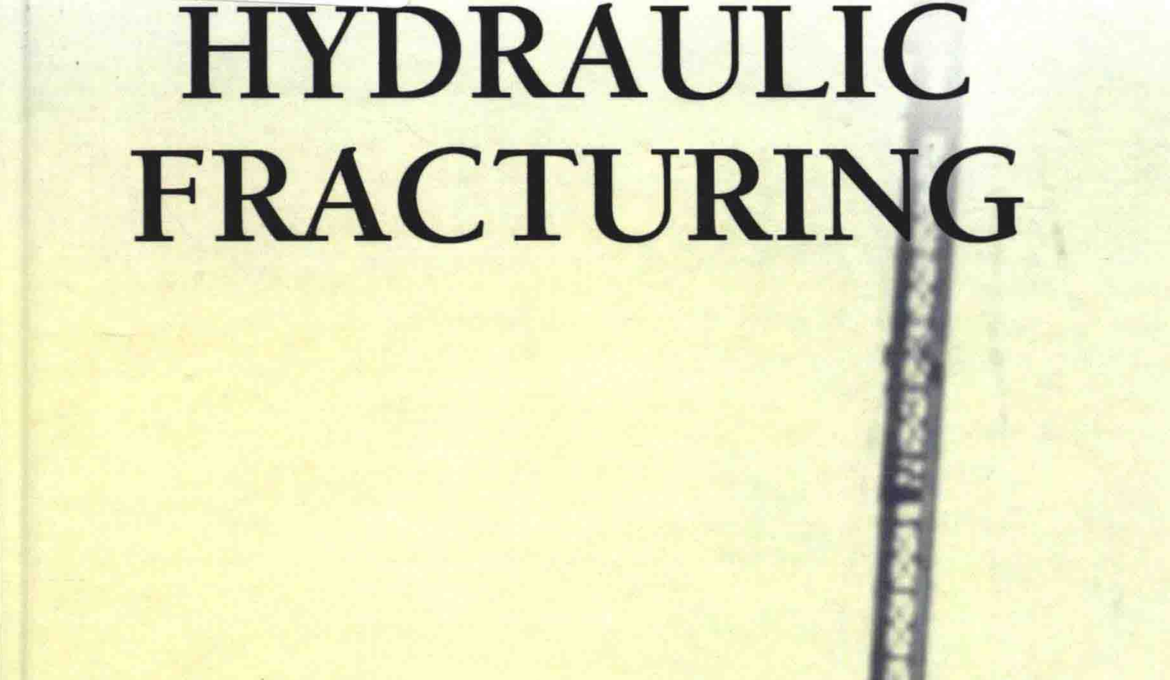
HYDRAULIC FRACTURING



Michael Berry Smith
Carl T. Montgomery

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Michael Berry Smith
Carl T. Montgomery

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HYDRAULIC FRACTURING

Emerging Trends and Technologies in Petroleum Engineering

Series Editor
Abhijit Y. Dandekar

PUBLISHED TITLES:

Hydraulic Fracturing, *Michael Berry Smith and Carl T. Montgomery*

Wax Deposition: Experimental Characterizations, Theoretical Modeling, and Field Practices, *Zhenyu Huang, Sheng Zheng, H. Scott Fogler*

This book is dedicated to all the pioneers that developed the concepts and physics that we use daily to design and execute hydraulic fracturing treatments. Many of these pioneers have been identified in the "Legends of Hydraulic Fracturing" program and include

Claude E. Cook, Jr.
Robert R. Hannah
Ronald P. Nordgren
Francis E. Dollarhide
Larry J. Harrington
Tomas K. Perkins
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Mike Prats
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Series Preface

This book series on petroleum engineering includes works on all aspects of petroleum science and engineering, but with special focus on emerging trends and technologies that pertain to the paradigm shift in the petroleum engineering field. It deals with the increased exploitation of technically challenged and atypical hydrocarbon resources that are receiving a lot of attention from today's petroleum industry, as well as the potential use of advanced nontraditional or nonconventional technologies such as nanotechnology in diverse petroleum engineering applications. These areas have assumed a position of prominence in today's petroleum engineering field. However, although scientific literature exists on these emerging areas in the form of various publications, much of it is scattered and highly specific. The purpose of this book series is to provide a centralized and comprehensive collection of reference books and textbooks covering fundamentals but paying close attention to these emerging trends and technologies from the standpoint of the main disciplines of drilling engineering, production engineering, and reservoir engineering.

