# Multiphase Flow And Transport Processes In The Subsurface A Contribution To The Modeling Of Hydrosystems Environmental Science And Engineering

Continuum and Kinetic Theory Descriptions
Theory and Modeling
Computational & Experimental Methods
Massively Parallel Simulation of Flow and Transport in Variably Saturated Porous and Fractured Media
Multiphase Fluid Dynamics
Multiphase Flow and Transport in the Subsurface
Reactive Transport in Natural and Engineered Systems
Transport Phenomena in Multiphase Systems
From Pore to Core and Beyond
Upscaling Multiphase Flow in Porous Media
Computational Methods for Multiphase Flows in Porous Media
Advances in Transport Processes
Transport Processes in Porous Media
Transport Processes at Fluidic Interfaces
Multiphase Fluid Dynamics
Computational Methods in Subsurface Flow
Multiphase Flow
The Influence of Repository Thermal Load on Multiphase Flow and Heat Transfer in the Unsaturated Zone of Yucca Mountain
Multiphase Flow in Porous Media
Thermo-fluid Dynamics of Two-Phase Flow
Investigating Capillary Pressure and Interfacial Area for Multiphase Flow in Porous Media Using Pore-scale Imaging and Lattice-Boltzmann Modeling
Applications to Cities, Vegetative Canopies and Industry
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Transport Processes in Porous Media
In Conventional and Miniature Systems
Transport Phenomena in Multiphase Systems
Convective Heat and Mass Transfer
Proceedings of the Fifth International FZK/TNO Conference on Contaminated Soil, 30 October–3 November 1995, Maastricht, The Netherlands
Investigation of Fluid Flow and Contaminant Transport Processes in Heterogeneous

## DOYLE JEFFERSON

**Continuum and Kinetic Theory Descriptions** Academic Press
Introduction to the transport of energy, mass, and momentum in chemically reacting fluids for graduate or undergraduate students with no prior background in fluid mechanics. Solutions to selected exercises.

**Theory and Modeling** Cambridge University Press
Treating multiphase systems with emphasis on the aspect of fluid dynamics and as an introduction to research in multiphase flow, this book covers definitive concepts, methods, and theories which have been validated by experimental results. A textbook for college seniors and graduate students and a research reference, it is a coherent presentation that facilitates the understanding of physical interactions. The book's focus is fluid dynamics, with extension to other transport processes of heat and mass transfer, and chemical relations to illustrate applications of multiphase flow. The exercise problems at the end of each chapter assist the reader in formulating and solving physical problems and gaining a sense of magnitude of interacting effects and events. Extended details and corollaries are also included in these exercise problems. Some of the topics in the exercise problems may also be incorporated as topics for the lectures.

*Computational & Experimental Methods* CRC Press
Improved capabilities for modeling multiphase flow in the subsurface requires that several aspects of the system which impact the flow and transport processes be more properly accounted for. A distinguishing feature of multiphase flow in comparison to single phase flow is the existence of interfaces between fluids. At the microscopic (pore) scale, these interfaces are known to influence system behavior by supporting non-zero stresses such that the pressures in adjacent phases are not equal. In problems of interphase transport at the

macroscopic (core) scale, knowledge of the total amount of interfacial area in the system provides a clue to the effectiveness of the communication between phases. Although interfacial processes are central to multiphase flow physics, their treatment in traditional porous-media theories has been implicit rather than explicit; and no attempts have been made to systematically account for the evolution of the interfacial area in dynamic systems or to include the dependence of constitutive functions, such as capillary pressure, on the interfacial area. This project implements a three-pronged approach to assessing the importance of various features of multiphase flow to its description. The research contributes to the improved understanding and precise physical description of multiphase subsurface flow by combining: (1) theoretical derivation of equations, (2) lattice Boltzmann modeling of hydrodynamics to identify characteristics and parameters, and (3) solution of the field-scale equations using a discrete numerical method to assess the advantages and disadvantages of the complete theory. This approach includes both fundamental scientific inquiry and a path for inclusion of the scientific results obtained in a technical tool that will improve assessment capabilities for multiphase flow situations that have arisen due to the introduction of organic materials in the natural environment. This report summarizes work after 1.5 years of a 3-year project.

