Drilling Engineering

J.J. Azar

Professor Emeritus and former Director of Drilling Research (TUDRP) Petroleum Engineering Department University of Tulsa, Tulsa

G. Robello Samuel

Senior Technical Advisor (Drilling and Completions) Halliburton Company (Drilling, Evaluation and Digital Solutions) Houston



Contents

Acknowledgments xii 1. Rotary Drilling for Oil and Natural Gas 1 Introduction 1 The Process of Rotary Drilling 1 Rotary Drilling Rigs 4 Rig Selection 9 Rotary Drilling Systems 10 Mud System Evaluation 15 Rotary System 22 Well Control System 22 Well Control System 22 Well Control System 25 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluids 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M, P, P, P, M, M, P, P, P) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 76	Preface	xi
1. Rotary Drilling for Oil and Natural Gas 1 Introduction 1 The Process of Rotary Drilling 1 Rotary Drilling Rigs 4 Rig Selection 9 Rotary Drilling Systems 10 Mud System Evaluation 15 Rotary System 22 Well Control System 25 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Characteristics of a Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 65 Introduction 85 </th <th>Acknowledgments</th> <th> xii</th>	Acknowledgments	xii
1. Notary Drilling for On and Vatural Gas 1 Introduction 1 The Process of Rotary Drilling. 1 Rotary Drilling Rigs 4 Rig Selection 9 Rotary Drilling Systems. 10 Mud System Evaluation 15 Rotary System 22 Well Control System 22 Well Control System 25 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling. 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid. 37 Characteristics of a Drilling Fluids 44 Water-Based Drilling-Mud Contaminants. 47 Drilling-Huid Selection 44 Water-Based Drilling-Mud Contaminants. 47 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 76 Circulating System 78 Nomenclature 85 <tr< th=""><th>1 Potowy Dvilling for Ail and Natural Cas</th><th>1</th></tr<>	1 Potowy Dvilling for Ail and Natural Cas	1
The Process of Rotary Drilling. 1 Rotary Drilling Rigs 4 Rig Selection 9 Rotary Drilling Systems 10 Mud System Evaluation 15 Rotary System 22 Well Control System 22 Well Control System 22 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M _p P ₁ , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 64 Drilling-Mud Additives 76 Supplementary Problems	Introduction	1
Rotary Drilling Rigs 4 Rig Selection 9 Rotary Drilling Systems 10 Mud System Evaluation 15 Rotary System 22 Well Control System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Characteristics of a Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M, P, P, M, M, P, P, P) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 61 Circulating System 85 Introduction 85 Mechanical Ener	The Process of Rotary Drilling	1
Rig Selection9Rotary Drilling Systems10Mud System Evaluation15Rotary System22Well Control System25Data Acquisition and Monitoring System25Data Acquisition and Monitoring System27Special Systems for Offshore Drilling28Supplementary Problems29Nomenclature362. Drilling Fluids37Characteristics of a Drilling Fluid37Drilling-Fluid Selection41Classification of Drilling Fluids44Water-Based Drilling-Mud Contaminants47Drilling-Mud Properties, Field Tests, and Control49Alkalinity (Mp, Pr, Pm, Mm, Pr, P2)60Mud Rheology64Drilling-Mud Additives76Supplementary Problems78Nomenclature823. Fluid Flow and Associated Pressures in the Rotary Rig78Circulating System85Introduction85Mechanical Energy and Pressure Balance90Pressure Drop across the Bit Nozzles (Jets)92Friction Pressure Losses in the Rotary Rig Circulating System94Friction Pressure Losses in Pipes and Annuli—Laminar Flow16Equivalent Newtonian Viscosity118Turbulent Pipe Flow of Non-Newtonian Fluids121Annular Friction Pressure Losses Due to Pipe Movement125	Rotary Drilling Rigs	
NoticeNoticeRotary Drilling Systems10Mud System Evaluation15Rotary System22Well Control System25Data Acquisition and Monitoring System27Special Systems for Offshore Drilling28Supplementary Problems29Nomenclature36 2. Drilling Fluids 37Characteristics of a Drilling Fluid37Drilling-Fluid Selection41Classification of Drilling Fluids44Water-Based Drilling-Mud Contaminants47Drilling-Mud Properties, Field Tests, and Control49Alkalinity (Mr, Pr, Pm, Mm, Pr, P2)60Mud Rheology64Drilling-Mud Additives78Supplementary Problems78Nomenclature82 3. Fluid Flow and Associated Pressures in the Rotary Rig 78Circulating System85Introduction85Mechanical Energy and Pressure Balance90Pressure Drop across the Bit Nozzles (Jets)92Friction Pressure Losses in the Rotary Rig Circulating System94Friction Pressure Losses in Pipes and Annuli—Laminar Flow16Equivalent Newtonian Viscosity118Turbulent Pipe Flow of Non-Newtonian Fluids119Turbulent Pipe Flow of Non-Newtonian Fluids121Annular Friction Pressure Losses Due to Pipe Movement125	Rig Selection	9
Mud Šystem Evaluation 15 Rotary System 22 Well Control System 25 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M, P ₁ , P _m , M _m , P, P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 64 Drilling System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in the Rotary Rig Circul	Rotary Drilling Systems	
Rotary System 22 Well Control System 25 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M, P ₁ , P _m , M _m , P, P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 64 Drilling System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressu	Mud System Evaluation	15
