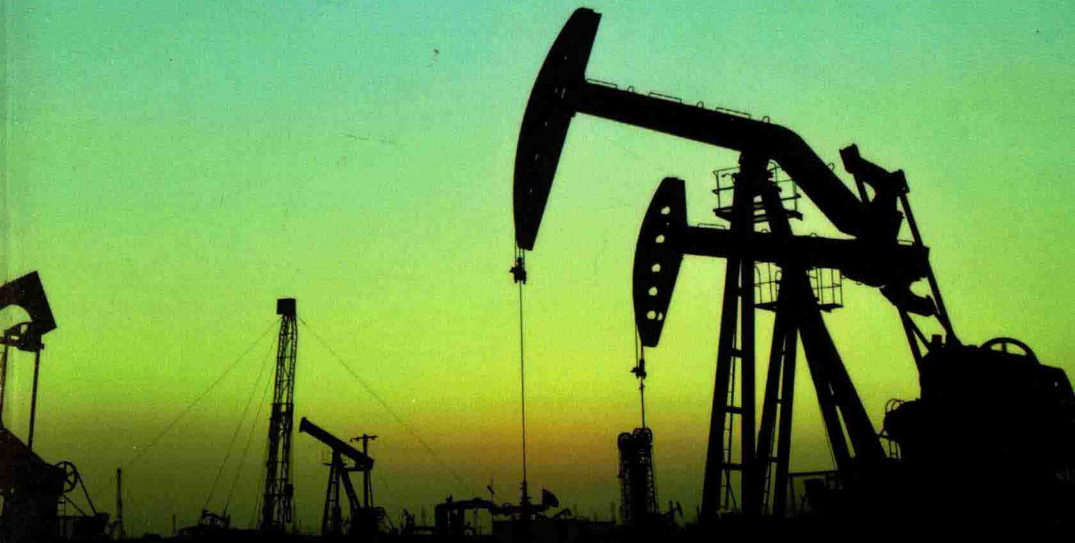




石油工业出版社
PETROLEUM INDUSTRY PRESS



Advanced Production Decline Analysis and Application

Hedong Sun



Advanced Production Decline Analysis and Application

Edited by

Hedong Sun



ELSEVIER



石油工业出版社

PETROLEUM INDUSTRY PRESS

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Gulf Professional Publishing is an Imprint of Elsevier



Gulf Professional Publishing is an imprint of Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

Copyright © 2015 Petroleum Industry Press. Published by Elsevier Inc. All rights reserved.

Note: Chinese language rights retained by the Proprietor.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-802411-9

For information on all Gulf Professional Publishing publications
visit our website at <http://store.elsevier.com/>

Typeset by Thomson Digital



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

Advanced Production Decline Analysis and Application

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.

Academicians of Chinese Academy of Engineering
Dakuang Han

中国工程院院士



2013年7月31日

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 Shiyu 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 Shiyu 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.

The work of this book was supported in part by China Postdoctoral Science Foundation (No. 2011M500403), China Postdoctoral Science Foundation – the fifth special (No. 2012T50140), and Youth Innovation Fund of Research Institute of Petroleum Exploration and Development (RIPED) (No. 2009A1715).

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.

Thank you to the Elsevier staff who worked on the book, most notably Nicky Carter and Simon Tian.

