Table of Contents

Chapter 1 Introduction 1

1.1 The Formation of Petroleum Reservoirs 1
1.2 Typical Characteristics of Petroleum Reservoirs 1
1.3 The Significance of Petroleum Reservoir Rock and Fluid Properties 3

Chapter 2 Preamble to Petroleum Reservoir Rock Properties 5

2.1 Introduction 5
2.2 Coring Methods 6
2.2.1 Rotary Method 6
2.2.2 Sidewall Coring 6
2.2.3 High-Pressure Coring 6
2.3 Important Issues Related to Coring Methods 7
2.4 Types of Cores 7
2.4.1 Whole Core 7
2.4.2 Core Plug 8
2.5 Allocation of Core Data for Measurement of Reservoir Rock Properties 9
2.6 Handling of Reservoir Rock Core Samples 9
2.7 Types of Core Tests 10
2.7.1 Routine or Conventional Core Analysis 10
2.7.2 Special Core Analysis 10
References 11

Chapter 3 Porosity 13

3.1 Significance and Definition 13
3.2 Types of Porosities 13
3.2.1 Total or Absolute Porosity 14
3.2.2 Effective Porosity 15
3.2.3 Ineffective Porosity 15
3.3 Classification of Porosity 16
3.4 Parameters That Influence Porosity 16
3.5 Laboratory Measurement of Porosity 17
3.5.1 Porosity Determination Using Routine Core Analysis 18
3.5.1.1 Bulk Volume Measurement 18
3.5.1.2 Pore Volume Measurement 19
3.5.1.3 Grain Volume Measurement 21
3.6 Nonconventional Methods of Porosity Measurements 22
3.7 Averaging of Porosity 23
3.8 Examples of Typical Porosities 24

Problems 25
References 26

Chapter 4 Absolute Permeability 27

4.1 Significance and Definition 27
4.2 Mathematical Expression of Permeability: Darcy's Law 27
4.3 Dimensional Analysis of Permeability and Definition of a Darcy 30
4.4 Application of Darcy's Law to Inclined Flow and Radial Flow 31
4.5 Averaging of Permeabilities 33
4.5.1 Parallel Flow 34
4.5.2 Series Flow 35
4.6 Permeability of Fractures and Channels 37
4.7 Darcy's Law in Field Units 39
4.8 Laboratory Measurement of Absolute Permeability 40
4.8.1 Measurement of Absolute Permeability Using Liquids 40
4.8.2 Measurement of Absolute Permeability Using Gases 42
4.9 Factors Affecting Absolute Permeability 45
4.9.1 Rock-Related Factors 46
4.9.2 Fluid Phase-Related Factors 47
4.9.3 Thermodynamic Factors 49
4.9.4 Mechanical Factors 49
4.10 Porosity and Permeability Relationships 50
4.11 Permeabilities of Different Types of Rocks 52
Problems 52
References 54

Chapter 5 Mechanical and Electrical Properties of Reservoir Rocks 55

5.1 Introduction 55
5.2 Mechanical Properties 56
5.2.1 Stress 56
5.2.2 Strain 56
5.2.3 The Stress–Strain Relationship 57
5.2.3.1 Factors Affecting the Stress–Strain Relationship 58
5.2.4 Rock Strength 59
5.2.5 Rock Mechanics Parameters 59
5.2.5.1 Poisson's Ratio 59
5.2.5.2 Young's Modulus 60
5.2.5.3 Modulus of Rigidity 61
5.2.5.4 Bulk Modulus 61
5.2.6 Laboratory Measurement of Rock Strength 61
5.2.6.1 Triaxial Cell 62
5.2.7 Reservoir Rock Compressibility 64
5.2.7.1 Empirical Correlations of Formation Compressibility 66
5.3 Electrical Properties 66
5.3.1 Fundamental Concepts and the Archie Equation 67

5.3.1.1 Formation Factor 67
5.3.1.2. Tortuosity 68
5.3.1.3 Cementation Factor 68
5.3.1.4 Resistivity Index 68
5.3.2 Effect of Wettability on Electrical Properties 71
5.3.3 Effect of Clay on Electrical Properties 73
Problems 75
References 77

