

Essentials of Hydraulic Fracturing

Contents

Preface	xi
Acknowledgments	xiii
1 Introduction	1
Hydraulic Fracturing	2
The Primary Hydraulic Fracturing Treatment Goal	7
The Typical Concept versus the Actual Fracture	9
Treatment Implementation Aspects	15
Non-Stimulation Fracturing Applications and Considerations	18
Controllable Factors Pertinent to Hydraulic Fracturing Treatment Design	19
Treatment Design Factors Imposed by Nature	20
A Successful Fracturing Treatment?	22
Refracturing of Previously Hydraulically Fractured Wells	24
Environmental Impacts of Hydraulic Fracturing Treatments	24
Disciplines Pertinent to Hydraulic Fracturing	26
The Design Engineer's Job	27
Hydraulic Fracturing in the Future—Let's Do It Right!	28
Issues to Be Addressed	30
Implications for the Future	32
References	32
2 Overview: Important Fracture Design Aspects	35
Factors Pertinent to Fracturing Behavior and Economics	35
Preliminary Post-Fracture Production Estimates	37
Formation Permeability Distribution	62
Mechanical Rock Properties and In Situ Stress	64
Fracture Propagation Behavior and Patterns—Near-Wellbore and Far-Field Regions	79
Formation Composition and Temperature	80
Fracturing Fluid Loss to the Formation	83
Fracturing Fluid System Rheology, Viscosity, and Proppant Transport	86
Propping Agents and Fracture Conductivity	93
Overview Commentary	102
Exercises	103
Nomenclature	110
References	112
3 Rock Mechanics and Fracture Propagation: Rock Properties—In Situ Stresses, Net Fracturing Pressures, and Fracture Geometry	115
Mechanical Rock Properties and In Situ Stresses in Fracture Propagation Models ...	116
Mechanical Rock Properties Basic to Hydraulic Fracturing Behavior	118
In Situ Stress	132
Net Fracturing Pressure	149

In Situ Stress and Net Fracturing Pressure Effects on Fracture Height, Width, Penetration, and Volumetric Propagation Geometry	153
Calculating Fracture Height with In Situ Stress Profile Data	154
Pore Pressure Effects on In Situ Stress and Fracture Propagation Behavior	162
Interval Interface Slippage, Ductility and Fluid-Loss Confining Effects	169
Fracture Width	169
Fracture Volume Calculations from Width, Height, and Lateral Penetration.	178
Fracturing in Horizontal Wellbores	179
Hydraulic Fracturing Studies with a Quasi Three-Dimensional Rock Mechanics (Q-3D-RM) Spreadsheet Model.	179
Summary of Data Acquisition Pertinent to Mechanical Rock Properties, In Situ Stresses, and Net Fracturing Pressures.	188
Exercises.	190
Nomenclature	195
References	196
4 Fracturing Fluid Systems.	199
Design Engineer and Service Company Engineer Interaction.	201
Fracturing Fluid System Requirements	202
Selecting a Fracturing Fluid System	203
Types of Fluid Systems	205
Fluid System Databases.	207
Base Fluid System Components	207
Fracturing Fluid System Performance Control Agents	211
Decision Flowcharts to Facilitate and Accelerate Fluid System Selection.	215
Particle Fraction Effect on Viscosity	217
Comments from Outside Reviewers.	217
The Expanding World of Fracturing Fluid Systems and Additives	218
Exercises.	219
Resources.	219
References	219
5 Fracturing Fluid Loss to the Formation	221
Total Fluid Loss.	222
Terminology: Laboratory-Determined Spurt-Loss and Fluid-Loss Coefficient, and Field-Determined Fracturing Efficiency, Total Fluid-Loss Coefficient	223
Determining Fluid-Loss Behavior.	225
Formation Permeability, Gel Concentration, Temperature, and Additives.	254
CVC versus Pressure Differential between the Fracture and the Reservoir	256
Fluid System Viscosity Increase by Virtue of Fluid Loss.	259
Effect of Fluid Shear on Fluid Loss	260
Reducing Floss into Vugs, Joints, Fissures, Fractures, Faults	261
Pad Volumes Calculated from Fracturing Fluid Efficiency.	262
Summary of Fluid-loss Considerations for Fracture Treatment Design	265
Data and Information Resources for Fluid-loss Behavior.	267
Exercises.	268
Nomenclature	270
Resources.	271
References	271

