing with processes involving porous materials can benefit. Motivation, description, and executive summary of the various topics covered in this book are presented.

Description and characterization of porous media and processes occurring therein have been attempted by many different methods. The following approaches are among the outstanding methods used for this purpose (Chhabra et al., 2001):

- *Bundle of capillary tube models.* The fluid flowing through the connected pore space is assumed to follow a number of preferential capillary tortuous flow paths (Kozeny, 1927; Carman, 1938, 1956). The wall friction effect of the capillary tubes is considered as exerting resistance to flow. The effect of irregularities (interconnectivity and entanglement) involved in and the interactions (cross-flow) occurring between the fluids flowing through the various capillary flow paths are ignored (Chhabra et al., 2001; Civan, 2001). However, this issue can be alleviated by means of the leaky-tube model (Civan, 2001, 2002b,d, 2003, 2005a).

Porous Media Transport Phenomena, First Edition. Faruk Civan.

- *Pack of solid grain models.* The drag exerted against fluid flowing through a pack of solid grains of assumed shapes, such as spherical particles, in a prescribed arrangement, such as cubic packing, is considered for prediction of frictional pressure loss during flow (Chhabra et al., 2001). This method has been implemented by three main approaches: (1) correlating the experimental data to express the drag as a function of porosity (pore volume fraction) or solidity, or packing (grain volume fraction) of porous media without considering the solid particle arrangement; (2) predicting the drag by solution of the momentum equations for a prescribed arrangement of solid grains; and (3) adjustment of the drag of a single grain in a cell for intergrain interactions by simulation (Chhabra et al., 2001).
- *Averaging of microscopic field equations.* The microscopic conservation equations governing the flow of fluids in porous media are averaged over a representative elementary volume of porous media. However, averaging over time is also carried out for rapid turbulent flow of fluids.
- *Dimensionless empirical correlation methods.* Empirical models are developed based on the method of dimensional analysis and empirically obtained mathematical relationships between the relevant dimensionless groups.
- *Hybrid models.* These combine the various features of the aformentioned methods.

This book presents a concise review and treatise of the relevant developments and theoretical foundations required for understanding, investigation, and formulation of processes involving porous media. The overall objective is to provide the readers with one source to acquire the bottom-line information in a convenient and practical manner. This book is written to provide engineering students, scientists, professionals, and practicing engineers with an updated and comprehensive review of the knowledge accumulated in the literature on the understanding, mathematical treatment, and modeling of the processes involving porous media, fluid, and species interactions and transport. However, presentation is limited to the most critical information needed for applications of practical importance and further developments without overwhelming the readers with unnecessary encyclopedic details.

Fundamental theories, principles, and methods involved in the analysis and modeling of single- and multiphase fluid and species transport in porous media are covered. Special emphasis is placed on the phenomenological modeling of the processes involved in the transport of fluids, species, and particulates in porous materials, oil and gas recovery, geothermal energy recovery, and groundwater contamination and remediation. This book presents the fundamental knowledge and the recent developments in the analysis, formulation, and applications of flow through porous materials. Formulation of mass, momentum, and energy transport phenomena and rate processes; model-assisted analysis of experimental data; and modeling of processes occurring in porous media are described in a practical manner and are illustrated by various example problems. Experimental and measurement techniques used for the study of the processes in porous media and for the determination of relevant process parameters are described and demonstrated by applications.

Among the topics covered in this book are characterization of porous materials; phenomenological description of commonly encountered processes, formulation of equations for mathematical description of porous media transport, and their associated initial and/or boundary conditions; analyses of porous media processes by various approaches including constitutive relationships, dimensional analysis, control volume conservation analysis, and representative volume and time averaging; development and applications of the multiphase transport models, including the noncompositional, limited compositional, and fully compositional types; treatment of potential flow, phase transition, physical and chemical reactions, porous media deformation, particulates, heterogeneity, and anisotropy; and basic numerical simulation examples. Examples exploring and demonstrating the applications of the various formulations are presented for instructional purposes, and exercise problems are provided at the end of the chapters for further practice on the subject matter. Most problems dealing with porous media transport involve subsurface porous media, and therefore some examples given in this book relate to processes occurring in such media. The state of the knowledge is presented in plain language with equal emphasis on the various topics in a uniform format and nomenclature using the consistent International System of Units (SI). Instructive figures are presented to explain the relevant phenomena, mechanisms, and modeling approaches and results. A comprehensive list of relevant references is provided at the end of the book.