Well Control System 25 Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M _p , P ₁ , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 61 Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow <	Rotary System	22
Data Acquisition and Monitoring System 27 Special Systems for Offshore Drilling 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M _p , P ₁ , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 29 Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 94 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Annular Flow of Non-Newtonian Fluids <td< td=""><td>Well Control System</td><td>25</td></td<>	Well Control System	25
Special Systems for Offshore Drilling. 28 Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M _p , P ₁ , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Priction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular	Data Acquisition and Monitoring System	27
Supplementary Problems 29 Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control. 49 Alkalinity (Mr, Pr, Pm, Mm, Pr, P2) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Special Systems for Offshore Drilling	28
Nomenclature 36 2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M_p , P_t , P_m , M_m , P_1 , P_2) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 121 Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Supplementary Problems	29
2. Drilling Fluids 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity ($M_p P_f, P_m, M_m, P_1, P_2$) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 121 Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Nomenclature	36
2. Drining rulus 37 Characteristics of a Drilling Fluid 37 Drilling-Fluid Selection 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants. 47 Drilling-Mud Properties, Field Tests, and Control. 49 Alkalinity (M _r , P ₁ , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	9 Drilling Fluide	27
Characteristics of a Driming Fluids 41 Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants. 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M _p , P ₁ , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Characteristics of a Drilling Fluid	97 27
Classification of Drilling Fluids 44 Water-Based Drilling-Mud Contaminants. 47 Drilling-Mud Properties, Field Tests, and Control 49 Alkalinity (M _p , P _f , P _m , M _m , P ₁ , P ₂) 60 Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Drilling-Fluid Selection	
Water-Based Drilling-Mud Contaminants	Classification of Drilling Fluids	
Drilling-Mud Properties, Field Tests, and Control	Water-Based Drilling-Mud Contaminants.	
Alkalinity (M _p , P ₁ , P _m , M _m , P ₁ , P ₂)	Drilling-Mud Properties, Field Tests, and Control	
Mud Rheology 64 Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Alkalinity $(M_a, P_c, P_c, M_c, P_c, P_a)$	
Drilling-Mud Additives 76 Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Mud Rheology	64
Supplementary Problems 78 Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Drilling-Mud Additives	76
Nomenclature 82 3. Fluid Flow and Associated Pressures in the Rotary Rig 85 Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Supplementary Problems	
3. Fluid Flow and Associated Pressures in the Rotary Rig Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Nomenclature	
3. Fluid Flow and Associated Pressures in the Rotary Rig Circulating System 85 Introduction 85 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125		
Circulating SystemIntroduction85Mechanical Energy and Pressure Balance90Pressure Drop across the Bit Nozzles (Jets)92Friction Pressure Losses in the Rotary Rig Circulating System94Friction Pressure Losses in Pipes and Annuli—Laminar Flow97Friction Pressure Losses in Pipes and Annuli—Turbulent Flow116Equivalent Newtonian Viscosity118Turbulent Pipe Flow of Non-Newtonian Fluids119Turbulent Annular Flow of Non-Newtonian Fluids121Annular Friction Pressure Losses Due to Pipe Movement125	3. Fluid Flow and Associated Pressures in the Kotary Kig	0E
Microduction 83 Mechanical Energy and Pressure Balance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Introduction	
We channel Linergy and Pressure Datance 90 Pressure Drop across the Bit Nozzles (Jets) 92 Friction Pressure Losses in the Rotary Rig Circulating System 94 Friction Pressure Losses in Pipes and Annuli—Laminar Flow 97 Friction Pressure Losses in Pipes and Annuli—Turbulent Flow 116 Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Machanical Energy and Procesure Balance	
Friction Pressure Losses in the Rotary Rig Circulating System	Pressure Drop across the Rit Nozzles (Jets)	
Friction Pressure Losses in Pipes and Annuli—Laminar Flow	Friction Pressure Losses in the Rotary Rig Circulating System	
Friction Pressure Losses in Pipes and Annuli—Turbulent Flow	Friction Pressure Losses in the Rotary Rig enculating bystem	
Equivalent Newtonian Viscosity 118 Turbulent Pipe Flow of Non-Newtonian Fluids 119 Turbulent Annular Flow of Non-Newtonian Fluids 121 Annular Friction Pressure Losses Due to Pipe Movement 125	Friction Pressure Losses in Pipes and Annuli—Turbulent Flow	
Turbulent Pipe Flow of Non-Newtonian Fluids	Equivalent Newtonian Viscosity	
Turbulent Annular Flow of Non-Newtonian Fluids	Turbulent Pipe Flow of Non-Newtonian Fluids	
Annular Friction Pressure Losses Due to Pipe Movement	Turbulent Annular Flow of Non-Newtonian Fluids	
	Annular Friction Pressure Losses Due to Pipe Movement	125