6	Fracturing Fluid System Rheology and Proppant Transport	273
	In-Fracture Fluid System Temperature—Wellbore to Fracture Tip	274
	Approaches to Fluid System In-Fracture Temperature Distribution	276
	Algorithms for In-Fracture Temperature Calculations	278
	Whitsitt and Dysart approach	280
	Apparent Viscosity	283
	Fluid System Behavior	285
	Resources for Fluid System Apparent Viscosity and Rheology Data	290
	Developing Equations for Fracturing Fluid Systems Rheology Behavior	291
	Temperature and Shear Rate Effects on Apparent Viscosity Behavior	320
	Apparent Viscosity of Foam Fluid Systems	327
	Fluid System Apparent Viscosity Increase due to Proppant Concentration	329
	Hydraulic Horsepower Injection Requirements	333
	Tubular Friction Loss during Injection	338
	Friction Loss (Turbulent Tubular Flow)—Proppant-Laden Slurries	350
	Proppant Transport	360
	Proppant Transport In Fractures	363
	Laboratory Proppant Transport Testing Developments After 1990	366
	Fluid System Pumping, Staging, and Scheduling Considerations	370
	Flowback—Fluid System Recovery and Cleanup Enhancement	371
	Mitigating Microcrack Gumming in the Formation	372
	Summary of Considerations for Fluid System Flow Behavior and Proppant Transport	372
	Data and Information Resources (Hard Copy, Website, etc.)	373
	Exercises	374
	Nomenclature	376
	Resources	378
	References	378
7	Proppants and Fracture Conductivity	381
	Proppants	382
	Fracture Permeability and Conductivity	403
	Proppant Transport, Closed Fracture Width, and Proppant Specific Gravity	414
	Economic Perspectives of Fracture Conductivity	417
	Closed Fracture Width versus Proppant Concentration and Post-Fracture Production	428
	Proppant Selection Criteria	442
	Data Sources: Specifications for Fracture Permeability and Conductivity	444
	Acknowledgments	445
	Exercises	445
	Nomenclature	446
	Resources	447
	References	448
8	Fracture Propagation Computer Models	451
	Model Types	451
	Model Evolution	452
	About Model Fracturing Treatment Designs	453
	Model Supplements	453

Model Availability	453
Model Development History	453
Model Augmentations and Supplemental Features	458
Model—Construction, Capability, Applicability	458
Modelling Fracture Propagation Blunting	482
Modeling—Simultaneous Multi-Interval Propagation—Vertical or Deviated Wellbore	484
Fluid Loss and Rheology Effects	490
Treatment Designs—Predictions versus In Situ Propagation	492
Selecting the Appropriate Model for Design	494
Model Design Limitations and Validation	495
Recommended Fracturing Model Treatment Design and Analysis Practices	497
Supplemental Comments by Outside Reviewers	499
Fracturing Model Resources	499
Exercises	500
References	504
9 Fracture Treatment Design, Implementation, and Post-Fracture Operations	505
Twelve Points to Improve Fracturing Success and Economic Returns	505
General Treatment Design Phases	509
Candidacy Considerations	512
Pre-Design Activities	513
Data Acquisition Programs for Pre-Fracture Treatment Design	519
Treatment Design	521
Scenario Designs	524
Final Economic Optimized Treatment Design	526
Treatment Implementation Planning	527
Management Involvement	541
Onsite Fracturing Treatment Implementation	542
Programs for Improving Economic Returns on Future Wells	543
Fracture Design Data and Analysis Resources	547
Exercises	548
Nomenclature	550
10 Pre-Fracture Treatment: Model Design Examples	551
Model Design Practices	551
Fracturing Economic Returns	552
About Treatment Designs: Vertical versus Horizontal Wellbores	552
About the Examples	553
Model Approaches—Treatment Design Sequences	555
Model Description	556
Example 10–1. Description, Data, and Design Process	558
GOHFER Model Treatment Design	597
Example 10–1 Description and Design Considerations	598
Potential for Enhanced Economics by Propping Outside the Pay	609
Summary of Results for Examples 10–1 and 10–2, and Ideas for Redesign	610
Considerations for Treatment Redesign	611
Commentary on Pre-Fracture Treatment Designs with Models	612
Exercises	614

