RESERVOIR ENGINEERING OF CONVENTIONAL AND UNCONVENTIONAL PETROLEUM RESOURCES

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Dedication

To the enduring memory of my parents, Vincent Nweke and Rosaline Oriaku, for their commitment, courage, and sacrifices they made toward my education and those of my brother and sisters. This book is truly a testament that the seed they planted and nurtured have borne bountiful fruit for all.

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Preface

This book was envisioned as a partial but important update of the original book, "Petroleum Reservoir Engineering Practice," published in 2010 by Prentice Hall. The vision was to add several chapters on analyses of unconventional reservoirs and a chapter on economic evaluation of petroleum projects to the original book. I think this book provides adequate coverage of both subjects which will enhance its value to engineers. A chapter was added on low salinity waterflooding as an important technology for improved oil recovery. Another important expansion of the book is the addition of problems at the end of each chapter to help readers test their understanding of the subject matter presented in the chapter. The addition of problems will also assist lecturers to assign homework from the book. Except in these four main areas, this book retains substantial portions of material covered in the original book although important changes in wording and presentation were made in this version.

Unconventional reservoirs have completely changed the landscape in American petroleum industry. United States of America (USA) is currently one of the largest oil producers in the world surpassing Saudi Arabia and Russia. This tremendous reversal in oil productivity trend is driven by revolution in the productivity of unconventional reservoirs in the USA. In Chapter 1, the differences between conventional and unconventional reservoirs are presented. Also, in this chapter, unconventional reservoirs were shown to hold the future of hydrocarbon supply in the USA and the rest of the world. The potential of unconventional resources are almost limitless as the technologies developed in the USA are applied to similar resources found around the world. Engineers pursuing a career in the petroleum industry are advised to develop knowledge and skills on the engineering of unconventional reservoirs.

In Chapters 2 to 7, the sources and applications of basic rock and fluid properties data that are fundamental for all petroleum reservoir engineering calculations are presented. Chapter 2 presents the sources and applications of porosity. Chapter 3 covers sources and applications of permeability and relative permeability. Chapter 4 discusses methods and models for determination of fluid saturations, and classification of reservoir rocks for volumetric calculations. These topics are presented at the introductory to intermediate levels. The main objective is to emphasize the importance of these sources of data as basic inputs for most reservoir engineering calculations. Chapter 5 was devoted to rigorous calculations of Pressure-Volume-Temperature (PVT) properties of reservoir fluids from correlations. In concert with Chapter 5, Chapter 6 presents routine reservoir fluid sampling methods, and laboratory measurements of PVT properties from reservoir fluid samples. In Chapter 7, the prediction of PVT properties from equations of state is presented. The application of equations of state in compositional simulation justified the presentation of this subject at the intermediate-to-advance levels for many engineers who are involved in compositional reservoir simulation work.

The fundamentals of petroleum reservoir engineering are treated from Chapters 8 to 10. The general material balance equation is developed from basic concepts in Chapter 8 and applied as a fundamental tool for basic reservoir engineering analysis. In Chapter 9, volumetric and graphical methods for calculation of gas-in-place for different types of gas reservoirs are discussed. This approach is extended to oil reservoirs in Chapter 10. The use of case histories to illustrate analytic methods for evaluation of performance of gas and oil reservoirs is demonstrated in Chapters 9 and 10.

Production forecasting for conventional and unconventional reservoirs is discussed in Chapter 11. This is based primarily on Arps' decline equations which have become the workhorse of the petroleum industry for production forecasting on conventional and unconventional reservoirs. The methodologies (decline curve analysis or DCA) for using Arps' equation for production forecasting on conventional reservoirs are applicable to unconventional reservoirs although rate transient analysis (RTA) techniques should be applied to account for production characteristics of unconventional reservoirs such as relatively long transient flow periods and influence of boundary dominated flows (BDF). The Stretched Exponential Decline Model (SEDM) and the Duong Model are presented in the chapter as two transient decline models which can be coupled with the modified Arps' decline equations to improve production forecasting for unconventional reservoirs. These applications are illustrated with examples.

Fluid flow in petroleum reservoirs is introduced in Chapter 12 with the derivation of the continuity equation and the radial diffusivity equation. In Chapter 12, the fundamental equations that form the bases for pressure transient analysis (PTA) by straightline methods are developed and applied later in Chapter 13. The use of type curves in well test analysis, especially Gringarten and Bourdet type curves, are presented in Chapter 14 with emphasis on procedures for type-curve matching. Well test analysis methods for hydraulically fractured wells and naturally fractured conventional reservoirs are presented in Chapter 15. Deconvolution concepts for well test analysis are covered in Chapter 16. This is followed with the presentation of well test analysis in unconventional reservoirs in Chapter 17 based mainly on diagnostic fracture injection tests (DFIT). Note that many characteristic behaviors of fracture flow are applicable to both conventional and unconventional reservoirs.