December 2, 2014

Hedong Sun

Contents

About the author	xi
Preface	xiii
Introduction	xv
1 Fundamentals of Advanced Production Decline Analysis	1
1.1 History of Advanced Production Decline Analysis (APDA)	1
1.2 Similarities and Differences between Production Decline Analysis and Well Test Analysis	3
1.3 Basic Concepts	3
1.3.1 Wellbore Storage Effect	3
1.3.2 Skin Effect	5
1.3.3 Apparent Wellbore Radius	6
1.3.4 Infinite Formation Line-Source Solution	7
1.3.5 Steady State, Pseudo-Steady State, and Boundary-Dominated Flows	8
1.3.6 Investigation Radius	12
1.3.7 Dimensionless Variables	12
1.3.8 Shape Factor and Pseudo-Steady State Arrival Time	15
1.3.9 Superposition Principle	17
1.3.10 Pseudo-Pressure, Pseudo-Time	19
1.3.11 Material Balance Time	21
1.3.12 Flow Regime Identification	22
1.3.13 Type Curve Matching Principle	22
1.3.14 Recoverable Reserves	26
1.3.15 Dynamic Reserve	27
2 Arps Decline Curves Analysis	31
2.1 Arps Equations	31
2.1.1 Exponential Decline	31
2.1.2 Hyperbolic Decline	33
2.1.3 Harmonic Decline	35
2.1.4 Comparison of Three Decline Types	37
2.1.5 Modified Hyperbolic Decline	38
2.1.6 Fluid in Place and Drainage Area	42
2.2 Theoretical Fundamentals of Arps Production Decline	42
2.2.1 Flow Rate Equation of Waterdrive Reservoir	42
2.2.2 Exponential Decline Equation of Waterdrive Reservoir	43

2.2.3	Hyperbolic Decline Equation of Waterdrive Reservoir	44
2.2.4	Harmonic Decline Equation of Water Drive Reservoir	46
2.2.5	Decline Equation of Bounded Elastic Drive—Constant Pressure Production	46
2.2.6	Decline Equation of Multilayer Oil Well—Constant Pressure Production	48
2.2.7	Decline Equation of Gas Well in Volumetric Gas Reservoir—Constant Pressure Production	48
2.3	Arps Type Curves	49
2.3.1	Gentry–Arps Type Curve	50
2.3.2	Arps Dimensionless Decline Flow Rate Type Curve	52
2.3.3	Arps Dimensionless Decline Cumulative Production Curve	52
2.3.4	Arps Dimensionless Decline Flow Rate Integral Type Curve	54
2.3.5	Arps Dimensionless Decline Flow Rate Integral Derivative Type Curve	56
2.3.6	Arps Type Curve	58
2.4	Power Function Analysis	59
2.4.1	IIK Method	59
2.4.2	Mattar Method	60
2.5	Case Analysis of Arps Method	61
2.5.1	Identification of Decline Law	61
2.5.2	Arps Exponential Decline Analysis	63
2.5.3	Arps Harmonic Decline Analysis	64
2.5.4	Result Correlation and Analysis	65
3	Fetkovich Decline Curves Analysis	67
3.1	Solution for a Well in a Closed Circular Reservoir: Constant Pressure Production	67
3.2	Fetkovich Decline Curve Plotting	70
3.2.1	Fetkovich Dimensionless Variables	70
3.2.2	Fetkovich Dimensionless Decline Rate and Decline Cumulative Production Type Curves	73
3.2.3	Fetkovich–Arps Dimensionless Decline Rate and Decline Cumulative Production Type Curves	76
3.2.4	Fetkovich–Arps Dimensionless Decline Rate Integral Type Curves	78
3.2.5	Fetkovich–Arps Dimensionless Decline Rate Integral Derivative Type Curves	81
3.3	Decline Curve Analysis Using Fetkovich-Style Type Curves	83
3.3.1	Conventional Decline Curve Analysis	83
3.3.2	Normalized Decline Curve Analysis	86
3.3.3	The Multiplicity of Fetkovich–Arps Decline Curve Analysis	90
3.4	Example of Fetkovich–Arps Method	91