Supplementary Problems	130
Nomenclature	138
References	139
4. Drill Bit Hydraulics	141
Introduction	141
Pump Pressure Requirement in Rotary Drilling	142
Hydraulic Power Requirement	143
Flow Exponent (α)	144
Maximum Drill Bit Hydraulic Horsepower Criterion	145
Maximum Jet Impact Force Criterion	152
Supplementary Problems	156
Nomenclature	169
References	170
5. Transport of Drilled Cuttings	
Introduction	171
Factors that Affect the Transport of Drilled Cuttings	171
Cuttings Transport in Vertical Well Drilling	179
Cuttings Transport in Directional Well Drilling	182
Empirical Correlations for Cuttings Transport in High-Angle Wells ($\theta > 50^{\circ}$)	185
Supplementary Problems	188
Nomenclature	189
References	189
6. Prevention and Control Mechanics of Well Blowouts	191
Introduction	191
Kick Causes	191
Kick Detection	195
Kick Prevention	196
Fundamentals of Well Control	196
Well Control System	199
Principles of Well Control	206
Commonly Used Well Control Methods	216
Nonconventional Kick Situations	225
Supplementary Problems	230
Nomenclature	234
References	235
7. Directional and Horizontal Well Drilling	237
Directional Well Drilling	237
Horizontal Well Drilling	254
Tortuosity	265
Supplementary Problems	271
Nomenclature	274
References	

8. Drill Bit Mechanics	277
Introduction	277
Bit Selection	277
Types of Drill Bits	
Classification of Roller Cone Drill Bits	
Drill Bit Operating Parameters	
Grading of Dull Drill Bits	
Classification of Drag Drill Bits	
Rock Mechanics	
Performance Mechanics of Drag Drill Bits	305
Supplementary Problems	
Nomenclature	
References	
9. Drill String Design	
Definition and Components	
Design Criteria	
Buckling of the Drill String	
Drill String Fatigue	
Dril String Vibration	
BHA Design for Directional Drilling	
Deviation Tools	
Supplementary Problems	351
Nomenclature	
References	353
10. Drilling Problems and Solutions	355
Introduction	355
Pipe Sticking	355
Loss of Circulation	
Hole Deviation	
Drill Pipe Failures	
Borehole Instability	
Mud Contamination	
Producing-Formation Damage	
Hole Cleaning	
Hydrogen Sulfide–Bearing Zones and Shallow Gas	
Equipment- and Personnel-Related Problems	
Supplementary Problems	
Nomenclature	
References	
11. Casing and Cementing Design	
Drilling the Pay Zone: Selecting the Interval and the Initial Design	381
Initial Completion Design	382
Casing Design	389
Guerra D. 001211	