Basic concepts in immiscible fluid displacement are discussed in Chapter 18. These include derivations of the fractional flow equation, the Buckley-Leverett equation, and the Welge method. This is followed with the introduction of secondary recovery methods in Chapter 19 focused mainly on waterflooding and gasflooding.

Low salinity waterflooding is presented in Chapter 20 as an improved oil recovery method distinct from secondary recovery methods of Chapter 19 or enhanced oil recovery methods presented in Chapter 21. This definition of low salinity waterflooding is solely at the discretion of this author since it can be categorized as a secondary recovery method or an enhanced oil recovery method depending on any particular perspective. Either categorization is completely acceptable to the author.

Enhanced oil recovery methods are discussed in Chapter 21. In the chapter, special emphasis is placed on screening criteria and field implementation of enhanced oil recovery processes because many engineers should expect to be involved in such activities someday in their careers.

Chapters 18 to 21 are designed to introduce practicing engineers to fundamental methodologies for application of secondary, improved, and enhanced oil recovery processes, and also to develop practical procedures for field implementation of these processes.

Geologic modeling and reservoir characterization methods and procedures are presented in Chapter 22. This is followed with concepts in reservoir simulation in Chapter 23. In both chapters, the focus was on presenting methods and procedures for applying these tools on the practical aspects of building reservoir models rather than on theory.

The principles of reservoir management that I first enunciated in 2003 are presented in Chapter 24. These principles of reservoir management were developed from my experience from managing various types of reservoirs around the world. The principles are simple and practical and can be applied to any reservoir anywhere in the world. The application of the five principles of reservoir management are illustrated with case histories in Chapter 24.

Economic evaluation is key to the success of any petroleum project. Every project in the petroleum industry must be shown to be economic and profitable before it can be sanctioned and implemented. Chapter 25 presents fundamental criteria that can be used to judge the economic profitability of most projects. The chapter also discusses concepts, contracts, and economic models used in many petroleum operations involving host countries and international oil companies.

This book could not have been written without the support of my wife and children who endured long hours of my seclusion over many years to work on material for the book. I am very grateful for their patience and understanding. I give special thanks to my wife, Anulika, and my children (Nkemdirim, Chukwuemeka, Chioma, Ifeoma, Obinna, and Ezenwanyi). The odyssey of writing this book made my love for them much stronger.

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About the Author

Dr. Nnaemeka Ezekwe is a world renowned reservoir engineer who has practiced in all the major oil producing regions in Africa, Asia, Europe, Middle East, North America, and South America. This vast experience on various types of reservoirs was applied in crafting this book as a guide for practicing engineers or a textbook for college students. Dr. Ezekwe worked for sixteen years in key supervisory and managerial roles for Bechtel Petroleum Operations. In 1998, he joined Pennzoil Exploration and Production Company as a senior petroleum engineer advisor responsible for providing technical guidance on domestic projects in the Permian Basin and Gulf of Mexico, and also on international projects in the Caspian Sea, Egypt, Equatorial Guinea, and Venezuela. In 2000, as a senior reservoir engineer advisor at Devon Energy Corporation, he led pioneering analyses on the appraisal and development of several major Lower Tertiary deepwater reservoirs in the Gulf of Mexico. He also led appraisal and development of pre-salt reservoirs in the Campos and Santos Basins in Brazil, and deepwater reservoirs in Angola. Dr. Ezekwe is the author of *Petroleum Reservoir Engineering Practice*, a best-selling book on reservoir engineering published by Prentice Hall in 2010. In 2011, he joined BP America as EOR Deployment Manager responsible for implementation of low salinity waterflooding for improved oil recovery on all BP reservoirs worldwide. In 2015, he was contracted by Petrobras Oil & Gas B.V. as a reservoir engineer expert to provide technical guidance on appraisal and development of all petroleum assets in Africa including producing deepwater reservoirs in West Africa. In 2017, Dr. Ezekwe founded TIGA Petroleum, Inc., as a reservoir engineering consulting firm based in Houston, Texas. He holds BS, MS, and PhD degrees in chemical and petroleum engineering, and an MBA degree, all from the University of Kansas. He has published many technical papers in chemical and petroleum engineering journals. Dr. Ezekwe served twice as an SPE Distinguished Lecturer in 2004 and in 2012. In this role, he lectured on reservoir management strategies and intelligent well/field technologies in more than 100 countries around the world. He was elected SPE Distinguished Member in 2013. Dr. Ezekwe is a registered professional engineer in California and Texas, USA.