Nomenclature.....	615
Reference.....	615
11 Fracturing Horizontal Wellbores.....	617
Introduction.....	617
Fracturing Technology.....	619
Fracture Orientation.....	623
Complex and Planar Fractures.....	627
Well Spacing and Orientation.....	633
Placement of Fractures.....	634
Stress Factors Affecting Fracturing from Horizontal Wells.....	638
Completion Design.....	641
Microseismic and Other Monitoring Methods.....	641
Perforating Horizontal Wells for Fracturing.....	642
Fracturing.....	643
Fracture Initiation and Early Fracture Growth.....	643
Rate.....	648
Fracture Extension and Later Stage Fracturing Behavior.....	649
Simultaneous and Sequential Fracturing.....	651
Refracturing.....	652
Fracture Hits.....	653
Fracture Flowback.....	654
References.....	657
12 Fracturing Diagnostics.....	667
Fracturing Diagnostic Methods.....	668
Near-Wellbore Vertical Fracture Extent.....	670
Post-Fracture Wellbore In-Flow Production Profiling.....	679
Fracture Propagation Azimuth and Propagation Geometry.....	682
Commentary on Fracturing Diagnostics.....	700
References.....	701
Appendix A: Fracture Vertical Height Calculations.....	703
Descriptions and Comparisons of Figures A–1, A–2–1, and A–2–2.....	705
Utility of the Height Growth Curves.....	707
Regression of the Height Growth Curve Data.....	707
The hS/h Calculation Approach.....	708
Calculating Relative Fracture Heights, hS/h, as a Function of $f(\sigma, P_f)$ and $\Delta\sigma_R$	708
Preferential Downward versus Upward Vertical Growth.....	712
Bounding Intervals with Multiple Layers Where σ , E, and K_{IC} Vary from Layer to Layer.....	713
Conclusions.....	713
Nomenclature.....	714
Appendix B: A Quasi-Three-Dimensional Rock Mechanics Spreadsheet (Q-3D-RMS) Model.....	715
Differences between the Q-3D-RMS and Planar Three-Dimensional (P-3D) Models.....	716
Q-3D-RMS Model Input Data.....	716
Relative Fluid Viscosity Behavior and Retained $\Delta P_f/\Delta X_f$	717

Well Injection Pressure (P_w)	719
Creating and Using a Q-3D-RMS Model.	719
Fracturing Intervals in a Q-3D-RMS Model	720
Q-3D-RMS versus Other Models	721
Q-3D-RMS Model Vertical and Horizontal Configuration	721
Q-3D-RMS Model Calculations	724
Q-3D-RMS Spreadsheet Model Calculations Using Chapter 3, Example 3–15 Data	728
Commentary about this Q-3D-RMS Spreadsheet Model.	735
Nomenclature	736
Appendix C: Example Spreadsheet Program for Fracturing Fluid Efficiency and SIPD Type-Curve Fluid-Loss Coefficient Calculations	739
Spreadsheet Calculations of Fracturing Fluid Efficiency	740
Spreadsheet Applicable Master Type-Curves.	741
Spreadsheet Processing of SIPD Data	743
Appendix D: Bibliography for Chapter 11	755
Answers to Selected Exercises	763
Index.	781
About the Authors	811

Preface

In 1989, the publication SPE Monograph V. 12, *Recent Advances in Hydraulic Fracturing*, addressed four decades of fracturing technology. Since then, hydraulic fracturing has moved from vertical wellbore, massive hydraulic fracturing in tight microdarcy gas reservoirs to new frontiers addressing horizontal wellbore fracturing in massive nanodarcy formations. Accordingly, the industry has kept pace with advances in extended horizontal drilling and fracturing applications. New fracturing materials, techniques, and applications have emerged. However, the fundamental basics of fracture propagation behavior and diagnostics remain the same.

This book focuses on consolidating the old and the new in a format that assists both current and future fracturing design engineers in their practice. It is beyond the scope of this book to extensively cover the entire gamut of fracturing intricacies; rather, the purpose is to provide [1] a basic understanding of (a) fracture propagation behavior, (b) the effects of fracturing on post-treatment well production, and (c) the important aspects pertinent to fracture treatment design application and [2] insight and methods for applying that knowledge to achieve maximum economic returns from a fracturing treatment.