1.2 SYNOPSES OF TOPICS COVERED IN VARIOUS CHAPTERS

This book contains 11 chapters covering the most critical topics and formulation of porous media transport phenomena. Chapter 1 presents an overview and executive summaries of the various topics covered in this book.

Chapter 2 presents the transport properties of porous media. The effects of pore connectivity, the valve action of pore throats, and cementation are considered in a bundle of tortuous, leaky capillary tubes of flow for a macroscopic model of permeability of porous media. Practical straight-line plotting and parameter determination schemes are presented for convenient correlation of the porosity–permeability of porous media using a simplified macroscopic model. The permeability of porous media is correlated by means of a single continuous function over the full range of porosity using a power-law flow unit equation. The parameters of the power-law flow unit equation incorporate the fractal attributes of interconnected pore space into a bundle of tortuous, leaky hydraulic tube model of porous media. These parameters are strong functions of the coordination number of porous media and are significantly different from those of the Kozeny–Carman equation. The mathematical relationships of the power-law parameters to the coordination number are also presented. The associated analysis also lends itself to the physical interpretation of the pore connectivity and cementation factor in terms of the relationship of permeability to porosity. From a practical point of view, the primary advantage of the present macroscopic modeling approach is that it leads to a single, simple, compact, and convenient equation, which can be readily incorporated into the modeling of porous media processes without adding appreciable complexity and computational burden into large-scale field simulations. This macroscopic model is an improvement over the Kozeny–Carman equation, which has a more limited application. It is more beneficial than the microscopic pore-scale network models because it requires significantly less computational burden while providing sufficient accuracy for large field-scale applications.

Chapter 3 presents the macroscopic transport equations. First, the methodology for temporal, spatial, and double averaging of microscopic conservation equations for derivation of the porous media macroscopic conservation equations is presented and illustrated by several examples. The volume and mass-weighted volume averaging of the microscopic equation of conservation results in different macroscopic equations. Properly formulated closure schemes, such as the gradient theory, are required for formulation of terms involving the averages of the products of various quantities representing deviations from their volume-average values. It is emphasized that both time and space averaging are necessary by means of double decomposition for macroscopic description of processes involving transport through coarse porous media, where the pore fluid volume is large enough to undergo some turbulence effects. Second, the methodology for direct derivation of the porous media conservation equations by control volume analysis is presented as an alternative approach, which can provide different insights into the nature of macroscopic equations.

Chapter 4 presents the scaling and correlation of transport in porous media. Applications of dimensional and inspection analysis methods to porous media processes are demonstrated and elaborated. Their outstanding advantages and disadvantages are delineated. The benefits of using normalized variables are emphasized. Important dimensionless groups and mathematical relationships are derived and applied for several cases. Analysis and interpretation of experimental results using dimensionless groups and self-similarity transformations are presented. Strategies for effective scaling and generalization of experimental results are discussed.

Chapter 5 presents the fluid motion in porous media. The equation of motion for single-phase fluid flow through porous media is derived by various approaches, including the analysis of forces acting on fluid based on dimensional analysis and a control volume momentum balance approach. Resistive forces associated with pore surface and pore throat are characterized by the capillary orifice model of porous media. Several issues are emphasized, including the porous media averaging of the pressure and shear stress terms, the effect of porous media heterogeneity and anisotropy, source terms, correlation of parameters, flow demarcation criteria, entropy generation, viscous dissipation, generalization of Darcy's law, non-Newtonian versus Newtonian fluid rheology, and threshold pressure gradient that must be overcome for fluid to flow through porous media.

Chapter 6 presents the gas transport in tight porous media. The flow of gases through tight porous media is treated differently from liquids. Walls of tight pores in porous media interfere with the mean free motion of gas molecules and cause a strong deviation from Darcy's law. Darcy's law cannot describe the flow of gas in tight formations under the Knudsen and slip flow conditions because Darcy's law was designed to represent the viscous flow by analogy to liquid flow. A multiplemechanism transfer model can provide an accurate description of gas flow in tight porous media. A Darcy-like equation using an apparent permeability is presented by considering the gas transport by several mechanisms, which may occur in tight pore spaces under different Knudsen number criteria. This equation incorporates the Knudsen, transition, slip, viscous, surface diffusion, and condensate flow mechanisms into the description of gas flow, each prevailing under different conditions. The characteristics of porous media are represented by fractal description and by considering the pore size distribution. Various issues involved in the proper derivation of relevant formulas based on the realization of the preferential flow paths in porous media by means of a bundle of tortuous tubes are presented. The mechanisms, characteristic parameters, and modeling of gas transport through tight porous media under various conditions are reviewed. Formulations and methodology are described for accurate and meaningful correlations of data considering the effect of the characteristic parameters of porous media, including intrinsic permeability, porosity, and tortuosity, as well as the apparent gas permeability, rarefaction coefficient, and Klinkenberg gas slippage factor.