4	Blasingame Decline Curves Analysis	95
4.1	Pressure Distribution in a Closed Circular Reservoir: Constant Rate Production	95
4.2	Blasingame Type Curve Plotting	101
4.2.1	Material Balance Time of Oil Well	101
4.2.2	Material Balance Time of Gas Well	104
4.2.3	Material Balance Time Curve	107
4.2.4	Blasingame Dimensionless Decline Flow Rate Curve	108
4.2.5	Blasingame Normalized Dimensionless Decline Flow Rate Integral Curves	111
4.2.6	Blasingame Normalized Dimensionless Decline Flow Rate Integral Derivative Curve	112
4.2.7	Blasingame Type Curves	112
4.3	Decline Curves Analysis Using Blasingame-Style Type Curves	114
4.3.1	Type Curves Matching Procedure—Oil Well	114
4.3.2	Type Curves Matching Procedure—Gas Well	116
4.4	Case Study of Blasingame Decline Curves Analysis	118
5	Agarwal–Gardner Decline Curves Analysis	125
5.1	Agarwal–Gardner Type Curves Plotting	125
5.1.1	Agarwal–Gardner Dimensionless Flow Rate	125
5.1.2	Agarwal–Gardner Dimensionless Flow Rate Curves	126
5.1.3	Agarwal–Gardner Dimensionless Inverse Normalized Pressure Derivative Curves	128
5.1.4	Agarwal–Gardner Dimensionless Inverse Normalized Pressure Integral Derivative Curves	128
5.1.5	Agarwal–Gardner Decline Curve	130
5.2	Decline Curves Analysis Using Agarwal–Gardner Style Type Curves	130
5.2.1	Type Curves Matching Procedure—Oil Well	130
5.2.2	Type Curves Matching Procedure—Gas Well	133
5.3	Case Study of Agarwal–Gardner Decline Curves Analysis	135
6	NPI Decline Curves Analysis	141
6.1	NPI Decline Curve Plotting	141
6.1.1	NPI Dimensionless Variables	141
6.1.2	NPI Dimensionless Pressure Curves	142
6.1.3	NPI Dimensionless Pressure Integral Curves	143
6.1.4	NPI Dimensionless Pressure Integral Derivative Curves	143
6.1.5	NPI Decline Curves	144
6.2	Decline Curves Analysis Using NPI Style Type Curves	145
6.2.1	Type Curves Matching Procedure—Oil Well	145
6.2.2	Type Curves Matching Procedure—Gas Well	147
6.3	Case Study of NPI Decline Curves Analysis	148

7	Transient Decline Curves Analysis	155
7.1	Transient Decline Curve Plotting	155
7.1.1	Pressure Distribution in a Closed Circular Reservoir: Constant Rate Production	155
7.1.2	Dimensionless Decline Flow Rate Curves	156
7.1.3	Dimensionless Decline Inverse Pressure Integral Curves	156
7.1.4	Dimensionless Decline Inverse Pressure Integral Derivative Curves	157
7.1.5	Transient Decline Curves	158
7.2	Decline Curves Analysis Using Transient Style Type Curves	159
7.2.1	Type Curves Matching Procedure—Oil Well	159
7.2.2	Type Curves Matching Procedure—Gas Well	160
7.3	Case Study of Transient Decline Curves Analysis	163
8	Decline Curves Analysis of Long Linear Flow	169
8.1	Vertically Fractured Well at the Center of a Rectangular Homogeneous Reservoir	169
8.1.1	Pressure Distribution of Vertically Fractured Well in a Rectangular Reservoir: Constant Rate Production	169
8.1.2	Wattenbarger Type Curves	172
8.1.3	Wattenbarger Type Curves Matching Procedure—Oil Well	173
8.1.4	Wattenbarger Type Curves Matching Procedure—Gas Well	174
8.1.5	Case Study of Wattenbarger Decline Curves Analysis	176
8.2	Vertically Fractured Well at the Centre of a Rectangular Dual-Porosity Reservoir	181
8.2.1	Physical Model	181
8.2.2	Linear Pseudo-Steady Mathematical Model	182
8.2.3	Linear Transient Mathematical Model	183
8.2.4	Laplace Space Solutions	184
8.2.5	Curve Characteristics of El-Banbi	188
8.3	Vertically Fractured Well at the Centre of a Closed Circular Reservoir	189
8.3.1	Type Curve Plotting	189
8.3.2	Type Curves Matching Procedure	190
8.3.3	Case Study	193
9	Dynamic Material Balance Method	197
9.1	Mattar Method	197
9.1.1	Flow Material Balance Method (Constant Rate)	197
9.1.2	Dynamic Material Balance Method (Variable Rate)	199
9.2	Agarwal-Gardner Method	201
9.2.1	Agarwal-Gardner Method for Oil Well	201
9.2.2	Agarwal-Gardner Method for Gas Well	201