Chapter 6 Fluid Saturation 79

6.1 Significance and Definition 79
6.2 Distribution of Fluid Saturation in a Petroleum Reservoir 80
6.3 Definition and Mathematical Expressions for Fluid Saturation 80
6.4 Reservoir Rock Samples Used for Fluid Saturation Determination 82
6.5 Laboratory Measurement of Fluid Saturation 83
6.5.1 Retort Distillation 84
6.5.2 Dean–Stark Extraction 86
6.6 Assessing the Validity of Fluid Saturation Data Measured on the Plug-End Trim for the Core Plug Sample 88
6.7 Special Types of Fluid Saturations 89
6.7.1 Critical Gas Saturation 90
6.7.2 Residual Oil Saturation 90
6.7.3 Irreducible Water Saturation 93
6.8 Saturation Averaging 94
6.9 Factors Affecting Fluid Saturation Determination 95
6.9.1 Effect of Drilling Muds on Fluid Saturation 95
6.9.2 Effect of Fluid Expansion on Fluid Saturation 97
6.9.3 Combined Effects of Mud Filtrate Invasion and Fluid Expansion on Fluid Saturation 98
6.9.4 Mitigation of Mud Filtrate Invasion and Fluid Expansion Effects on Fluid Saturation 100
6.9.4.1 Measures That Avoid or Account for Mud Filtrate Invasion 101
6.9.4.2 Measures That Avoid or Account for Fluid Expansion 104
Problems 106
References 107

Chapter 7 Interfacial Tension and Wettability 109

7.1 Introduction and Fundamental Concepts 109
7.2 Interfacial and Surface Tension 110
7.2.1 Effect of Pressure and Temperature on Interfacial Tension and Surface Tension 112
7.2.2 Laboratory Measurement of Interfacial Tension 115
7.3 Wettability 116
7.4 Fundamental Concepts of Wettability 117

7.5 A Discussion on Practical Aspects of Wettability 121
7.5.1 Classification/Types of Wettability 122
7.5.1.1 Water-Wet 122
7.5.1.2 Oil-Wet 122
7.5.1.3 Intermediate Wet 122
7.5.1.4 Fractional Wettability 123
7.5.1.5 Mixed Wettability 123
7.6 Measurement of Reservoir Rock Wettability 123
7.6.1 Contact Angle Measurement 124
7.6.1.1 Effect of Pressure and Temperature on Contact Angles 126
7.6.2 Core Samples for Amott Test and USBM Methods 126
7.6.3 Amott Test 128
7.6.3.1 Modification of the Amott Test (Amott–Harvey Test) 130
7.6.4 USBM Method 131
7.7 Factors Affecting Wettability 133
7.7.1 Composition of the Reservoir Oil 133
7.7.2 Composition of the Brine 134
7.7.3 Reservoir Pressure and Temperature 135
7.7.4 Depth of the Reservoir Structure 136
7.8 Relationship between Wettability and Irreducible Water Saturation and Residual Oil Saturation 137
7.8.1 Wettability and Irreducible Water Saturation 137
7.8.2 Wettability and Residual Oil Saturation 138
Problems 140
References 141

Chapter 8 Capillary Pressure 145

8.1 Introduction 145
8.2 Basic Mathematical Expression of Capillary Pressure 146
8.3 The Rise of Liquid in Capillaries 147
8.4 Dependence of Capillary Pressure On Rock and Fluid Properties 150
8.5 Capillary Pressure and Saturation History 151
8.6 Laboratory Measurement of Capillary Pressure 153
8.6.1 Leverett's Capillary Pressure Experiments 154
8.6.2 Porous Diaphragm Method 156
8.6.3 Mercury Injection Method 157
8.6.4 Centrifuge Method 159
8.7 Characteristics of Capillary Pressure Curves 160
8.7.1 Saturation Scale 161
8.7.2 Pressure Scale 161
8.7.3 Capillary Hysterisis 162
8.7.4 Capillary Pressure and Permeability 163
8.8 Converting Laboratory Capillary Pressure Data to Reservoir Conditions 163
8.9 Averaging Capillary Pressure: The *J* Function 166
8.10 Calculation of Permeability from Capillary Pressure 168