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Introduction

This book focuses more on the “how to” than the theoretical aspects of fracture treatment design and execution. Much of what is contained here is also presented more esoterically and comprehensively in the SPE monograph cited here:

Gidley, John L., Stephen A. Holditch, Dale E. Nierode, Ralph W. Veatch, eds. 1989. *Recent Advances in Hydraulic Fracturing* (SPE Monograph V. 12). Richardson, TX: Society of Petroleum Engineers.

Additionally, fracturing advances that have emerged since monograph publication are presented herein.

The SPE monograph, though published in 1989, covers basic theoretical fundamentals and approaches, and basic fracturing materials available at that time. The basic fundamentals seldom change, nor do the properties and behaviors of materials found in nature. The monograph exhaustively and esoterically addresses them. While it’s not necessary for readers to have a copy of the monograph, it is a good resource for reference.

Many other books with basic information are also available and worth having in one’s technical library, such as

- *Reservoir Stimulation*, 2nd ed. (1989), by Michael J. Economides and Kenneth G. Nolte. Schlumberger Educational Services, Houston.
- *Modern Fracturing, Enhancing Natural Gas Production* (2007), by Michael J. Economides and Tony Martin. BJ Services and Energy Tribune Publishing, Houston.
- *Hydraulic Fracture Mechanics* (1996), by Peter Valc6 and Michael J. Economides. John Wiley & Sons, Hoboken, NJ.

In the SPE monograph, and to some degree in the other books referenced above, the discussion of similar fracturing aspects are located in more than one chapter and in the appendices. Hence, efforts have been made in this book to consolidate, as much as possible, discussions pertinent to each separate aspect of fracture design into a single chapter.

Hopefully, the authors’ consolidation efforts, and those made to put the presentation into a practical application format, will facilitate design engineers in their efforts to apply state-of-the-art practices for fracturing treatment designs.

The contents of this book are intended to serve

- Design engineers currently involved in fracturing applications
- As a textbook for university engineering students
- Engineers designated for future fracturing involvement
- Line managers responsible for economic returns from fracturing

What it presents includes

- Aspects that are basic to treatment design
- Their effects (singularly and interactively) on fracture propagation and performance behavior
- Their relative impact on post-frac production and revenue
- Algorithms and examples pertinent to treatment design and analysis
- Fracturing treatment design methods and processes
- Pre- and post-fracturing approaches and diagnostics for evaluating treatment performance, and for improving performance on future wells

The intended purpose of the book is to serve the reader in several ways, including but not limited to providing

- An understanding of how basic factors and phenomena pertinent to fracture propagation geometry and fracture conductivity impact the results of a treatment
- Awareness of important considerations pertinent to treatment design and execution
- A menu of data requirements and procedures necessary to design and analyze treatments
- Methods and procedures for processing design data and creating designs
- Encouragement to communicate with all entities associated with fracturing the target well, including: management, geologists, geophysicists, reservoir engineers, computer modelers, consultants, field operating personnel, service companies, equipment and material suppliers, etc.
- A focus on the most important goals of hydraulic fracturing, i.e.,
 - Safety
 - Environmental prudence
 - Maximum economic returns

Hydraulic Fracturing

The following discussion is obviously oversimplified for experienced design engineers. However, it is cast as such to provide insight to those less familiar with the topic of hydraulic fracturing. Many fracturing treatments are unique to specific wells and to the design addressing them. It benefits even the experienced to revisit those mentioned in the simplified discussion.

Also, after some engineers have been involved in hydraulic fracturing for several years, especially in a given locale, they may develop somewhat of a “fracturing expert” posture. This may,

Refracturing of Previously Hydraulically Fractured Wells

Refracturing of previously fractured wells has been common practice throughout the history of hydraulic fracturing. Refracturing pertains to wells that were successfully stimulated, and then produced until the oil and gas flow rates declined to an uncomfortably low level, as opposed to redoing an unsuccessful treatment. Economic and/or logistic success has ranged by varying degrees from poor to excellent. This has been for a variety of reasons. Although refracturing per se is not covered in this book, several aspects pertinent to refracturing are addressed. The primary one being in situ stress reduction in the target fracturing interval by virtue of reservoir pressure depletion. With a refracturing treatment, the reduced in situ stress from reduced pore pressure results in wider fractures and more vertical growth confinement. There is another stress-related issue that comes into play: the in situ stress field imposed by the residual proppant pack width. This can affect refracture propagation behavior. Other issues are pertinent, such as the inhibiting effects of in-place proppant packs on slurry flow.