Massively Parallel Simulation of Flow and Transport in Variably Saturated Porous and Fractured Media Gulf Professional Publishing

Useful as a reference for engineers in industry and as an advanced level text for graduate engineering students, Multiphase Flow and Fluidization takes the reader beyond the theoretical to demonstrate how multiphase flow equations can be used to provide applied, practical, predictive solutions to industrial fluidization problems. Written to help advance progress in the emerging science of multiphase flow, this book begins with the development of the conservation laws and moves on through kinetic theory, clarifying many physical concepts (such as particulate viscosity and solids pressure) and introducing the new dependent variable--the volume fraction of the dispersed phase. Exercises at the end of each chapterare provided for further study and lead into applications not covered in the text itself. Treats fluidization as a branch of transport phenomena Demonstrates how to do transient, multidimensional simulation of multiphase processes The first book to apply kinetic theory to flow of particulates Is the only book to discuss numerical stability of multiphase equations and whether or not such equations are well-posed Explains the origin of bubbles and the concept of critical granular flow Presents clearly written exercises at the end of each chapter to facilitate understanding and further study

**Multiphase Fluid Dynamics** Halsted Press

This book provides concise, up-to-date and easy-to-follow information on certain aspects of an ever important research area: multiphase flow in porous media. This flow type is of great significance in many petroleum and environmental engineering problems, such as in secondary and tertiary oil recovery, subsurface remediation and CO2 sequestration. This book contains a collection of selected papers (all refereed) from a number of well-known experts on multiphase flow. The papers describe both recent and state-of-the-art modeling and experimental techniques for study of multiphase flow phenomena in porous media. Specifically, the book analyses three advanced topics: upscaling, pore-scale modeling, and dynamic effects in multiphase flow in porous media. This will be an invaluable reference for the development of new theories and computer-based modeling techniques for solving realistic multiphase flow problems. Part of this book has already been published in a journal. Audience This book will be of interest to academics, researchers and consultants working in the area of flow in porous media.

Multiphase Flow and Transport in the Subsurface Springer

This book offers a fundamental and practical introduction to the use of computational methods. A thorough discussion of practical aspects of the subject is presented in a consistent manner, and the level of treatment is rigorous without being unnecessarily abstract. Each chapter ends with bibliographic information and exercises.

Reactive Transport in Natural and Engineered Systems EOLSS Publications

The general formulation of a model is an important precondition for modeling multiphase flow and transport processes in subsurface hydrosystems. This book presents a consistent and easily accessible formulation of the fundamental phenomena and concepts, a uniform description of mathematical and numerical modeling, and latest developments in the field of simulation of multiphase processes, especially in porous and heterogeneous media. The author discusses in detail not only general aspects of the selection of relevant processes and corresponding parameters but also the mathematical and numerical modeling concepts.

Transport Phenomena in Multiphase Systems Birkhäuser

Recent advances in imaging technology and numerical modeling have greatly enhanced pore-scale investigations of multiphase flow and transport in porous media. It is now feasible to obtain high resolution 3-dimensional pore-scale data, and numerical methods such as the lattice- Boltzmann (LB) technique have been developed specifically for simulating such phenomena. Traditional macro-scale multiphase flow models rely heavily on empirical relationships. For example, the interaction between fluids at their interfaces is accounted for indirectly through the empirical relative permeability relationship. Nevertheless, it has recently been hypothesized that the single most important variable missing from current macro-scale models is the measure of interfacial dynamics between fluids within the pores. Furthermore, the empirical capillary pressure-saturation relationship used in macro-scale multiphase flow simulators has been shown to be a function of interfacial area per volume. This study focuses on (1) the measurement and modeling of the capillary pressure-saturation relationship; and (2) the characterization of the fluid-fluid interfacial area per volume as a function of saturation. The study synthesizes experimental results derived from pore-scale computerized micro-tomographic (CMT) images with LB simulations. An image analysis algorithm for quantifying fluid-fluid interfacial area per volume from experimental CMT and simulation images was developed and verified. The experimental results were shown to be in good agreement with values reported in the literature. Furthermore, the capillary ressure-saturation curves were used to validate a recently proposed macro-scale interfacial area model. New LB simulations of drainage and imbibition for an air-water system were developed, in which the full geometry from the experimental system was used to define the lattice. This allowed for the direct comparison of experimental and simulated phase distributions within the pores. LB simulations showed excellent agreement with experimental results, considering no optimization or calibration to the data was required. Collectively, results show that there is a complex functional relationship between capillary pressure, saturation and interfacial area that provides insights into multiphase flow and transport processes that can not be obtained from the capillary pressure-saturation relationship alone.