Cementing	
Supplementary Problems	
Nomenclature	
References	
12. Well Planning in Drilling Engineering	451
Introduction	
Objectives	
Information Needed for Effective Well Planning	
Responsibilities of the Drilling Engineer	
Considerations in Well Planning	
The Drilling Program	454
Post-Well Analysis	455
Well Cost Estimation	456
Learning Curve	
Cost Control in Well Drilling	
Time Value of Money	
Price Elasticity	
Supplementary Problems	
Nomenclature	
References	
Index	465

Preface

Drilling engineering is a challenging discipline in the oil patch. It goes beyond what is found in textbooks. The technological advances in the past two decades have been very significant. These advances have allowed the oil industry worldwide to economically and successfully exploit oil and gas fields that may have not been possible before.

The fundamentals of fluid mechanics and solid mechanics, along with the basic scientific concepts of chemistry, form the basis of drilling engineering. The rewards and successes of drilling projects are predicated on the ability of the drilling engineer who fully understands all the engineering aspects and equipment required to drill a usable hole at the lowest dollar per foot (\$/ft), in vertical well drilling, or at the highest equivalent barrel of oil per foot (bbl/ft) in horizontal/multilateral well drilling.

In the oil industry, it is common practice to assume that problems may be encountered during the drilling process of a well and can differ from one well to the other, even in the same area. The drilling engineer has the responsibility to be able to think beyond simply the engineering equations in combating some of these problems. He or she must anticipate drilling problems, devise solutions, and choose the best alternatives. They must be intuitive, must have common sense, and be able to think quickly and decisively. In this book, the authors have prepared illustrative examples and supplementary problems that hopefully will encourage the students to cultivate their creative thinking, develop confidence in reaching independently for what is needed to solve problems, and above all, energize their common sense to make wise decisions.

The book is written for educating students in drilling engineering in a two-semester course series: Drilling I and Drilling II. It is also intended to serve as a reference to engineers in field operations. It is suggested that Drilling I cover the following chapters: chapter 1—Rotary Drilling for Oil and Natural Gas, Chapter 2—Drilling Fluids, chapter 3— Fluid Flow and Associated Pressures in the Rotary Rig Circulating System, chapter 4—Drill Bit Hydraulics, chapter 5—Transport of Drilled Cuttings, and chapter 6—Prevention and Control Mechanics of Well Blowouts; where Drilling II covers: chapter 7—Directional and Horizontal Well Drilling, chapter 8—Drill Bit Mechanics, chapter 9—Drill String Design, chapter 10—Drilling Problems and Solutions, chapter 11—Casing and Cementing Design, and Chapter 12—Well Planning in Drilling Engineering.

It is recommended that non-conventional drilling techniques, which is not included in this text, such as under-balance drilling, slim hole drilling, coiled-tubing drilling, casing drilling, etc., be given to students in Drilling II as special topics assignments.



Introduction

Drilling for oil and natural gas requires two major constituents: manpower and hardware systems. The manpower encompasses a drilling-engineering group and a rig-operations group. The first group provides engineering support for optimum drilling operations, including rig selection and design of the mud program, casing and cementing programs, the hydraulic program, the drill bit program, the drill string program, and the well control program. After drilling begins, the daily operations are handled by the second group, which consists of a tool pusher and several drilling crews (derrick and motor personnel, drillers, etc.). The hardware systems that make up a rotary drilling rig are

- 1. A power generation system
- 2. A hoisting system
- 3. A drilling fluid circulating system
- 4. A rotary system
- 5. Well blowout control systems
- 6. A drilling data acquisition and monitoring system

This chapter will primarily address the form and functions of these systems and their various components.

The Process of Rotary Drilling

Whether drilling a *vertical hole* or a *directional hole* (fig. 1–1) for the purpose of producing oil and/or natural gas, several elements are needed to drill the hole successfully and economically (illustrated in fig. 1–2), including

- A force acting downward on a drill bit
- Rotation of the drill bit
- Circulation of fluid, called drilling fluid (liquid, gas, or gasified liquid), from the surface through the tubular, called the drill string, and back to the surface through the annular space, the area between the hole wall and the outside wall of the drill string

14 Drilling Engineering

This method neglects the effect of buoyancy and the weight of the block and hook. In straight holes, buoyancy can be assumed to be offset by pipe drag. In directional holes, drag has to be considered.

