Petroleum Science and Technology

Recent Advances in Practical Applied Well Test Analysis

Freddy Humberto Escobar

PETROLEUM SCIENCE AND TECHNOLOGY

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RECENT ADVANCES IN PRACTICAL APPLIED WELL TEST ANALYSIS

This book is dedicated to…

God for being my Creator and for all the blessings I have received throughout my entire life, and also to the Most Holy Virgin Mary, Mother of God, who helps me follow Jesus, the only Son of God.

Dr. Djebbar Tiab for being my mentor, friend and professor. He created the TDS technique, which is the basis of this work.

My beautiful children, Jennifer Andrea, Freddy Alonso and Maria Gabriela, for being my pride and a great blessing from God to my life.

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I thank my wife and children for being my support.

FOREWORD

The publication of this book, *Recent Advances in Practical Applied Well Test Analysis* by Freddy Humberto Escobar, will be of great interest to reservoir engineers, reservoir characterization geologists, teachers and advanced students in these fields, and all others who are interested in well test design and analysis.

Having the opportunity to share with this passionate researcher the wealth of information he has acquired and developed during a long career devoted to a concentrated scholarly study and practical investigation of well test analysis is, indeed, a privilege for me.

This book aims at providing advanced applications for well testing under different well and reservoir geological boundaries and production conditions. Since the discovery of the pressure derivative by Tiab and Kumar in the middle 70s, no other significant advances have revolutionized the practical aspects of reservoir engineering and well testing as the pressure derivative did. Further creative developments by Dr. Tiab, the father of the pressure derivative, led to a more precise and simplified method of diagnostics in well testing, called Tiab's direct synthesis technique, or TDS. This technique provides a powerful tool in the interpretation of pressure data from well tests and confers a tremendous certainty in detecting the flow model and reservoir properties. In addition, the beauty of TDS is that it deepens the understanding of both pressure and rate-transient response and behavior of the analytical solutions. The interpretation of well tests using conventional techniques compares favorably with the TDS in the extensive examples used throughout the entire book. It validates and demonstrates the simplicity and creativity of TDS and provides a superior and simpler way to understand oil and gas reservoirs as well.

One of the interesting shifts the modern practice of well testing analysis has taken in the last decade is that it has become truly interdisciplinary. Reservoir engineers, geologists and geophysicists integrate together the results of pressure well test interpretation into building geological models. Throughout this book, there is a detailed discussion of analytical solutions for several conditions, followed by well test examples illustrating the data interpretation results and the benefits of the TDS technique.

The Escobar volume is a clear, practical, readable account, but, most importantly, it is adequately seasoned with multiple examples of well tests. Every single example in the book illustrates and shows how the TDS technique simplifies the interpretation of several complex combinations of geological setting and well flow condition: Well pressure data sets associated to heavy oil; sealing faults, conductive faults, and/or parallel faults; channels, fractured fractal porous media, etc., enrich the understanding of every chapter. A wealth of figures clarifies the text and is a mine of reference information. The author treats the topics in a logical and reasonable way, and a particularly strong point is the attention the book gives to the practical procedure of TDS and its valuable contribution to the modern interpretation of well pressure data.

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INTRODUCTION

Contrary to many fields in science, petroleum engineers neither design nor see the system with which they are working. Actually, it is through the well that petroleum engineers make contact with the reservoirs; using such indirect measurements as sound traveling, spontaneous potential, hydrogen content, formation and fluid resistivities, densities, pressure wave traveling, etc., petroleum engineers can obtain the desired reservoir parameters.

Well testing is a valuable and economical tool in the oil and gas industry. Thanks to the advances in mathematical modeling, measurement devices and computer capabilities, well testing remains a continuously growing subject. The information obtained from well testing is analyzed with the purpose of obtaining important reservoir information useful for hydrocarbon field management. The intricate mathematical models developed by numerous researchers during past and recent years attempt to show the benefit of mathematics in well test interpretation.

The conventional straight line method was the first tool introduced to interpret well pressure transient behavior. This is based on plotting either pressure or pressure drop (the reciprocal rate can be also used) against a function of time, which depends upon the given flow regime. Then, plots of pressure versus logarithm of time, square root of time or fourth root of time, among others, are meant to be applied for radial, linear and bilinear flow regimes, respectively. This method, however, has two major drawbacks: (1) the difficulty in defining flow regimes and (2) the inability to verify the obtained parameters. Type-curve matching was thus introduced to improve well test interpretation; however, it is both tedious and basically a trial-and-error procedure.