**From Pore to Core and Beyond**

Springer Science & Business Media

The research included in this volume focuses on using synergies between experimental and computational techniques to gain a better understanding of all classes of multiphase and complex flow. The included papers illustrate the close interaction between numerical modellers and researchers working to gradually resolve the many outstanding issues in our understanding of multiphase flow. Recently multiphase fluid dynamics have generated a great deal of attention, leading to many notable advances in experimental, analytical and numerical studies. Progress in numerical methods has permitted the solution of many practical problems, helping to improve our understanding of the physics involved. Multiphase flows are found in all areas of technology and the range of related problems of interest is vast, including astrophysics, biology, geophysics, atmospheric process, and many areas of engineering.

Upscaling Multiphase Flow in Porous Media Academic Press

Open system behavior is predicated on a fundamental relationship between the timescale over which mass is transported and the timescale over which it is chemically transformed. This relationship describes the basis for the multidisciplinary field of reactive transport (RT). In the 20 years since publication of Review in Mineralogy and Geochemistry volume 34: Reactive Transport in Porous Media, RT principles have expanded beyond early applications largely based in contaminant hydrology to become broadly utilized throughout the Earth Sciences. RT is now employed to address a wide variety of natural and engineered systems across diverse spatial and temporal scales, in tandem with advances in computational capability, quantitative imaging and reactive interface characterization techniques. The present volume reviews the diversity of reactive transport applications developed over the past 20 years, ranging from the understanding of basic processes at the nano- to micrometer scale to the prediction of Earth global cycling processes at the watershed scale. Key areas of RT development are highlighted to continue advancing our capabilities to predict mass and energy transfer in natural and engineered systems.

Computational Methods for Multiphase Flows in Porous Media Routledge

This is the first book that reviews problems in different fluid mechanics disciplines that led to the concept of

canopy, or penetrable roughness. Despite their diversity, many flows may be theoretically united by means of introducing distributed sinks and/or sources of momentum and heat and mass. These and other flows in engineering and environmental situations over surfaces with many obstacles are reviewed in terms of general concepts of fluid mechanics.
*Advances in Transport Processes* Springer
Learn the fundamental concepts that underlie the physics of multiphase flow and transport in porous media with the information in Essentials of Multiphase Flow in Porous Media, which demonstrates the mathematical-physical ways to express and address multiphase flow problems. Find a logical, step-by-step introduction to everything from the simple concepts to the advanced equations useful for addressing real-world problems like infiltration, groundwater contamination, and movement of non-aqueous phase liquids. Discover and apply the governing equations for application to these and other problems in light of the physics that influence system behavior.
**Transport Processes in Porous Media** Springer
This volume contains the invited lectures presented during the NATO/ASI conducted in Pullman, Washington, July 9-18, 1989. This is the third in a series of NATO/ASIs on transport phenomena in porous media. The first two, which took place at Newark, Delaware in 1982 and 1985, are devoted to various topics related to the Fundamentals of Transport Processes in Porous Media. The contents of the books resulting from previous NATO/ASIs are given at the end of this book. Transport of extensive quantities such as mass of a fluid phase, mass of chemical species carried by a fluid phase, energy and electric charge in porous media, as encountered in a large variety of engineering disciplines, is an emerging interdisciplinary field. The groundwater flow, the simultaneous flow of gas, oil and water in petroleum reservoirs, the movement and accumulation of pollutants in the saturated and unsaturated subsurface zones, thermal energy storage in reservoirs, land subsidence in response to charges in overburden loads, or to pumping of fluids from underground formations, wave propagation in seismic investigations or as produced by earthquakes, chemical reactors, water flow through sand filters and the movement of fluids through kidneys, may serve as examples of fields in which the theory of transport in porous media is employed.
**Transport Processes at Fluidic Interfaces** Elsevier
The 500-700 m thick Yucca Mountain unsaturated zone (UZ) is under extensive investigation as a subsurface repository for the permanent disposal of high-level nuclear wastes. The site characterization has been mostly carried out for analyzing unsaturated flow and radionuclide transport under ambient, isothermal conditions. However, significant research effort has also been devoted to understand the nature of flow and transport processes under non-isothermal conditions. In particular, substantial repository heating from radioactive waste decay has motivated investigations of the coupled thermo-hydrologic (TH) behavior of the UZ under repository heating and its potential impact on repository performance. Significant progress has been made in quantitative coupled TH studies in the last decade. Despite the significant