Chapter 7 presents the coupling fluid mass and motion in porous media. The flow of fluids through porous media under isothermal conditions requires the simultaneous solution of the mass and momentum conservation equations. Hence, this chapter describes the coupling of these two equations in various applications of practical importance involving single- and multiphase fluid systems. The concept of the leaky-tank model is introduced, allowing for the determination of the essential parameters of flow occurring in porous media around the wells. Special convenient formulations are derived for fractional flow, end-point mobility, and streamline/stream tube flow descriptions. Applications of the method of superposition, images, and front tracking are described for potential flow problems. Numerical solutions of various problems are presented for instructional purposes.

Chapter 8 presents the characterization of parameters for fluid transfer. A review of the methods required for defining and determining the essential parameters affecting fluid transport through porous media is presented. Wettability and wall drag, wettability index, capillary pressure and measurement, relative permeability and measurement, temperature dependence, and interfacial drag are discussed. Application of the Arrhenius equation is reviewed for the correlation of the temperature effect on wettability-related properties of material, including the work of immiscible displacement, unfrozen water content, wettability index, and fluid saturation in porous media. The correlation with the Arrhenius equation provides useful information about the activation energy requirements associated with the imbibition and drainage processes involving the flow of immiscible fluids in porous materials. Determination of the relative permeability and capillary pressure from laboratory core tests by direct and indirect methods based on steady-state and unsteady-state core flow tests is described.

Chapter 9 presents the modeling transport in porous media. Applications of coupled mass, momentum, and energy conservation equations are discussed and presented for various problems. Transport of species through porous media by different mechanisms is described. Dispersivity and dispersion in heterogeneous and anisotropic porous media issues are reviewed. Formulation of compositional multiphase flow through porous media is presented in the following categories: the general multiphase, fully compositional nonisothermal mixture model, the isothermal black oil model of nonvolatile oil systems, the isothermal limited compositional model of volatile oil systems, and shape-averaged models. Formulation of source/sink terms in conservation equations is discussed. Analyses and formulations of problems involving phase change and transport in porous media, such as gas condensation, freezing/thawing of moist soil, and production of natural gas from hydrate-bearing formations, are presented.

Chapter 10 presents the modeling of particulate transport in porous media. Formulation of deep-bed and cake filtration processes involving particle transport and retention, and resulting porosity and permeability variation in porous media, is described. Phenomenological modeling considering temperature variation and particle transport by advection and dispersion is discussed. Temperature dependence is accounted for through the filtration rate coefficient and porous matrix thermal deformation. Other factors affecting the filtration coefficient and permeability are considered by means of empirical correlations. Applications are presented concerning the transport of colloids and particles through porous media and compressible cake filtration involving smaller particles packing through the large particles that form the skeleton of the filter cake. The effect of dispersion mechanism and temperature variation on particle transport and retention, and the consequent porosity and permeability impairment, is demonstrated by several examples.

Chapter 11 presents the modeling of transport in heterogeneous porous media. This chapter presents formulations and solutions that apply to heterogeneous systems having various transport units in fractured porous media, where the permeability of the fracture system is relatively greater than that of the porous matrix, and therefore the fractures form the preferential flow paths while the matrix forms a source of fluid for fractures. The objectives of this chapter are to develop an understanding of the mechanism of the matrix-to-fracture fluid transfer by the various processes and the formulation of transport in fractured porous media. The analytical and numerical solutions are presented for relatively simplified cases and systems undergoing an imbibition-drive matrix-to-fracture fluid transfer.

