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Edited by

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About the author

Hedong Sun, PhD, SPE member, born in 1973, is a senior engineer, and earned his PhD degree from Xi'an Jiaotong University in 2004. Since 2004, he has been a Research Engineer in Research Institute of Petroleum Exploration and Development (RIPED)-Langfang Branch, which is the R&D center of China National Petroleum Corporation (CNPC). Hedong has over 18 years of reservoir engineering experience in well test analysis and production analysis. He has been one of the academic leaders of reservoir engineering of RIPED-Langfang Branch since 2008. In 2013, he was appointed as a technical expert of Well Testing Analysis and Productivity Evaluation in RIPED-Langfang Branch. He is the reviewer for five journals, including ACTA Petrolei Sinica and Well testing etc. He has published over 40 papers in peer-reviewed journals and SPE conferences. He has published two books – entitled *Modern Well Test Analysis and Deliverability Analysis of Complex Gas Reservoir* (2012) and *Advanced Production Decline Analysis and Application* (2013).

Preface

Over the past 20 years, advanced production decline analysis (APDA) evolved fast with the improvement of wellhead pressure (WHP) measurement and flow metering techniques. Today, it has become a well-established technique. In field applications, APDA is essential and beneficial for performance monitoring, and plays a major role in the fine description of reservoirs and the analysis of field development. In the past decade, the APDA-based production analysis software has been widely applied in various oil and gas fields. Unfortunately, this technique and its theory have never been systematically and thoroughly formulated in any existing work. The publication of the book entitled "Advanced Production Decline Analysis and Application" will break the situation.

This book considers the advanced production decline analysis by way of manual matching for a vertical well centered in a closed circular reservoir. Based on the APDA concepts, several production decline methods, such as Arps, Fetkovich, Blasingame, Agarwal-Gardner, Normalized Pressure Integral (NPI), Transient, Long-term Linear Flow and Dynamic Material Balance, are discussed thoroughly, including their principles, processes, cases, and application. The plotting and analysis of APDA curves are introduced in detail for complex reservoir, such as closed circular composite reservoir, two-layered reservoir, and dual-porosity reservoir. In the appendix, the theoretical curves of Blasingame method and the calculation procedure for normalized pseudo-pressure of gas well are presented, in order that the readers can understand how the type curves are plotted and what the "black box" of analysis software contains. Accordingly, this book is a relatively complete and systematic work concerning advanced production decline analysis for oil and gas wells.

This book integrates the author's achievements and experience in his long-term research, so it is meaningful both theoretically and practically. Its publication will be helpful to the promotion and application of APDA, thereby further identifying the performance variation of oil and gas fields and enhancing the field development. Besides, it will have positive and significant effects on the development of reservoir engineering personnel.

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Introduction

Advanced production decline analysis (APDA), or production analysis or rate transient analysis, has become a hotspot in reservoir engineering in recent years. Based on transient filtration theory, the technique can provide novel typical curves by way of reservoir engineering and modern well test analysis. It is also used to analyze the daily production data and quantify the reservoir parameters, percolation characteristics and OOIP (OGIP) with type curve matching method.

APDA involves four kinds of methods, including (1) empirical method, e.g., Arps; (2) classical analysis method, e.g., Fetkovich; (3) log-log type curve matching analysis, e.g., Blasingame; and (4) reservoir engineering method, e.g., FMB. This technique, together with Lifecycle Modern Well Test Analysis, has become one of the main methods for dynamic reservoir description, and APDA-based analysis software has been widely used in oil and gas fields. However, to the best of our knowledge, there is no book that provides a systematic introduction on this technique.

Under this background, this book entitled *Advanced Production Decline Analysis and Application* is launched. It is compiled with reference to the previous research results, and in combination with the author's experience in dynamic reservoir description. This book keeps a foothold by carrying out advanced production decline analysis manually. As Professor Nengqiang Liu noted, a famous well test expert of CNPC logging, the modern well test interpretation process is basically the recapitulation of manual operation on the computer, so the operator must learn manual operation first, which will provide great help for thoroughly understanding the programs, instructions, and procedures and providing the best interpretation using computer software freely. The same is true for the APDA technique.

This book presents the APDA technique to the reservoir engineering professionals, serving as a modest spur to induce them to effectively learn the overseas advanced technologies and improve the reservoir production analysis. In view of the basic concept of APDA, this book thoroughly and systematically elaborates the basic principles, analysis process and cases of APDA methods, including Arps, Fetkovich, Blasingame, Agarwal–Gardner, NPI, Transient, Long-term Linear Flow and FMB methods, when they are used in a vertical well in closed circular reservoir. Combining with the field cases, this book also explains the integrated application of APDA process in the practical production. Besides, the plotting and analysis of APDA curves with Blasingame method are briefly introduced for complex reservoir, such as radial composite reservoir and two-layered reservoir. Online downloadable computer programs such as Arps, Fetkovich, Blasingame method and the calculation programs for normalized pseudo-pressure of gas well are available, so that the readers can understand how the type curves are plotted or the pertinent APDA models and theoretical curves are derived and plotted based on this book. (Details provided in http://booksite.elsevier.com/9780128024119/ or http://team.agoil.cn/sunhedong/.)