Nowadays, most petroleum engineers use computer software for modeling pressure test behavior. The softwares use either analytical or numerical models that automatically match the well test data by means of nonlinear regression analysis, which is subject of none uniqueness of the solution. The appropriate model selection and the initial input values are the key for a successful interpretation. Some other engineers misuse the software modeling, performing an inverse problem by using models randomly with the aim of matching the well test data to provide the output solution. This procedure is wrong since the engineer must choose the reservoir model.

It is the author's opinion that there have been three milestones that have revolutionized the science of well test interpretation: (1) the introduction of the pressure derivative function, which was first formally used by Tiab in 1976 and spread by Bourdet in the middle 80s; (2)

deconvolution, which allows going deeper in the reservoir; and (3) the *TDS* technique invented by Tiab in 1993.

This book revolves around the *TDS* technique. This revolutionary method is strongly based on the logarithm pressure derivative versus time log-log plot. It is applied to specific regions, features and flow regimes that can be easily identified in the pressure derivative curve so several analytical expressions are obtained for a practical, easy and exact way of conducting a well test interpretation. This tool is powerful and also allows verifying most of the estimated parameters. All the known commercial softwares include it without referring to it by its original name. Over several years of providing training to numerous engineers and companies in Latin America, the author has noticed that whoever knows and uses the *TDS* technique will end up taking it as their favorite interpretation method. Then, they take the outcomes from *TDS* to computer software to set the bounds for faster and less risky modeling.

The book contains the latest application of the *TDS* technique to several important reservoir/fluid scenarios. Several step-by-step examples are given for a better understanding of the interpretation methodology. The book is divided into 15 chapters distributed in three parts. The chapters are not expected to be read in chronological order. However, for beginners with the *TDS* technique or junior engineers, it is strongly recommended to read chapter 1, which deals with infinite, finite and elongated reservoir cases. When possible, conventional analysis is also included in the chapters. Chapter 2 contains a characterization of double-porosity reservoirs and the determination of the average reservoir pressure by the *TDS* technique. Chapter 3 continues working on naturally fractured reservoirs but for cases when the transition period does not fall in the radial flow regime but before fractured wells or after elongated systems. Chapter 4 is focused on the application of the TDS technique to double-permeability reservoirs. And chapters 5 and 6 deals with triple-porosity, single-permeability and triple-porosity, double-permeability reservoirs, respectively. Then, the first part of the book covers homogeneous and heterogeneous reservoirs.

Part 2 deals with non-Newtonian fluids in which heavy oil may fall and some enhanced oil recovery and stimulation projects. Chapter 7 studies infinite systems, and interpretation by conventional analysis is also included. This chapter includes spherical flow, which has a unique pressure derivative behavior, and hydraulically fractured vertical wells. Chapter 8 presents the pressure transient and interpretation of the injection of foams, gels or any non-Newtonian fluid in a well whose reservoir contains conventional Newtonian oil. Wrong interpretation may result from not handling such cases appropriately. The chapter includes the injection of either a dilatant or pseudoplastic power-law non-Newtonian fluids. Chapter 9 considers both bounded and constant-pressure reservoirs with the purpose of determining the well-drainage area. Only the *TDS* technique exists for such situations. Part 3 ends with chapter 10, which presents both the TDS technique and conventional analysis for naturally fractured reservoirs. Bingham fluids in vertical wells are also included in this chapter.

Part 3 is concerned with modern topics recently studied by the author. It starts with chapter 11, which deals with transient rate analysis in homogenous and heterogeneous finite and infinite oil and gas reservoirs. Hydraulically fractured wells producing under constant-pressure conditions and also treated there along with elongated gas reservoirs are also considered. Chapter 12 presents both the conventional analysis and the *TDS* technique for finite-conductivity faults with or without mobility contrast. Chapter 13 is dedicated to composite reservoirs resulting from steam injection, hot water injection or in situ combustion-enhanced oil recovery projects. Only the *TDS* technique is applied in such cases. Chapter 14 includes a characterization of the leakage factor in coalbed methane reservoirs and the spherical stabilization flow regime. Both *TDS* and conventional techniques are used in chapter 14. Finally, chapter 15 deals with the most popular subject in today's oil and gas industry: shale reservoirs. Only two models are considered in this chapter, and the conventional technique exists for only one of them.

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PART ONE: HOMOGENEOUS AND HETEROGENEOUS RESERVOIRS

Chapter 1

FUNDAMENTALS OF TRANSIENT PRESSURE ANALYSIS IN HOMOGENEOUS RESERVOIRS

INFINITE BEHAVIOR

Well testing fundamentals are originally based on a book on heat transfer written by Carslaw and Jaeger (1959), who provided the differential equation for heat flow in cylindrical and spherical polar coordinates. Since then, many researchers, starting with Matthews and Russell (1967), have used the famous line-source solution.

