HORIZONTAL WELL TECHNOLOGY

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PREFACE

The major purpose of writing this book is to summarize the state-of-the-art of horizontal well technology. Recent advances in drilling and completion have resulted in a rapid increase in the number of horizontal wells drilled each year around the world. A horizontal well, to some extent, is different from a vertical well because it requires an interdisciplinary interaction between various professionals, such as geologists, reservoir engineers, drilling engineers, production engineers, and completion engineers. Because of the large volume of literature that is available in different disciplines, I have decided to divide this book into two parts. The first part (Volume 1), is presented here. This first volume mainly deals with reservoir and production engineering.

In this book, I have included published literature available as of June 1990. Additionally, I have included example problems to illustrate the use of various theoretical solutions. Wherever possible, I have not only discussed practical difficulties that one may encounter while using theoretical solutions, but I have also listed some of the methods that one can use to obtain the desired information. I have included descriptions on field histories wherever they were available. The available field histories that I have chosen not only represent successes of horizontal well technology but also include some economic failures.

To some extent, writing this book was difficult because of the interdisciplinary nature of horizontal well technology. The book is mainly directed to the practicing professionals who make engineering calculations and decisions on horizontal well applications. This book can also be used as a graduate level textbook. For managers, the book helps to review the present state of the art. I have also outlined some of the gaps in technology that exist today. These gaps in technology will be useful for research engineers and research professionals to determine the areas of future research.

Many solutions which are presented are based upon my personal experiences dealing with various vertical well and horizontal well field projects around the world. I am thankful to the many companies with whom I had the opportunity to work on the field projects. I am also thankful to all the people who have suffered through my teaching of horizontal well classes.

Our class discussions and their suggestions were very valuable in making this book useful to a practicing engineer.

Chapter 1 of this book is an overview of horizontal well technology and is a general introduction to the technology from a reservoir, drilling, and completion standpoint.

Chapter 2 mainly looks at the reservoir engineering concepts and their application for horizontal wells. The chapter also includes a discussion on well spacing of horizontal wells.

Chapter 3 includes steady state solutions and their applications. It also includes discussions on formation damage problems in horizontal wells. In addition to horizontal wells, it also contains a discussion of slant wells. There are cases where slant wells may be more beneficial than horizontal wells.

Chapter 4 deals with the influence of well eccentricity on productivity of a horizontal well. Well eccentricity represents a vertical distance between the horizontal well location and the center of the pay zone. Though influence of the well eccentricity on productivity of a well is minimal, it will have a strong influence on the ultimate reserves for a horizontal well drilled in reservoirs with top gas or bottom water.

Chapter 5 compares horizontal and fractured vertical wells. This chapter discusses practical aspects of hydraulic fracturing of a vertical well, its advantages, and the limitations. The chapter also includes reasons for stimulating horizontal wells and calculation of productivities for fractured horizontal wells.

Chapter 6 focuses on transient well testing. In general, transient well testing is a highly mathematical subject. At the same time, it is one of the most important and useful subjects to understand the well behavior in a given reservoir. To make the chapter complete, I have included all the necessary mathematics and many concepts which are essential to interpret the behavior of a horizontal well.

Chapter 7 deals with pseudo-steady state solutions. In this chapter, I have listed various solutions for vertical wells, fractured vertical wells, and horizontal wells. I have also included available solutions for the partially perforated or partially open horizontal wells. The chapter also describes the performance of horizontal wells completed in solution gas drive reservoirs.

Chapter 8 examines water and gas coning in vertical and horizontal wells. It outlines many of the available solutions for calculating water and gas coning behavior in horizontal and vertical wells. It also contains discussion of available field histories. The histories not only show successes but also the failure of horizontal wells in minimizing water and gas coning. The chapter also outlines benefits and risks associated with production testing of vertical wells to estimate the potential of horizontal wells.

Chapter 9 looks at the application of horizontal wells in gas reservoirs. In my opinion, horizontal wells are highly suitable for low permeability as well as high permeability gas reservoirs.

Chapter 10 deals with the pressure drop through a horizontal well and how important it is in the estimation of horizontal well performance.

To make the book complete, I have included *Appendix A* which refers to fluid properties. *Appendix B* includes data on gas compressibility. *Appendix C* contains various conversion factors. (I have included Appendix C because the book is written in U.S. field units, and Appendix C will be helpful to convert the examples to different field units.) *Appendix D* includes a discussion about various pseudo-skin factors and their definitions. *Appendix E* consists of tables of recovery factors that one can expect from various types of reservoirs and under different types of drive mechanisms. *Appendix F* is a glossary of the terms that are used in this book. I believe this glossary will be useful for people who are not familiar with reservoir and production engineering terminology.