The completion of the manuscript requires the help of a large number of people. I hereby express my heart-felt gratitude to my postgraduate supervisor, Professor Chengtai Gao of Xi'an Shiyou University, doctoral supervisor, Professor Fangde Zhou of Xi'an Jiaotong University, as well as postdoctoral supervisor, Yuewu Liu, research fellow of Institute of Mechanics, CAS. It is their guidance that attracted me to the road of scientific research and encouraged me to make achievements in reservoir engineering. I am also grateful to Professor Xiaodong Wang of China University of Geosciences, as well as Professor Junbin Chen and Jia'en Lin of Xi'an Shiyou University, for their assistance during the compilation of this book. I also owe my sincere thanks to Professor Tongwen Jiang, Zhongqian Zhu, and Wenqing Pan of PetroChina Tarim Oilfield Company; project directors as Chunshu Luo, Ying Shi, Xiangjiao Xiao, Xingliang Deng, and Jianping Yang; as well as Jiwu Fan, director of Sulige Research Center, PCOC; Bin Wang, director of Research Institute of Exploration and Development, PetroChina Xinjiang Oilfield Company; Hu Sun and Jianting Duan of CCDC Changqing Downhole Technology Company; Lianchao Jia of PCOC No. 2 Gas Recovery Plant, etc., for their assistance and help in the project. My gratitude then goes to Doctor Weiyang Wang, Mingliang Luo, Huijuan Chen of China University of Petroleum (Huadong), who provided substantial help for literature delivery. I'm also indebted to Professor Xizhe Li and Jianjun Chen of Institute of Petroleum Exploration and Development (RIPED)-Langfang Branch; Jialiang Lu, Daojiang Long, Yujin Wan, and Yongxin Han of Gas Development Institute. Their guidance and encouragement propelled me to successfully complete the task. Thanks also go to Wen Cao and Xifei Yang, etc. for their assistance and help during the editing, proofreading, and publishing of this book.

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Due to the limited level of knowledge and experience, the author could not avoid inappropriate statements in this book. Your comments and criticism are thereby warmly welcomed.

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Hedong Sun

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Fundamentals of Advanced Production Decline Analysis

1

Advanced production decline analysis (APDA), or rate transient analysis or production analysis, is a procedure to process and interpret the daily production data of wells for obtaining parameters of such wells or reservoirs. This chapter introduces the history of APDA based on filtration theory, its similarities to and differences with well test analysis. In addition, this chapter also introduces several concepts related to the APDA.

1.1 History of Advanced Production Decline Analysis (APDA)

At the middle and later stages of reservoir development, daily production data of a well becomes the focus for reservoir analysis. They can be used to forecast the most probable well life, evaluate well production in the future, and determine the interwell communication relation and infill potential. Currently, the production decline analysis technique consists of the conventional Arps (1945) method, classical Fetkovich (1980) type curve matching method, modern Palacio and Blasingame (1993) and Agarwal et al. (1998) type curve matching methods and FMB (1998) reservoir engineering method.

Extrapolating the characteristic trend of some variables of a well can be helpful for our jobs. As to a well, the simplest and the most easily available variable is its production. If the flow rate versus time or cumulative production curve is plotted and extrapolated, the ultimate cumulative production can be obtained. The trend or mathematical relations indicated by the entire rate history of a well can be used to forecast the production performance in the future, which is referred to as the conventional Arps (1945) decline curve analysis method. This method magnificently describes the production decline laws of well at a constant bottom hole flowing pressure (BHFP) and in the completely boundary-dominated flow period. The greatest advantage of this method is that formation parameters are not necessarily obtained. On the other hand, it is not suitable for data analysis from the transient flow stage.

A variety of interpretations may occur for the data of one well or one reservoir, mostly resulting from the experiences of appraisers or the difference of appraisal targets. Just as pointed out by Ramsay (1968), "Some new papers contributing to the decline curve analysis were published in 1964-1968, but there was hardly any new technique." Slider (1968) developed a matching method applicable to the production-time data, which is similar to the log–log type curve matching method in well test analysis and uncovers a new direction for decline curve analysis. Because this method was quick and easy, Ramsay extensively used it to determine the distribution of decline exponent b in the appraisal of more than 200 wells. Gentry (1972) plotted three Arps decline curves on one chart to match the decline data of wells, where the dimensionless time was defined the same as with the Fetkovich (1980) method, and the dimensionless production was the reciprocal of relevant variables in Fetkovich method.

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Arps type curve can only be used to analyze the data of a boundary-dominated flow period. Fetkovich (1980), on the basis of homogeneous bounded formation transient filtration theory, introduced the transient flow formula in well test analysis to the decline analysis, so that the Arps type curve is extended to the transient flow period prior to boundary-dominated flow, and the transient rate decline curve and the Arps rate decline equation are organically combined. In this way, the production decline laws and the effect of boundary are intuitively shown, and a set of relatively complete log–log production decline curve matching analysis method similar to well test analysis is developed. The greatest advantage of the method is its ability to reliably determine whether the production is in a transient flow period or in a boundary-dominated flow period.