Environmental Impacts of Hydraulic Fracturing Treatments

Environmental issues have entered the fracturing world to a significant degree. They will continue to be a large factor in the environmentally friendly development of wells that need to be fracture-treated. To do it right requires a familiarity with pertinent regulations at all governmental levels and that corporate communication lines pertinent to environmental aspects are open and active.

Recently, public interest has grown and may possibly continue doing so about several issues, such as

- Does hydraulic fracturing affect drinking water aquifers?
- Does hydraulic fracturing cause issues with earthquakes?

These two issues are being debated as the authors write this book, so there will be much information to come in the following years. Design engineers have some control over the drinking water issue. These are discussed. In regard to earthquakes, there is not sufficient definitive information on a global basis to serve as guidance for a design engineer. Consequently, the issue is pending credible investigations pertinent to specific locales. Disposal is emerging as the cause.

Prospective subsurface fresh water issues?

The following addresses two more commonly discussed fresh water pollution questions that are repeatedly discussed as possible causes of fresh water aquifer issues.

- Wellbore annulus invasion—prospective vertically upward fluid migration outside the casing?
- Prospective fracture vertical growth?

Note: In figure 2–2, propped vertical fracture height (h_f) equals net pay height (h_i), so the entire net pay is effectively propped. Tinsley et al. presents other charts where net pay is not totally propped. Consequences for this are obvious: lower FOI. This emphasizes the importance of treatment designs that always effectively prop the entire pay.

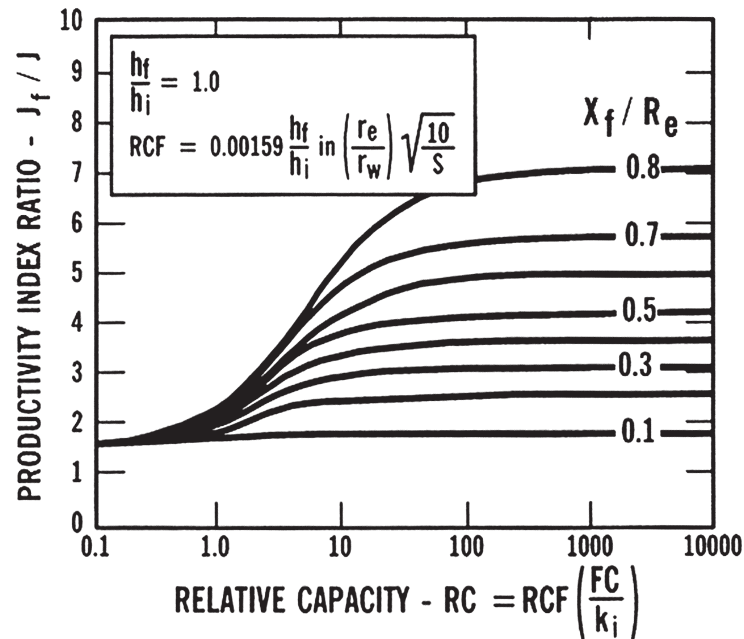


Fig. 2–2. Tinsley et al. FOI chart

Source: “Figure 1.4,” Gidley et al. 1989, 2.

In the chart, it is easily seen that as k_i decreases, RC increases (to the right), and higher values of the productivity index ratio or FOIs can be achieved with deeper fracture penetrations (X_f/R_e). For $RC > 100$, FOI is governed primarily by fracture penetration. For $RC > 500$, FOI remains essentially constant, regardless of RC magnitude.

However, as k_i increases, RC decreases (to the left), and here, FC dominates. Note that for $RC < 1$, fracture penetration has little impact on FOI. In this range, maximum achievable values are $FOI = 2$ or lower.

As a general rule of thumb for a semi-steady state reservoir flow, low-permeability formations require deeply penetrating fractures to increase the productivity index. For these low-permeability reservoirs, fracture conductivity is not as important as fracture length as long as sufficient conductivity exists for the fracture fluid to clean up in the fracture. Conversely, the optimum fracture for high permeability formations generally consists of shorter but higher conductivity fractures to provide sufficient permeability contrast with the formation. Hence, an accurate estimate of formation permeability prior to designing the fracture treatment is essential for success.