Given the dwindling supply of easy-to-produce conventional oil, rapidly climbing energy demands, the sustained ~$100 billion oil price, and technological advances, the petroleum industry is increasingly in pursuit of E&P of atypical or unconventional and technically challenged oil and gas resources, which may eventually become the future of the petroleum industry. Unconventional resources typically include (1) coal bed methane, or CBM, gas; (2) tight sands gas in ultralow permeability formations; (3) shale gas and shale oil in very low permeability shales; (4) oil shales; (5) heavy and viscous oils; (6) tar sands; and (7) methane hydrates. Compared to the world's proven conventional natural gas reserves of 6600+ trillion cubic feet (TCF), the combined CBM, shale gas, tight sands gas, and methane hydrate resource estimates are in excess of 730,000 TCF.[1–3] Similarly, out of the world's total 9 to 13 trillion barrels of oil resources, the conventional (light and medium oil) is only 30%, whereas heavy oil, extra heavy oil, tar sands, and bitumen combined make up the remaining 70%.[4] In addition, shale-based oil resources worldwide are estimated to be between 6 and 8 trillion barrels.[5] As a case in point, shale-based oil production in North Dakota has increased from a mere 3000 barrels/day in 2005 to a whopping 400,000+ barrels/day in 2011.[6] Even the most conservative technical and economic recovery estimates of the unconventional resources represent a very substantial future energy portfolio that dwarfs the conventional gas and oil reserves. However, to a large extent these particular resources, unlike the conventional ones, do not fit the typical profile and are to some extent in the stages of infancy, thus needing a different and unique approach from the drilling, production, and reservoir engineering perspective.

The petroleum engineering academic and industry communities also are aggressively pursuing nanotechnology with the hope of identifying innovative solutions for problems faced in the overall process of oil and gas recovery. In particular, a big spurt in this area in the last decade or so is evident from the significant activities in terms of research publications, meetings, formation of different consortia, workshops, and dedicated sessions in petroleum engineering conferences. A simple literature search for the keyword *nanotechnology* on http://www.onepetro.org, managed by the Society of Petroleum Engineers (SPE), returns over 250 publications dating from 2001 onward, with the bulk of them in the last five or six years. Since 2008, SPE also organized three different applied technology workshops specifically focused on nanotechnology in the E&P industry. An Advanced Energy Consortium (AEC) with sponsorships from some major operators and service companies was also formed in 2007 with the mission of facilitating research in "micro and nanotechnology materials and sensors having the potential to create a positive and disruptive change in the recovery of petroleum and gas from new and existing reservoirs." Companies such as Saudi Aramco have taken the lead in taking the first strides in evaluating the potential of employing nanotechnology in the E&P industry. Their trademarked Resbots™ are designed for deployment with the injection fluids for in situ reservoir sensing (temperature, pressure, and fluid type) and intervention, which will eventually lead to more accurate reservoir characterization once fully developed. Following successful laboratory core flood tests, they conducted the industry's first field trial of reservoir nanoagents.[7]

The foregoing is clearly a statement of the new wave in the petroleum engineering field that is being created by emerging trends in unconventional resources and new technologies. The publisher and its series editor are fully aware of the rapidly evolving nature of these key areas and their long-lasting influence on the current state and future of the petroleum industry. The series is envisioned to have a very broad scope that includes but is not limited to analytical, experimental, and numerical studies and methods and field cases, thus delivering readers in both academia and industry an authoritative information source of trends and technologies that have shaped and will continue to impact the petroleum industry.