CHAPTER 2

TRANSPORT PROPERTIES OF POROUS MEDIA

2.1 INTRODUCTION

Permeability is an important property of porous formation and a complex function of many variables.* The essential variables include (1) the configuration of the pore structure determined by the arrangement of grains and pores, and described by fabric, texture, and morphology; (2) type, size, shape, and composition of pore deposits, cement, and grains; (3) coordination number defined as either the number of pore space connections or the number of grain contacts, here referred to as the pore coordination number and the grain coordination number, respectively; (4) hydraulic diameter, specific pore surface, areosity, or the area of pores open for flow, nonzero transport threshold, and tortuosity of the flow paths; (5) grain consolidation by cementing, fusing, and other means; and (6) for porous media undergoing an alteration, the evolution of the pore structure and creation of noncontributing porosity by porous matrix deformation, rock–fluid interactions, and other relevant processes (Kozeny, 1927; Carman, 1937a,b, 1956; Nelson, 1994, 2000; Saito et al., 1995; Revil and Cathles, 1999; van der Marck, 1999; Civan, 2000a,b). Cement is any material acting as a grain consolidation agent. Obviously, it is impractical to take into account all details in a simplified model. However, the majority of the simplified modeling approaches have strived at determining permeability from porosity alone, as pointed out by Nelson (1994, 2000). Nevertheless, porosity appears to be common to many of the critical factors affecting permeability, such as the coordination number, pore or grain surface area, and tortuosity. Civan (2002d) considered the porosity, coordination number, and cementation factor of natural

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Civan, F. 2003. Leaky-tube permeability model for identification, characterization, and calibration of reservoir flow units. Paper SPE 84603, SPE Annual Technical Conference and Exhibition, Denver, Colorado, October 5–8, 2003, © 2003 SPE, with permission from the Society of Petroleum Engineers.

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porous media as the primary independent variables and showed that these are sufficient to define a meaningful relationship for permeability. The secondary factors, such as the interconnectivity parameter and exponent of the power-law flow unit equation of permeability suggested by Civan (1996c, 2001, 2002b,d, 2003, 2005a), are related to permeability through porosity.

Many natural and engineering processes occur in porous media. Among other factors, the transport of fluids through subsurface geological formations is primarily influenced by the permeability distribution in these formations. Accurate and theoretically meaningful description and prediction of the permeability of natural and engineering porous materials are of continuing interest. Improved, compact, and convenient macroscopic permeability models are required for representing the variation of the permeability of porous materials in large-scale geological subsurface reservoirs. In such media, the pore structure and thence permeability may vary by rock, fluid, and particle interactions and by thermal and mechanical stresses during flow of fluids. Various theoretical and laboratory studies have been carried out to determine the functional relationships between the hydrodynamic transport properties of porous materials, especially the permeability, with varying degrees of success (Nelson, 1994; Civan, 2000a,b, 2001, 2007a; Singh and Mohanty, 2000). Modeling at both the microscopic and the macroscopic levels has been attempted. Frequently, conventional approaches for the characterization of flow through porous media have resorted to the estimation of permeability based on the description of flow either around the grains (microscopic description) or through a bundle of capillary tubes (macroscopic description) (Rajani, 1988). Macroscopic models require significantly less computational complexity and are preferred to microscopic, locally detailed, pore-level distributed parameter and network models for large field-scale applications.

Among the various hydrodynamic transport properties, the prediction of permeability has predominated because of its importance in determining the rate of fluid transfer through porous materials. In spite of numerous experimental and theoretical works, there is a scarcity of satisfactory practical and simplified models, which can be incorporated into the mathematical description of porous media fluid flow (Civan, 2002b,d) without adding much complication and computational burden. Yet, these models are in great demand for large-scale flow field simulations of subsurface reservoirs. Complicated modeling that provides information about the details of flow patterns at the microscopic scale, such as the pore-level description using network models, may be an instructive and important research tool. However, it is also computationally demanding and impractical when dealing with processes in intricate porous media, and it requires a significant amount of computational effort. Therefore, simplified models are more advantageous for practical application. In this respect, the majority of attempts at improved, simplified modeling have focused on the extension and modification of the Kozeny–Carman equation as described by Nelson (1994), Singh and Mohanty (2000), and Civan (2000b,d, 2001, 2003, 2005a).

Descriptions of the functional relationship between the permeability and porosity of porous media have been attempted in numerous theoretical and laboratory studies with varying degrees of success. Among other factors, permeability and effective (interconnected) porosity of porous materials strongly depend on pore con-