advances made so far in modeling and understanding TH processes, the previous studies have been in general limited to modeling in 1-D and 2-D (instead of the full 3-D representation), and/or small spatial and temporal scale analysis. In addition to these limited modeling exercises, multidimensional modeling has been carried out for large-scale (at the scale of the entire mountain) TH analyses. However, these previous large, mountain-scale TH models utilized the effective continuum model (ECM), rather than the more rigorous dual-continuum model (DKM). This is primarily due to numerical difficulties and computational burden involved with simulating highly non-linear coupled two-phase fluid flow and heat transfer in the fractured unsaturated rock with over one hundred thousand grid blocks (required for mountain-scale simulations). In general, 3-D, mountain-scale, DKM investigations of coupled TH processes in the fractured rock of Yucca Mountain is lacking in the literature. In parallel to the TH modeling studies, significant progress has also been made in site characterization of UZ flow and transport processes. For example, field and modeling studies conducted over the past few years have updated and enhanced our understanding, and revealed many new insights into how the UZ system works under the natural, ambient conditions. As a result, both geological and conceptual models have been updated by model calibration and verification efforts, and fracture-matrix properties and model parameters are better estimated. In addition, the repository design and drift layout plan, which are different from the ones used in previous modeling studies, are also revised. These advances in site characterization, data collection and parameter estimates motivate this work for updated TH modeling efforts. This paper presents the results of our latest effort to develop a representative 3-D, mountain-scale TH model to investigate the coupled TH processes for the repository under thermal load. More specifically, the TH model implements the current geological framework and hydrogeological UZ flow conceptual models, and incorporates the most updated, best-estimated input parameters from the 3-D model calibration (Wu et. al., 2003). Using the more rigorous DKM approach, the TH model consists of (1) a 2-D north-south cross section modeling studies with refined meshes near and around the repository block and (2) a full 3-D representation of the repository and UZ system, which explicitly includes every waste emplacement drift of the repository. For better description of the ambient geothermal condition of the UZ system, the TH model is first calibrated against measured borehole temperature data. The temperature calibration provides the needed surface and water table boundary and initial conditions for the TH model.

**Multiphase Fluid Dynamics** Springer Hydraulic Structure, Equipment and Water Data Acquisition Systems is a component of Encyclopedia of Water Sciences, Engineering and Technology Resources in the global Encyclopedia of Life Support Systems (EOLSS), which is an integrated compendium of twenty one Encyclopedias. Hydraulic structures occupied a vital role in the development of civilization from the earliest recorded history up to the present, and undoubtedly will do so in the future. Humanity in ancient times settled mostly near perennial rivers, nomadic people frequented oases and springs, and to augment these natural ephemeral supplies, established societies built primitive dams and dug wells. This 4-volume set contains several chapters, each of size 5000-30000 words, with perspectives, applications and extensive illustrations. It carries state-of-the-art knowledge in the fields of Hydraulic Structure, Equipment and Water Data Acquisition Systems. In these volumes the historical origins, modern developments, and future perspectives in the field of water supply engineering are discussed. Various types of hydraulic structures, their associated equipment, and the various systems for collecting data are described. These four volumes are aimed at the following five major target audiences: University and College Students Educators, Professional Practitioners, Research Personnel and Policy Analysts, Managers, and Decision Makers, NGOs and GOs.

