Flow in Porous Rocks

Energy and Environmental Applications

Driven by the increasing need for energy resources and by worsening environmental scenarios, techniques to exploit flows in porous rocks, such as fracking and CO_2 sequestration, are gaining international importance.

This book describes some of the challenges of modelling flow in natural rocks, which often have a complex, layered or heterogeneous structure, and whose properties are typically unknown in detail. Simplified physical models are introduced to help identify the challenges associated with the recovery of oil and gas from hydrocarbon reservoirs, the long-term geosequestration of CO_2, geothermal power production, and the processes which drive underground contaminant dispersal relevant for example in assessing the long-term storage of nuclear waste. The author approaches these problems by developing simplified mathematical models which help to identify the key dimensionless variables that control the processes. Analytical solutions for flows are provided where possible, and analogue laboratory experiments are presented to help illustrate and provide a different perspective on the flows.

Based on the author's extensive research and teaching experience, this book provides an important introduction to the different controls on flow in porous rocks, especially relevant to the energy industry. Incorporating end-of-chapter exercises, it is a key resource for academic researchers, energy industry professionals and graduate students.

Andrew W. Woods is the BP Professor and Head of the BP Institute in the University of Cambridge, and a Fellow of St Johns College, Cambridge. His research interests include theoretical and experimental modelling of flows in porous rocks, phase changes, turbulent plumes, volcanic systems and other natural flows in the environment and near surface of the Earth. Professor Woods has received several awards including the 1997 Italgas Prize for work on geothermal systems, the 1997 Marcello Carapezza Prize for work on volcanic systems, and the 2002 Wager Medal of the International Association of Volcanology and Chemistry of the Earth's Interior.

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Andrew W. Woods
University of Cambridge

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Preface

This book originated with a series of lectures related to the production of oil and gas from layered permeable rocks, which were focused on the challenge of the areal sweep of oil from injection to production wells, through complex, heterogeneous rock. Over the past few years, these lectures have been combined with some of my ongoing research into various fluid mechanical aspects of (i) power generation from geothermal systems through recovery of heat; (ii) scale formation in porous rocks; problems of (iii) carbon sequestration; and (iv) the dispersion of radioactive contaminants from geological nuclear waste repositories, to form a graduate-level course related to the fluid mechanics of energy systems in porous rocks.

The book explores the physical processes which influence oil and gas production, CO_2 sequestration and geothermal energy production. It draws together a series of simplified physical models of the many complex processes relating to flow in porous media to provide insight into the different phenomena, and where possible results from laboratory experiments are used to illustrate the processes, as well as quantitative scalings which identify the dominant controls on the flows and help build up insight into the processes.

After a brief discussion of the importance of oil and gas resources for global energy supply, this book reviews the topology of various porous rocks and presents simplified models for pressure-driven flow through a variety of complex rock architectures. It then briefly discusses how such models may help quantify the impact of the uncertainty in the rock properties and structure in making predictions. We then discuss the processes of dispersion and mixing in pressure driven flows, both produced by the pore-scale flow and larger scale flows around lenses or layers of low or high permeability. Saffman–Taylor instability is discussed and generalised to problems of reaction, temperature change and erosion of loose sand. After a discussion of two-phase flow, and the Buckley–Leverett shock formation process, there is a chapter discussing reactions in rocks, including both compositional and thermally driven reactions; these ideas are generalised to discuss the injection of polymers and their gelling within a porous rock as may be desirable to modify properties of a reservoir. The book then turns to buoyancy-driven flows and introduces gravity currents, including effects of capillary trapping and leakage relevant for CO_2 sequestration. We then discuss the role of buoyancy in promoting mixing and dispersion, especially with complex rock structure, relevant for enhanced oil recovery through gas injection or CO_2 sequestration. Water injection into hot rocks to recover geothermal energy is then discussed, and the phenomena of boiling for steam generation, as well as the water flooding patterns which may be produced when the buoyancy depends on temperature and composition, are presented and explored. Finally, we present some models of compressible flow, which provide insight into gas production from layered and low permeability gas/shale-gas fields.

There are many texts on flow in porous media, including the comprehensive treatise by Bear (1972), on modelling flow in porous media, the fascinating book on reactions and flow in porous media by Phillips (1991), the work of Dagan on dispersion in porous media and the book *Enhanced Oil Recovery* by Lake (1991). The objective of this book is to complement these earlier works, focusing on the physical processes, with simple laboratory models supported by simplified mathematical models. The work draws from the well-established modelling of pressure-driven flow in layered and heterogeneous porous rocks, including the resulting processes of dispersion, interfacial instability, and two-phase flow dynamics, to explore problems of buoyancy-driven flows in porous media and the dispersion of flows in complex layered strata. There is an underlying theme of energy related applications throughout the text.

I have been extremely fortunate to work with many colleagues and students whose quest for knowledge and application to their research has driven forward much of the work reported in this volume, largely during my time in the BP Institute in Cambridge. This includes in particular Silvana Cardoso, Adrian Farcas, Will Rayward-Smith, Jason Furtney, Peter Dudfield, Thierry Menand, Mats Nigam, Gennaro Del Ioio and Karen Otto, who has kindly assisted with figures in Chapters 5, 6 and 9. I am also very grateful to Colm Caulfield for carefully checking the contents, as well as to Gil Arnaud, Alex Evans and Adrian Farcas. In addition, I have been very fortunate to work with numerous colleagues from industry who have shared their challenges and experience of real energy systems in helping to frame many of the problems set out in this work, including in particular Pete Smith, Andy Leonard, Ian Collins, Tony Espie, Simon Norris and Bryan Lovell.

I am first and foremost indebted to my family for their generous encouragement, patience and support in the writing of this book, and also the research reported herein, especially my wife Sharon.