Hoisting engines should have a horsepower rating for intermittent service equal to the required drawworks horsepower rating divided by 85% efficiency. Drawworks also have a rating of line pull efficiency; this factor depends on the number of lines strung between the crown block and the traveling block. (See table 1–1.)

Number of Lines	Efficiency Factor
6	0.874
8	0.841
10	0.81
12	0.77
14	0.74

Table 1-1. Line pull efficiency factor

Example 1-4 (Line pull calculation)

What line pull is required to handle a 500,000 lb casing load with 10 lines strung?

Solution:

 $\frac{500,000}{(10) (0.810)} = 61,800$ lbs

Fluid circulating system

The function of the fluid circulating system in rotary drilling is to allow the movement of a drilling fluid from the surface to the hole bottom and back to surface again. The main components of the system include

- Mud pumps/air compressors
- High-pressure surface connections
- Drill string
- Drill bit
- Return annulus
- Mud pits
- Mud treatment equipment

Figure 1–8 shows a schematic of the system.

the annulus when no pipe is present are called blind rams. These rams, if activated while the drill string is in the hole, will not shut in the annulus. Rams that are designed to shear off drill pipe while string is in hole are referred to as shear rams. These kind of rams are activated only if all other preventers fail to shut the well.

Annular preventers. Annular preventers are well control devices that employ a ring of reinforced synthetic rubber as a packing unit that surround the drill string to cause the shutoff. In the full open position, the inside diameter (ID) of the packing unit is equal to the diameter of the preventer bore. These preventers will close and shut in the well regardless of the shape or diameter of the conduit that might be in the hole.

Drilling spools. Drilling spools are drill-through—type fittings that are placed in the BOP stack assembly to provide space between two consecutive pipe rams for temporary storage of tool joints during stripping operations and to allow attachment of the kill and choke lines.

Data Acquisition and Monitoring System

The data acquisition and monitoring system of a rotary drilling rig consists of all the devices used to monitor, analyze, display, record, and retrieve information regarding drilling operations. The parameters that are of prime concern are the following:

- Drilling rate
- Hook load
- Hole depth
- Pump pressure
- Flow rate
- Torque
- Rotary speed
- Mud density, temperature, salinity, and flow properties
- Mud tank level
- Pump strokes
- Weight on bit
- Hoisting speed

Drilling problems, such as lost circulation, well kicks, and pipe sticking, can be easily detected by the monitoring equipment. Drilling breaks, which are easily seen on the drilling rate chart, can provide information on changes of lithology and formation pressures. Excessive torques may indicate a bit bearing failure or an extremely high concentration of drilled cuttings in the wellbore annulus. A drastic increase in hook load or decrease in mud returning to the surface could indicate that a lost circulation zone has been encountered. A sudden increase in pit level indicates that formation fluids are entering the wellbore and, hence, that blowout is eminent. The proper maintenance of rotary speed, weight on bit, mud properties, and flow rates is of utmost importance for achieving optimum drilling conditions.

In conclusion, the monitoring system is the functional pulse for the entire drilling process. With the advent of personal computers and downhole measuring devices, the monitoring, recording, analysis, storage, and retrieval of drilling data has become a routine part of the process of drilling operations.

- Casing program
- Makeup water
- Potential corrosion
- Environmental impact
- Availability of products in international operations

A discussion of each of these considerations follows.

Well type. Drilling may be classified as development or wildcat drilling: In areas where drilling has been conducted previously and the geological conditions are known, additional wells to be drilled are referred to as development wells. Otherwise, it is a wildcat well, commonly referred to as an exploratory well. In the latter, the drilling fluid must be chosen so that all geological information can be obtained easily and safely. Also, the drilling fluid must be of such composition to allow quick changes to yield a fluid system suited for whatever unexpected problems are encountered. By contrast, in development wells, the drilling-fluid program is selected and the mud systems are designed along with other programs (hydraulic, drill bit, casing, etc.) to meet the criterion of minimum overall drilling cost.