Production estimates for transient reservoir flow. The charts in figure 2–1 apply only to semi-steady state reservoir flow. If a reservoir exhibits transient flow over extended periods, the rule of thumb mentioned above, may not be completely applicable, but the principal of requiring deep penetrating fractures in low-permeability reservoirs remains valid. The problem is that the

Basic equations and associated figures pertinent to the above parameters are introduced in this chapter to provide a general perspective of their effects on fracture propagation behavior. Some are also included in chapter 3, “Rock Mechanics and Fracture Propagation,” along with expanded discussion, additional equations, figures, tables, and example calculations.

Data sources—values for treatment design

Figure 2–11 provides a perception of how the various formation properties interact in fracture propagation behavior. The following discussion explains how the design engineer can determine the values for the various rock properties and parameters required to compute fracture dimensions.

Overburden pressure

The value of the overburden stress is best obtained using downhole wellbore logs for interval thickness and formation density, since the value of the overburden stress at any depth is simply the weight of all the rocks and fluids above that point. Overburden at the top of any given interval can be calculated using equation 2–13.

$$P_{\text{OVRB}} = \sum_{I(1-N)} [\rho_{\text{GRAD}}(I)h_{\text{GROSS}}(I)] \quad \text{Equation 2–13}$$

where

P_{OVRB}	Overburden pressure at the interval top
N	Number of overlying intervals
$\rho_{\text{GRAD}}(I)$	Average density depth gradient of the I^{th} interval
$h_{\text{GROSS}}(I)$	Thickness of the I^{th} interval

P_{OVRB} is often calculated as the product of an assumed average ρ_{GRAD} (typically ranging from 0.9 to 1.1 psi/ft) multiplied by the total depth to the formation top. This estimate then serves as a starting point for in situ stress calculations in the underlying target fracturing interval.

Elastic modulus (E) and Poisson’s ratio (ν)

These values are obtained from either:

- Downhole compression and shear acoustic full-waveform logs (dynamic measurements);
- Laboratory measurements on cores (static measurements); or
- Published sources, obtained for a specified lithology.

Dynamic measurements (full-waveform) are made using sonic signals at relatively high frequencies. Dynamic measurements can be made using sonic logs or using sonic measurements on cores in the laboratory. Static measurements are made using stress-strain tests on cores in the laboratory.

Full-waveform acoustic logs provide by far the most usable data. They span all the layers of rock that are logged and evaluated. The results from the logs reflect the rock behavior under in situ confinement conditions. Additionally, the results represent a much larger formation sampling

e.g., “It’s a power-law fluid.” This is attributed to available test results spanning specified, common in-fracture shear rate ranges where the fluid system exhibits, more or less, a single behavior. This is possibly to the chagrin of classical rheologists. In spite of the fact that a given fluid system exhibits multiple rheology behaviors under different shear rate ranges, the vernacular prevails, and is generally accepted by the industry.

Figure 2–20 depicts an example that shows the two following aspects:

- Several rheology category behaviors for a given system
- Shear rate and temperature effects on apparent viscosity

The chart date covers a much wider shear rate spectrum than is conventionally available per standard test procedures. The fluid system comprises an aqueous-based 40 lbm/1,000 gal (40 parts/M-gal) hydroxypropyl guar (HPG) polymer fracturing fluid with no cross-linking agent.