Abhijit Dandekar
University of Alaska Fairbanks
Fairbanks, Alaska

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Preface

Hydraulic fracturing is one of the most important and enduring technologies ever developed by the oil industry. Hydraulic fracturing is today the primary means of increasing and maintaining well productivity. The combination of horizontal wells and hydraulic fracturing has greatly expanded the ability of producers to profitably recover natural gas and oil from low-permeability geologic plays—particularly shale. If one enters the term "hydraulic fracturing" into the OnePetro search engine, the results will show more than 14,000 papers that have the term in the title. There have been several books written on the subject, but most of these focus on the physics of the process and not how one actually designs a treatment. This book is intended to try and condense this huge amount of information into something that the practicing engineer can use. At times, it appears that hydraulic fracturing as a technology is a victim of its own success; "It works!" so well that the fact that it could work much better is lost. Unlike drilling technology that has seen huge improvements over the last decade, fracturing technology still resides in the arena of technologies that were, for the most part, developed in the 1950s and 1960s. There are many companies out there that still think that getting all the vast inventory of trucks, equipment, water, etc., to one location and then to the next location is "fracture optimization." That is a very important part of the fracturing process, but it is "logistics optimization" and has nothing to do with optimizing the fracture. The whole design process should be focused around matching the fracture design to the needs of the reservoir. If the engineer can just remember that fracture "conductivity" to maximize productivity at the minimum cost is the goal, they will improve the productivity and profitability of their well sometimes in a spectacular manner. This book is designed to lead the fracturing engineer through the process of maximizing the wells' productivity, and if the reader will follow the ideas and processes outlined in the book, there will certainly be additional success. To aid in the learning process, there are several design problems including a description of the well, a design spreadsheet, and a solution to each of the designs using a simple 2D fracturing model at the URL specified in the preface. Chapter 18 solves one of these problems by coupling the appropriate equation with the solution using the techniques described in the book.

When Taylor & Francis Group originally called us to write this book, we did not think it would be much work. We already had a manual in place that had been written over the years that included what, we thought, would be the major portion of the book. Little did we know that bringing the information up to date and providing working examples of the concepts and workflow required a tremendous amount of work and dedication. We missed two deadlines and the book is now about two years overdue, but it is done (we hope). There will certainly be errors and omissions that you, the reader, will find and we certainly want to hear from you about those, but we have done what we can to remove these. There are several people that have been a tremendous help to us along this most difficult path. We thank Ali Jalili and Claudia Craig for helping us with the formatting and getting all the copyright clearances and manuscript reviews. We also thank Terry Palisch from Carbo Ceramics, Brian Olman from KELRIC, LLC, Mickey Roth from Halliburton, Dr. Neal Nagel from Oilfield Geomechanics, and David Norman, Mark Anderson, and Dr. Ken Nolte all from NSI for writing the sidebars seen throughout the book. Thanks also to Dr. Prue Smith for reviewing and commenting on the problems outlined in Chapters 18 and 20.

Additional material is available from the CRC Press website: http://www.crcpress.com/product/isbn/9781466566859.

Chapter Abstracts

Chapter 1: History, Introduction, and How a Treatment Is Conducted

Hydraulic fracturing is one of the most important and enduring technologies ever developed by the oil industry. In the decades since its introduction in the late 1940s, the role of this technology in improving production and increasing recoverable reserves is probably second only to rotary drilling. Hydraulic fracturing is today the primary means of increasing and maintaining well productivity. With the 65th anniversary of hydraulic fracturing just recently behind us, this chapter is intended to give a brief history of the technology, an introduction into its use, and a summary of what equipment is used and how a treatment is performed at the surface.

Chapter 2: Definitions and Simple Geometry Models

This chapter outlines the basic parameters and theory used to build a simple fracture geometry model. It includes simple 2D and P3D fracture geometry models and the assumptions and limitation of these models. This includes discussions of material balance, modulus, elasticity, fluid flow, K_{Ic} (rock toughness or the resistance to fracture propagation), fluid loss, and net pressure. The chapter discusses where these values come from, what they mean, and what their impact is on the design.

Chapter 3: Fracture Design Variables

This chapter discusses the many parameters that go into analyzing fracturing pressure data or the fracture design processes. Like most engineering processes, most of these play only a marginal role and are only of critical importance in a few, select situations. Other variables play a major role in most situations. The purpose of the chapter is to discuss the six "major" fracture variables:

- Height (H_F, usually controlled by differences of in situ stress between formation layers)
- Modulus (*E*, "stiffness" of the rocks)
- Fluid loss (*C*, related to formation permeability and the filter cake characteristics of the fracturing fluid)
- K_{Ic}, apparent fracture toughness (which governs the pressure required to propagate the fracture)
- Fluid viscosity (μ, which affects the net pressure in the fracture, fluid loss, and proppant transport)
- Pump rate (*Q*, which affects nearly everything)

Chapter 4: Rock Stresses

This chapter discusses building a rock stress log, what assumptions are made, and how to minimize uncertainty. Pore pressure and calculations on how to determine effective in situ stress are included. How everything in fracturing flows from in situ stress, how/why this must be calibrated, and examples of stress test methods are included, but not detailed discussions of such testing.