**Computational Methods in Subsurface Flow** Springer Science & Business Media

This volume fills the need for a textbook presenting basic governing and constitutive equations, followed by several engineering problems on multiphase flow and transport that are not provided in current advanced texts, monographs, or handbooks. The unique emphasis of this book is on the sound formulation of the basic equations describing multiphase transport and how they can be used to design processes in selected industrially important fields. The clear underlying mathematical and physical bases of the interdisciplinary description of multiphase flow and transport are the main themes, along with advances in the kinetic theory for particle flow systems. The book may be used as an upper-level undergraduate or graduate textbook, as a reference by professionals in the design of processes that deal with a variety of multiphase systems, and by practitioners and experts in multiphase science in the area of computational fluid dynamics (CFD) at U.S. national laboratories, international universities, research laboratories and institutions, and in the chemical, pharmaceutical, and petroleum industries. Distinct from other books on multiphase flow, this volume shows clearly how the basic multiphase equations can be used in the design and scale-up of multiphase processes. The authors represent a combination of nearly two centuries of experience and innovative application of multiphase transport representing hundreds of publications and several books. This book serves to encapsulate the essence of their wisdom and insight, and:

**Multiphase Flow** Springer Science & Business Media

This paper describes a massively parallel simulation method and its application for modeling multiphase flow and multicomponent transport in porous and fractured reservoirs. The parallel-computing method has been implemented into the TOUGH2 code and its numerical performance is tested on a Cray T3E-900 and IBM SP. The efficiency and robustness of the parallel-computing algorithm are demonstrated by completing two simulations with more than one million gridblocks, using site-specific data obtained from a site-characterization study. The first application involves the development of a three-dimensional numerical model for flow in the unsaturated zone of Yucca Mountain, Nevada. The second application is the study of tracer/radionuclide transport through fracture-matrix rocks for the same site. The parallel-computing technique enhances modeling capabilities by achieving several-orders-of-magnitude speedup for large-scale and high resolution modeling studies. The resulting modeling results provide many new insights into flow and transport processes that could not be obtained from simulations using the single-CPU simulator.

*The Influence of Repository Thermal Load on Multiphase Flow and Heat Transfer in the Unsaturated Zone of Yucca Mountain* Springer Science & Business Media

Numerical simulation has become a widely practiced andaccepted technique for studying flow and transport processes in thevadose zone and other subsurface flow systems. This article discusses asuite of codes, developed primarily at Lawrence Berkeley NationalLaboratory (LBNL), with the capability to model multiphase flows withphase change. We summarize history and goals in the development of theTOUGH codes, and present the governing equations for multiphase, multicomponent flow. Special emphasis is given to space discretization bymeans of integral finite differences (IFD). Issues of code implementationand architecture are addressed, as well as code applications, maintenance, and future developments.

**Multiphase Flow in Porous Media**

Springer Science & Business Media

Hydrodynamics and Transport Processes of Inverse Bubbly Flow provides the science and fundamentals behind hydrodynamic characteristics, including flow regimes, gas entrainment, pressure drop, holdup and mixing characteristics, bubble size distribution, and the interfacial area of inverse bubble flow regimes. Special attention is given to mass and heat transfer. This book is an indispensable reference for researchers in academia and industry working in chemical and biochemical engineering. Hydrodynamics and Transport Processes of Inverse Bubbly Flow helps facilitate a better understanding of the phenomena of multiphase flow systems as used in chemical and biochemical industries. A first book in the market dedicated to the hydrodynamics of inverse bubbly flows Includes fundamentals of conventional and inverse bubble columns for different hydrodynamic parameters Includes recommendations for future applications of bubble flows

*Thermo-fluid Dynamics of Two-Phase Flow* John Wiley & Sons

There are several physico-chemical processes that determine the behavior of multiphase fluid systems – e.g., the fluid dynamics in the different phases and the dynamics of the interface(s), mass transport between the fluids, adsorption effects at the interface, and transport of surfactants on the interface – and result in heterogeneous interface properties. In general, these processes are strongly coupled and local properties of the interface play a crucial role. A thorough understanding of the behavior of such complex flow problems must be based on physically sound mathematical models, which especially account for the local processes at the interface. This book presents recent findings on the rigorous derivation and mathematical analysis of such models and on the development of numerical methods for direct numerical simulations. Validation results are based on specifically designed experiments using high-resolution experimental techniques. A special feature of this book is its focus on an interdisciplinary research approach combining Applied Analysis, Numerical Mathematics, Interface

Physics and Chemistry, as well as relevant research areas in the Engineering Sciences. The contributions originated from the joint interdisciplinary research projects in the DFG Priority Programme SPP 1506 “Transport Processes at Fluidic Interfaces.”

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