Problem formations. If either the formation that is being drilled or the fluid that is being used to drill it is affected, directly or indirectly, by the other, then the formation is classified as a problem formation. Examples are

- Shale formations—water sensitive (heaving and swelling) or pressured (caving and sloughing)
- Anhydrite formations (lime or gypsum)
- Salt formation
- High-temperature formation
- Abnormal pressure formation
- Inherently fractured formation (loss circulation zones)

Shale intervals. The problems associated with the drilling of shale intervals (depending on the type of shale) are

- Mechanical pipe sticking
- High torque/drag
- Annular hole-cleaning difficulties
- Logging difficulties
- Mud contamination

Depending on the severity of the problem, adjustments to the properties of the drilling fluid may control the shale. Otherwise, very careful and specific design requirements of the drilling fluid may have to be implemented.

Anhydrite intervals. When bentonite-treated freshwater muds are used to drill anhydrite formations, the calcium ions released into the mud system will retard bentonite hydration and flocculate the mud that has been hydrated, thus affecting mud viscosity and fluid loss. Depending on the massiveness of the intervals, either the calcium ions are treated out of the system or the mud is converted to an inhibitive one (e.g., a gypsum- or lime-treated

Equivalent circulating density. In small-diameter holes, those of 9⁷/₈ in. or less, friction pressure loss in the annulus becomes an important factor that must be taken into consideration. This pressure can cause a further, significant increase in mud weight as compared to the increase due to cuttings accumulations under low drilling rates.

The effect of friction loss is expressed in terms of mud weight and is called the *equivalent circulating density* (ECD) or the equivalent mud weight (EMW) and can be expressed as follows:

$$ECD = \gamma_{\rm m} + \frac{P_{\rm f}}{0.052D} \tag{2.16}$$

where

 γ_m is the mud weight, in lbs/gal, as measured on surface

 $P_{\rm f}$ is the annulus friction loss, in psi

D is the depth, in ft, at which the ECD is being calculated

Fluid loss

Fluid loss is defined as the loss of a mud filtrate (liquid phase) into a permeable formation that is being drilled. Because of positive differential pressure (i.e., the pressure difference between the mud pressure in the wellbore and the formation pore pressure), the mud filtrate tends to flow into the formation; this results in the buildup of mud solids deposited on the wellbore walls, thus forming what is commonly referred to as mud cake (filter cake). The term *spurt loss* is used to characterize the initial loss of filtrate to formation at time practically equal to zero. After a mud cake is formed, the loss of filtrate from then on is referred to as the continuous fluid loss.

It has been pointed out in the literature that high spurt loss is advantageous, while high continuous loss is detrimental. It is the general consensus that the rate and amount of high continuous fluid loss into a formation can adversely affect the rate of penetration, water-sensitive and sloughing shale, and the producing formation and can cause differentialpressure pipe sticking. Any or all of these can occur in the field. Therefore, emphasis is placed on specifying and controlling the mud fluid loss property. However, the general tendency is to specify fluid losses much lower than necessary. This can result in drilling problems and, therefore, higher well cost. The best solution, so as not to over- or underspecify fluid loss properties, is to obtain information from offset wells in the same area.

Fluid loss tests. There are two types of tests for fluid loss measurement:

- API static filtration test (standard low pressure and temperature and high pressure and temperature)
- Dynamic filtration test

The static filtration test includes the standard API test at room temperature and 100 psi differential pressure and is the *field test* for fluid loss measurement. The high-pressure, high-temperature test is a laboratory test and is conducted at a differential pressure of 500 psi and a temperature of 300°F. The static tests are indicative of the loss of fluid and the buildup of the filter cake when the fluid is not moving.

The dynamic test represents the loss of fluid and the filter cake buildup while the drilling mud is being circulated. Dynamic tests are strictly laboratory conducted tests.

For a non-Newtonian fluid,

- Using the Bingham plastic model ($\tau = \tau_v + \mu_p \gamma$),

$$\mu_{\rm p} = 300 \ \frac{\Theta_N}{N} - \frac{300\tau_y}{N} \tag{2.34}$$

For
$$N = 300,\,600$$
 rpm,

$$\mu_{\rm p} = \theta_{600} - \theta_{300} \tag{2.35a}$$

$$\tau_{\rm y} = 2\Theta_{300} - \Theta_{600} \tag{2.35b}$$

where

 μ_p = is the PV

 $\dot{\Theta}_{600}$, Θ_{300} are the viscometer dial readings at N = 600 rpm and N = 300 rpm, respectively τ_v is the YP in lbs/100 ft

 τ_g is the gel strength in lbs/100 ft taken after mud has been thoroughly stirred and then kept undisturbed for 10 s and 10 min time at a rotational speed of three rpm.