To the readers, I would very much be interested in any comments, suggestions, or questions you may have about the contents of the book. Please feel free to contact me directly:

Sadanand D. Joshi, Ph.D.
Joshi Technologies International, Inc.
5801 E. 41st St., Suite 603
Tulsa, OK 74135
(918) 665-6419

I consider myself to be a student of this technology. After writing this book, reading many published papers and working on various field projects, I realized more than ever that there are many more things which I need to learn before I will ever know all the answers.

Tulsa, Oklahoma
Sept. 6, 1990

CHAPTER 1

Overview of Horizontal Well Technology

INTRODUCTION

In the last few years, many horizontal wells have been drilled around the world.[1–27] The major purpose of a horizontal well is to enhance reservoir contact and thereby enhance well productivity. As an injection well, a long horizontal well provides a large contact area, and therefore enhances well injectivity, which is highly desirable for enhanced oil recovery (EOR) applications.

In general, a horizontal well is drilled parallel to the reservoir bedding plane. Strictly speaking, a vertical well is a well which intersects the reservoir bedding plane at 90°. In other words, a vertical well is drilled perpendicular to the bedding plane (see Fig. 1–1). If the reservoir bedding plane is vertical, then a conventional vertical well will be drilled parallel to the bedding plane and in the theoretical sense it would be a *horizontal well*. As shown in Figure 1–2, even in the reservoirs with vertical bedding plane, it is still possible to

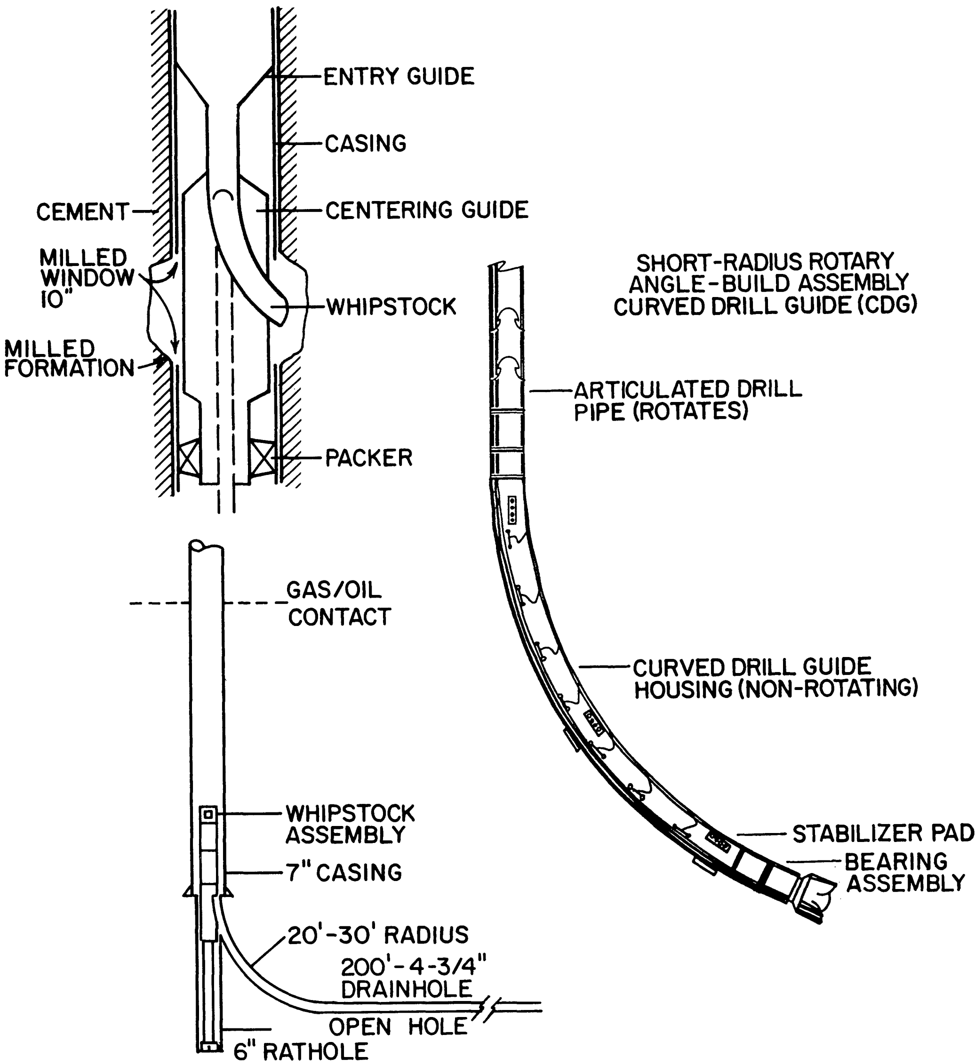

Figure 1–6 A Schematic of a Short-Radius Drilling Technique Using Flexible Drill Collar Joints (Eastman Christensen).

tion can be drilled through a vertical well with a minimum diameter of $4\frac{7}{8}$ in. As described later, these wells can be completed as an open hole or with slotted liners. Additionally, using this new technique, it is possible to drill about 1000-ft-long wells.