10	Decline Curves Analysis of Horizontal Well	203
10.1	Constant-Rate Solution of Horizontal Well in Rectangular Closed Homogeneous Reservoir	203
10.2	Blasingame Type Curves Plotting	204
10.2.1	Horizontal Well Shape Factor of Finite Conductivity	204
10.2.2	Blasingame Type Curve Plotting	206
10.3	Decline Curves Analysis Using Blasingame-Style Type Curves	208
10.3.1	Type Curves Matching Procedure—Oil Well	208
10.3.2	Type Curves Matching Procedure—Gas Well	209
10.4	Case Study of Blasingame Decline Curves Analysis	211
11	Decline Curves of Complex Reservoir	221
11.1	Decline Curve of Radial Composite Reservoir	221
11.1.1	Pressure Distribution in a Radial Composite Reservoir: Constant Rate Production	221
11.1.2	Blasingame Type Curve Plotting	226
11.1.3	Blasingame Type Curve Characteristics	226
11.2	Decline Curve of Two-Layered Reservoir	228
11.2.1	Pressure Distribution in a Closed Circular Two-Layered Commingled Reservoir with a Constant Rate Production	228
11.2.2	Blasingame Type Curve Plotting	231
11.2.3	Blasingame Type Curve Characteristics	232
11.2.4	Pressure Distribution in a Two-Layered Reservoir with Crossflow with Constant Rate Production	234
11.3	Decline Curve of Dual-Porosity Reservoir	234
11.3.1	Pressure Distribution in a Dual-Porosity Reservoir: Constant Rate Production	234
11.3.2	Blasingame Type Curve Plotting	237
11.3.3	Blasingame Type Curve Characteristics	238
11.4	Decline Curve of Triple-Porosity Reservoir	238
11.4.1	Physical Model of Triple-Porosity Reservoir	238
11.4.2	Blasingame Decline Curves of Triporosity Monopermeability Model	241
11.4.3	Blasingame Decline Curves of Triporosity Monopermeability Nesting Model	245
11.4.4	Blasingame Decline Curves of Triporosity Dual-Permeability Model	247
11.4.5	Blasingame Decline Curves of a Tricontinuum Model	254
11.5	Considerations in Plotting Advanced Production Decline Type Curves	256
11.5.1	Typical Errors in Plotting Blasingame Type Curves	257
11.5.2	Analysis on Causes of Wrongly Plotting Blasingame Type Curves	260
11.5.3	Blasingame Type Curve Plotting	260

12	Methodology and Cases for Decline Curve Analysis	263
12.1	Methodology of APDA	263
12.1.1	Data Preparation	263
12.1.2	Data Diagnoses	263
12.1.3	Model Diagnoses	264
12.1.4	Methodology of Decline Curve Analysis	266
12.2	Example of Gas Well	266
12.2.1	Basic Parameters	266
12.2.2	Decline Curves Analysis	267
12.3	Example of Oil Well	269
12.3.1	Basic Parameters	269
12.3.2	Decline Curves Analysis	269
12.4	Example for Integrating APDA and WTA	271
12.4.1	Adaptability Analysis of Classical Computational Method	272
12.4.2	Dynamic Reserves Estimate from Dynamic Description Method	274
12.5	Application of APDA Method in Oil and Gas Reservoir Engineering	283
12.5.1	Water Breakthrough Forewarning Analysis	283
12.5.2	Multitank Reservoir Dynamic Reserve Evaluation	285
12.5.3	Dynamic Reserve Analysis of Connected Well Group	287
12.5.4	Producing Pressure Drop Estimation	289
Appendix 1	Nomenclature (with China Statutory Units CSU)	291
Appendix 2	Commonly Used Units in Different Unit Systems	301
Appendix 3	Unit Conversions from China Statutory Unit to Other Unit Systems	303
Appendix 4	Formulae Commonly Used in Main Text (with China Statutory Units CSU)	307
Appendix 5	Late Time Solution for a Well in a Two-Region Composite Reservoir with Closed Circular Boundary	313
Appendix 6	Late Time Solution for a Well in a Two-Layer Commingled Reservoir with Closed Circular Boundary	319
	References	323
	Index	329

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.

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) characteristics 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 fracture 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,