The one-dimensional radial flow partial differential equation in dimensionless for is then:

$$\frac{1}{r_D}\frac{\partial}{\partial r_D}\left(r_D\frac{\partial P_D}{\partial r_D}\right)=\frac{\partial P_D}{\partial t_D} \tag{1.1}$$

Where the dimensionless quantities in oil-field units are defined by:

$$t_D=\frac{0.0002637kt}{\phi\mu c_t r_w^2} \tag{1.2}$$

$$P_D=\frac{kh(P_i-P)}{141.2q\mu B} \tag{1.3}$$

$$r_D=\frac{r}{r_w} \tag{1.4}$$

Neglecting both skin factor and wellbore storage effects, the line-source solution of Equation (1) for the constant-rate production well inside an infinite reservoir. is given by:

$$P_D(r_D,t_D) = -\frac{1}{2}\int_x^{\infty}\frac{e^{-x}}{x}dx \tag{1.5}$$

being x:

$$x = -\frac{r_D^2}{4t_D} = -\frac{948\phi\mu c_t r^2}{kt} \tag{1.6}$$

The integral expression provided in Equation (5) is better known as the exponential integral. Then, Equation (5) becomes:

$$P_D(r_D,t_D) = -\frac{1}{2}Ei\left(-\frac{r_D^2}{4t_D}\right) \tag{1.7}$$

Normally, at very short production times ($x \leq 0.0025$) the Ei(-x) can be taken as *ln* (1.781x) at the wellbore, and considering the skin effects, Equation (1.7) can be approximated as:

$$P_D + s = -\frac{1}{2}\ln(1.781x) \tag{1.8}$$

After substituting into Equation (8) the definition of dimensionless pressure given by Equation (3) and Equation (6), it yields:

$$P_{wf} = P_i - \frac{162.6q\mu B}{kh}\left[\log\left(\frac{kt}{\phi\mu c_t r_w^2}\right) - 3.2275 + 0.8686s\right] \tag{1.9}$$

The above expression suggests a semilog plot of flowing pressure versus time will provide a linear behavior during radial flow regime whose slope, m, and intercept, $P1hr$, allow obtaining:

$$T = \frac{kh}{\mu} = \left|\frac{162.6qB}{m}\right| \tag{1.10}$$

$$s = 1.1513\left[\frac{P_{1hr} - P_i}{m} - \log\left(\frac{k}{\phi\mu c_t r_w^2}\right) + 3.2275\right] \tag{1.11}$$

CLOSED-BOUNDARY SYSTEMS

Jones (1956) introduced the reservoir limit test. If the external infinite-boundary condition is changed to a closed-boundary condition, $\partial_{PD}/\partial_{rD} \mid r_e = 0$, then the late time pseudosteady-state solution is obtained (Ramey and Cobb 1971):

$$P_D = 2\pi t_{DA} + \frac{1}{2}\ln\left(\frac{A}{r_w^2}\right) + \frac{1}{2}\ln\left(\frac{2.5458}{C_A}\right) \tag{1.12}$$

From this, once the dimensionless quantities are replaced above, the Cartesian slope, m^*, and intercept, P_{INT},, during the late pseudosteady-state period are defined as:

$$m^* = -\frac{0.23395qB}{\phi c_t Ah} \tag{1.13}$$

$$P_{INT} = P_i - \frac{70.6q\mu B}{kh}\left[\ln\frac{A}{r_w^2} + \ln\left(\frac{2.2458}{C_A}\right) + 2s\right] \tag{1.14}$$

Solving the Dietz shape factor, C_A, from Equation (1.14) yields:

$$C_A = 5.456\frac{m}{m^*}e^{2.303\frac{P1hr - p_{INT}}{m}} \tag{1.15}$$

The above expression implies the reservoir drainage area can be estimated from the slope and the shape factor from the intercept of a Cartesian plot of pressure versus time during the late pseudosteady-state period.

The former expressions apply only to drawdown tests; for pressure buildup tests, time superposition applies, as do with Equations (1.3) and (1.8), leading to:

$$P_{ws} = P_i - \frac{162.6q\mu B}{kh}\log\left(\frac{t_p + \Delta t}{\Delta t}\right) \tag{1.16}$$

where the slope is similar to Equation (1.10). The skin factor is calculated from:

$$s = 1.1513\left[\frac{P_{1hr} - P_{wf}}{m} - \log\left(\frac{k}{\phi \mu c_t r_w^2}\right) + 3.2275\right] \tag{1.17}$$

$$s = 1.1513\left[\frac{P_{1hr} - P_{wf}}{m} + \log\left(1 + \frac{1}{t_p}\right) - \log\left(\frac{k}{\phi\mu c_t r_w^2}\right) + 3.2275\right]; \text{if } t_p < 1hr \tag{1.18}$$