3. *Medium:* Turning radius is 300 to 800 ft; build angle is 6° to 20°/100 ft. This is becoming a predominant method to drill horizontal wells. Because

TABLE 2–2 SUMMARY OF FLOW EQUATIONS

	STEADY STATE	SEMI-STEADY STATE*
General relationship between p and r	$p - p_{wf} = \frac{q\mu}{2\pi kh} \ln \frac{r}{r_w}$	$p - p_{wf} = \frac{q\mu}{2\pi kh} \left(\ln \frac{r}{r_w} - \frac{r^2}{2r_e^2} \right)$
Inflow equations expressed in terms of $p = p_e$ at $r = r_e$	$p_e - p_{wf} = \frac{q\mu}{2\pi kh} \ln \frac{r_e}{r_w}$	$p_e - p_{wf} = \frac{q\mu}{2\pi kh} \left(\ln \frac{r_e}{r_w} - \frac{1}{2} \right)$
Inflow equations expressed in terms of the average pressure	$\bar{p} - p_{wf} = \frac{q\mu}{2\pi kh} \left(\ln \frac{r_e}{r_w} - \frac{1}{2} \right)$	$\bar{p} - p_{wf} = \frac{q\mu}{2\pi kh} \left(\ln \frac{r_e}{r_w} - \frac{3}{4} \right)$

* Wells located centrally in drainage plane

To express in field units (stb/d, psi, mD, ft) the term $q\mu/(2\pi kh)$ should be replaced by $141.2q\mu B_o/(kh)$, in each of the above equations.

As an alternative, the skin factor can be accounted for in the inflow equation by changing the wellbore radius. For example, including the skin factor

$$\bar{p} - p_{wf} = \frac{q\mu}{2\pi kh} \left[\ln \left(\frac{r_e}{r'_w} \right) - \frac{3}{4} \right]$$

in which

$$r'_w = r_w e^{-s}$$

a) damaged well, $s > 0$
b) stimulated well, $s < 0$

2. **Van der Vlis et al. Method (Equations 3–39 and 3–40)**

$$
\begin{aligned}
L &= h/\cos(\alpha) = 600/\cos(30°) = 693 \text{ ft} \\
r'_w &= (L/4)[0.454 \sin(360° \, r_w/h)]^{h/L} \\
&= (693/4)[0.454 \sin(360° \times 0.35/600)]^{600/693} \\
&= 0.68 \text{ ft} \\
s_s &= -\ln(0.68/0.35) = -0.66 \\
J_s/J_v &= \ln(912/0.35)/\ln(912/0.68) = 1.09
\end{aligned}
$$

As shown below, the calculated results using these two methods are in good agreement with each other. Therefore, either equation could be used for predicting productivity improvements.

COMPARISON OF CINCO ET AL. AND VAN DER VLIS ET AL. METHODS

		Cinco et al.		Van der Vlis et al.	
α (deg)	***L*, ft**	s_s	J_s/J_v	r'_w **ft**	J_s/J_v
30	693	−0.91	1.14	0.68	1.09
45	849	−2.03	1.35	2.31	1.32
60	1200	−3.59	1.84	12.24	1.82
70	1754	−4.88	2.64	49.14	2.69

COMPARISON OF SLANT WELL AND HORIZONTAL WELL PRODUCTIVITIES

As noted earlier, horizontal wells are effective in thin reservoirs, while slant wells are highly effective in thick reservoirs. Therefore, one would like to find the optimum completion for a given reservoir thickness. One of the ways to do this is to assume a drilled well having a fixed length. This fixed drilled length could be either vertical, horizontal, or slant. Then one can compare productivities of horizontal, vertical, and slant wells with each other to determine the optimum completion method.

Figure 3–8 shows a typical comparison of slant wells and horizontal wells with vertical wells for a 100-ft-thick reservoir. The figure shows that a horizontal well will always do significantly better than any slant well in a 100-ft-thick reservoir, even for the small values of the permeability ratio, k_v/k_h. This clearly indicates that horizontal wells are preferred options in 100-ft-thick reservoirs.