Chapter 5: Petrophysics

By default, much or most of the information needed for treatment design must come from well logs. This results from the facts that it is impossible to measure design parameters such as stress or modulus on a foot-by-foot basis, added to the fact that it is impractical to gather direct data for the design variables on each well. Thus, it is critical to understand what well logs can tell us and, equally important, what they cannot tell us. As a general rule, however, all well logs absolutely require calibration. This is true for basic reservoir property logs such as porosity/resistivity, and it is particularly true for fracture design parameters. This chapter discusses what we are not measuring with a log and what we need to know. During the logging process, we are always measuring something else and using that to infer what it is we actually want.

Chapter 6: Predicting/Evaluating Pre- and Post-Frac Performance

There are many variables that ultimately affect the economic success of a well. These include formation thickness (i.e., net pay height, *h*), porosity, and water saturation; and most of these formation properties can be measured with varying degrees of accuracy using open hole logs, core correlations, etc. All of these properties affect the "gas in place" and thus may control the decision as to whether a given formation is worth fracturing. This chapter discusses which parameters directly impact the actual treatment design.

Chapter 7: Type of Designs and Building a Pump Schedule

Determining the treatment or job schedule is the last step in a stimulation design. Treatment scheduling consists of selecting a pad volume, a slurry volume to follow the pad, and a proppant addition schedule specifying the proppant concentrations to be used. The treatment schedule and the required proppant concentrations needed to create a desired final fracture length and conductivity for cross-linked gels, "linear" or "slickwater" fluids, and "tip screenout" (TSO) procedures are described.

Chapter 8: Fracture Pressure Analysis

Hydraulic fracturing, as with other drilling, completion, and reservoir behavior problems, is complicated in that the processes cannot be directly observed. For describing reservoir behavior, this deficiency has been overcome through the development over the past 50 years of analyses based on wellbore pressure and flow rate. This chapter describes the history of fracturing pressure analysis, its similarity to pressure transient analysis, the techniques used to measure the pressure response, and the methods used to analyze the data.

Chapter 9: Engineering the Fluid

When fracturing, viscosity plays a major role in providing sufficient fracture width to ensure proppant entrance into the fracture, carrying the proppant from the wellbore to the fracture tip, generating a desired net pressure to control height growth and providing fluid loss control. The fluid used to generate the desired viscosity must be safe to handle, environmentally friendly, nondamaging to the fracture conductivity and to the reservoir permeability, easy to mix, inexpensive, and able to control fluid loss. This is a very demanding list of requirements that has been recognized since the beginning of hydraulic fracturing. This chapter describes the history of fracturing fluids, the types of fracturing fluids used, the engineering requirement of a good fracturing fluid, how viscosity is measured, and what the limitations of the engineering design parameters are. This chapter is intended as a companion to Chapter 10 that describes all the components that make up a fracturing fluid.

Chapter 10: Fracturing Fluid Components

The materials and chemistry used to manufacture hydraulic fracture fluids are often confusing and difficult for the practicing hydraulic fracturing engineer to understand and optimize. Many times the failure of a particular fracturing treatment is blamed on the fluid because that is a major unknown from the design engineer's viewpoint. Many of the components and processes used to manufacture the fluid are held proprietary by the service company, which adds to the confusion and misunderstanding. This chapter makes an attempt to describe the components used in fracturing fluids at a level that the practicing fracturing engineer can understand and use. This chapter is intended as a companion to Chapter 9, which describes how to use the fluids to design a fracturing treatment.

Chapter 11: Proppants

After all the design, execution, and well cleanup are completed, the only thing left in the fracture is the proppant. The main objective of a hydraulic fracturing treatment is to provide sufficient contrast between the reservoir deliverability and the permeability of the fracture so that the well is able to achieve its maximum productivity over the economic life of the well. During pumping, the fracture is held open by the fluid pressure, but once pumping has stopped and the pressure drops because of fluid loss, the fracture will close on itself and lose most of the permeability that was created. To prevent this, a material is included in the fracturing fluid that will support the fracture once the pressure has dropped. This granular material is called a propping agent or proppant. This chapter describes the history, types, and design of these propping agents.