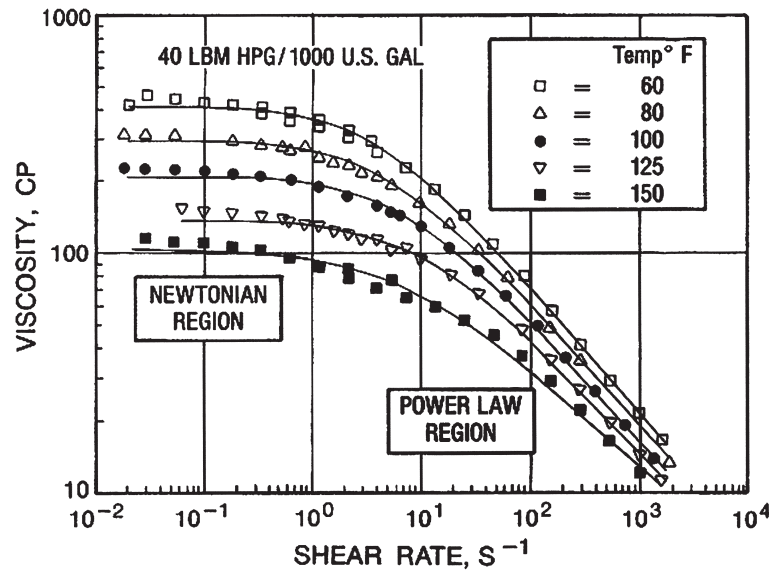


Fig. 2–20. Fluid viscosity versus shear rate
 Source: “Figure 9.8,” Gidley et al. 1989, 186.

Figure 2–20 shows a range of different viscosity behaviors over shear rates of $10^{-2} < \dot{\gamma} < 10^4$. Within that range, there are four behaviors:

- *Shear rates:* $\dot{\gamma} < 10^{-1}$ 1/sec: Newtonian—No, or minimal, effect of shear rate on apparent viscosity. Apparent viscosity \approx constant at a given temperature
- *Shear rates:* $10^{-1} < \dot{\gamma} < 10^1$ 1/sec: Non-power law—Logarithmically nonlinear. Apparent viscosity does not behave per equation 2–19
- *Shear rates:* $10^1 < \dot{\gamma} < 10^2$ 1/sec: Near-power law—Logarithmically nearly linear. Apparent viscosity \approx equation 2–19
- *Shear rates:* $10^2 < \dot{\gamma}$ 1/sec: Power law—Logarithmically linear. Apparent viscosity behaves per equation 2–19

The industry has become more aware that apparent viscosity flattens to a constant viscosity as shear rate decreases. However, this behavior may or may not be incorporated in some fracture

- Lithology
- Rock mechanical properties
 - Poisson's ratio
 - Elastic modulus
 - Fracture toughness
- In situ stress
- Net fracturing pressures
- Interval interface slippage effects

The above list is by no means exhaustive. Discussion in this chapter addresses individual aspects, along with the interactive effects of one parameter upon the others, and the effects imposed by fluid injection forces. Design engineers should strive to

- Acquire the most credible information that is economically possible
- Develop a thorough understanding of the basic concepts and the interdependencies pertinent to the interaction of all relevant parameters

Mechanical Rock Properties and In Situ Stresses in Fracture Propagation Models

How rock mechanics are integrated into fracture design models may seem somewhat obscure. The complexities in some models may seem somewhat convoluted. To simplify this, two long-standing, less complicated models are used for discussions. These have been used successfully for design since the advent of fracturing models and are depicted in figure 3–1.

- Perkins–Kern–Nordgren (PKN), which applies where total fracture length is greater than or equal to total fracture height
- Geertsma and deKlerk (GdK), which applies where total fracture length is less than or equal to total fracture height

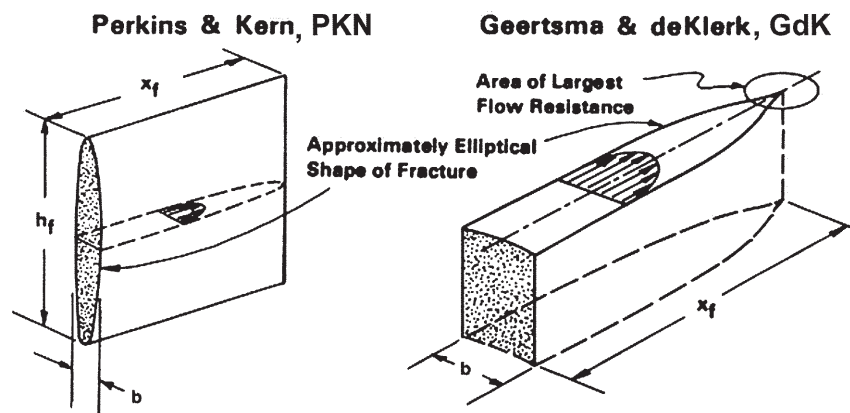


Fig. 3–1. Perkins–Kern–Nordgren (PKN) and Geertsma–deKlerk (GdK) models. Copyright 1989, SPE. Reproduced with permission of SPE. Further reproduction prohibited without permission.