– Using the power law fluid model ($\tau = K\gamma^n$),

$$n = 3.32 \log_{10} \frac{\Theta_{2N}}{\Theta_N}$$

$$K = \frac{\Theta_N}{\gamma_N^n}$$
(2.36)

where

n is the power law index *K* is the consistency index

– Using the yield power law fluid model ($\tau = \tau_v + K\gamma^n$),

$$n = 3.32 \log_{10} \frac{(\theta_{2N} - \theta_0)}{(\theta_N - \theta_0)}$$
(2.37)

$$K = \frac{(\Theta_N - \Theta_0)}{\gamma_N^n} \tag{2.38}$$

where θ_0 denotes zero gel (lbs/100 ft).

The shear rate, γ (in s⁻¹), imparted to a sample of drilling mud by a variable speed viscometer is commonly expressed in terms of the rotational speed, *N* (in rpm), of the rotating sleeve (rotor). Based on the geometry of these viscometers, the rotational speed can be converted to shear rate by the following equation:

$$\gamma = 1.7N \tag{2.39}$$

Problem 2–14. List the following:

- (a) Seven criteria used in the selection of drilling fluids.
- (b) The three basic types of drilling fluids.
- (c) Functions of dry-air drilling fluids.
- (d) The composition of drilling muds.

Problem 2–15. A kick was taken at the indicated depth for the well shown in figure 2–19 while drilling with 12 lbs/gal mud The recorded shut-in casing and shut-in drill pipe pressures were 600 psi and 800 psi, respectively. How much barite must be added to bring the well under control and maintain a 400 psi differential pressure while drilling the interval?

Nomenclature

- A Filtration area
- D Depth
- *D*_h Hole diameter
- $d_{\rm p}$ Particle diameter of largest dimension
- $\dot{D_{\rm p}}$ Outer pipe diameter
- F' Force
- $f_{\rm vc}$ Volume fraction of solids in cake
- $f_{\rm vf}$ Volume fraction of low specific gravity solids in final mixture
- $f_{\rm vo}$ Volume fraction of low specific gravity solids in original liquid
- $f_{\rm W}$ Volume percent of water, expressed as a fraction
- *h* Cake thickness
- k Cake permeability
- K Consistency index
- *n* Power law index
- *P*_{df} Drilling-fluid pressure
- $P_{\rm f}$ Annulus friction loss, in psi
- *P*_{ff} Formation fluid pressure
- P_h Hydrostatic pressure
- Q Flow rate, in gpm
- $Q_{\rm f}$ Amount of filtrate volume
- $Q_{\rm m}$ Total volume of mud filtered
- $Q_{\rm s}$ Volume of solids deposited in mud cake
- ΔP Differential pressure
- *R* Penetration rate (ROP)
- t Filtration time
- *v*_a Annular fluid velocity
- *V*_a Added material weight
- *V*_f Final mixture volume
- *V*_o Original liquid volume
- $v_{\rm sp}$ Particle settling velocity
- $W_{\rm a}$ Added material weight

98 Drilling Engineering

These forces are located at *r* and $r + \Delta r$ in the radial direction and at *L* and $L + \Delta L$ along the wellbore axis, as shown in figure 3–6.



Fig. 3-6. Elements of flowing fluid

Using Newton's law of motion, $\Sigma \vec{F} = m\vec{a}$, where *m* denotes mass and *a* denotes acceleration. Alternatively, for a nonaccelerating fluid, as is the case here, $\Sigma \vec{F} = \theta$.

Thus, summation of forces induced on the isolated layer of fluid owing to the fluid motion yields

$$(P_{\rm f} + \Delta P_{\rm f})(2\pi r)\Delta r - P_{\rm f}(2\pi r)\Delta r + (\tau + \Delta \tau)[2\pi(r + \Delta r)\Delta L] - \tau(2\pi r)\Delta L = 0$$
(3.23)