Both Arps and Fetkovich methods assume that the BHFP is constant to analyze the production data without considering the change of gas pressure–volume–temperature (PVT) charateristics with pressure. Palacio and Blasingame (1993) introduced the pseudo-pressure normalized production ($q/\Delta p_p$) and the material balance pseudo-time t_{ca} to develop the type curve, which considered the production at variable BHFP and the gas PVT changing with formation pressure.

Agarwal et al. (1998) used the relations of pseudo-pressure normalized production ($q/\Delta p_p$), material balance pseudo-time t_{ca}, and dimensionless parameters in well test analysis to develop the Agarwal-Gardner production decline analysis. Owing to the different definitions of dimensionless quantity, the early part of the curve is more discrete than the Blasingame chart and thus is in favor of reducing the ambiguity of matching analysis.

Both Blasingame and Agarwal-Gardner methods used the pseudo-pressure normalized production ($q/\Delta p_p$) and the material balance pseudo-time t_{ca} to create type curve, while the NPI (normalized pressure integral) method (Blasingame et al., 1989) used the production normalized pressure integral to analyze the data available, which was not affected by the scatter of data.

Palacio and Blasingame (1993) and Agarwal et al. (1998) type curve matching analysis methods introduced pseudo-time (or material balance pseudo-time) and production normalized pseudo-pressure (pseudo-pressure normalized production) to deal with variable BHFP, variable rate, and change of gas PVT with pressure. They used the flow rate integral, flow rate integral derivative, cumulative production–time, and flow rate–cumulative production type curves as the auxiliary matching analysis curves to reduce the ambiguity of interpretation results.

Her-Yuan and Teufel (2000) developed the method on the basis of Fetkovich's findings, and presented the linear flow characteristic curve usually occurring in low-permeability tight gas reservoir. Wattenbarger and El-Banbi (1998) and his students combined the linear flow model and the curve matching analysis method in well test analysis to present the analysis method for long-term linear flow production data of gas well in low-permeability tight gas reservoirs. Pratikno et al. (2003) developed the type curve and analysis method of a vertical fractúre well. Yong-Xin Han (2006) also made helpful research on the long-term linear flow of low-permeability fracture wells.

Mattar et al. (1998, 2006) and Agarwal et al. (1998) suggested using the "flow (dynamic) material balance" method to analyze the production data, and conducted detailed discussion on the calculation of material balance time. This method is simple and easy. Mattar and Anderson (2003) believes that there is no one universal production data analysis method that can meet all types of reservoirs, and the best way to eliminate analysis errors is to synthetically use all analysis methods and consider flowing pressure data.

Over nearly a century, the APDA technique has evolved with several advances, including target to be analyzed, that is, from purely production data to both flow rate and pressure data; analytic model, that is, from no model to both analytical model and numerical model; analytic method, that is, from the empirical Arps method to the log-log method represented by Blasingame; applicable conditions, that is, from simple constant pressure production data to variable pressure and variable rate data; and the estimation parameters, that is, from only cumulative production to many parameters such as formation permeability, skin factor, dynamic reserves and drainage area, as well as interwell communication and infill potential.

1.2 Similarities and Differences between Production Decline Analysis and Well Test Analysis

As to dynamic reservoir description, APDA and well test analysis are combined to appraise the reservoir where the well is located, with the high precision pressure data acquired from transient well test and the dynamic data like pressure and flow rate obtained in production test and actual production, and based on understandings obtained from static geologic data. The parameters to be appraised include reservoir permeability, skin factor, dynamic reserves, drainage radius, fault sealing, and advancing range of edge water. As two major techniques for dynamic reservoir description, the APDA and the well test analysis have both specific and common features. They should be well combined and constrained with each other, so as to minimize the uncertainties of parameters interpretation. The similarities and differences between them are shown in Table 1.1.

Both of them are based on the classical filtration theory, by using the curve-matching method to get parameters and applying numerical solution method by means of building models for cases like complicated boundary, multiphase flow, and multiwell interference. However, they are different with respect to the precision of appraisal data adopted in the workflow; that is, production decline analysis can be conducted using only the flow rate and pressure data calculated for each day, while well test analysis is conducted using the high precision transient pressure test data. The data source of different quality decides the reliability of appraisal results. That is, the production decline analysis technique adopts daily test flow rate and pressure data, which are of a great quantity but low precision, especially the BHFP data that are mostly converted from the WHP, thereby leading to some errors. In contrast, the well test analysis technique adopts transient pressure test data, which are available in great quantities and have high precision.

1.3 Basic Concepts

1.3.1 Wellbore Storage Effect

As the wellbore has the ability to store fluid and flow or shut in operation is carried out at wellhead, the changes in wellhead flow rate and bottom hole sandface rate are different,