8.11 Effect of Wettability on Capillary Pressure 170
8.12 Practical Application of Capillary Pressure 172
8.12.1 Pore Size Distribution 173
8.12.2 Pore Throat Sorting 176
8.12.3 Connate Water Saturation 176
8.12.4 Zonation, Fluid Contacts, and Initial Saturation Distribution in a Reservoir 177
8.12.4.1 Free Water Level 178
8.12.4.2 Oil–Water Contact 179
8.12.4.3 Transition Zone 179
8.12.4.4 Oil Pay Zone or Clean Oil Zone 180
8.12.4.5 Fluid Saturation in the Gas Zone 180
Problems 181
References 182

Chapter 9 Relative Permeability 185

9.1 Fundamental Concepts of Relative Permeability 185
9.2 Mathematical Expressions for Relative Permeability 186
9.3 Salient Features of Gas–Oil and Water–Oil Relative Permeability Curves 187
9.3.1 The End-Point Fluid Saturations 189
9.3.2 The Base Permeabilities 189
9.3.3 End-Point Permeabilities and Relative Permeability Curves 189
9.3.3.1 Gas–Oil Relative Permeability Curves 190
9.3.3.2 Oil–Water Relative Permeability Curves 190
9.3.4 The Direction of the Relative Permeability Curves 192
9.4 Laboratory Measurement of Relative Permeability 192
9.4.1 Flowchart for Relative Permeability Measurements 193
9.4.2 Core Plug Samples Used in Relative Permeability Measurements 195
9.4.3 Displacement Fluids and Test Conditions 196
9.4.3.1 Room Condition Tests 196
9.4.3.2 Partial Reservoir Condition Tests 196
9.4.3.3 Reservoir Condition Tests 197
9.4.4 Establishment of Initial Water Saturation 197
9.4.4.1 Preserved Core Plug Samples 197
9.4.4.2 Cleaned Core Plug Samples 198
9.4.5 Determination of Base Permeability 198
9.4.6 Displacement Apparatus for Relative Permeability 200
9.4.7 Steady-State Technique 201
9.4.8 Unsteady-State Technique 204
9.4.8.1 Buckley–Leverett to Welge to Johnson–Bossler–Naumann 205
9.4.8.2 Relative Permeabilities from the Alternate Method 217
9.4.9 Capillary End Effect 218

9.5 Determination of Relative Permeability from Capillary Pressure Data 220
9.6 Factors Affecting Relative Permeability Measurements 222
9.6.1 Effect of Fluid Saturation, History of Saturation, and Initial Water Saturation 223
9.6.2 Effect of Wettability on Relative Permeability 225
9.6.3 Effect of Rock Pore Structure 226
9.6.4 Effect of Overburden Stress (Confining Stress) 227
9.6.5 Effect of Clay Content and Movement of Fines 228
9.6.6 Effect of Temperature 228
9.6.7 Effect of Interfacial Tension, Viscosity, and Flow Velocity 228
9.7 Peculiarities of Relative Permeability Data 230
9.8 Assessing the Validity of Relative Permeability Data and Determination of Corey Exponents 232
9.9 Significance of Relative Permeability Data 234
9.9.1 Example of Practical Application of Relative Permeability Data 235
9.10 Three-Phase Relative Permeability 237
9.10.1 Representation of Three-Phase Relative Permeability Data 237
9.10.2 Empirical Models for Three-Phase Relative Permeability 239
Problems 241
References 244

Chapter 10 Introduction to Petroleum Reservoir Fluids 247

10.1 Introduction 247
10.2 Chemistry of Petroleum 247
10.2.1 Alkanes 248
10.2.2 Alkenes 249
10.2.3 Alkynes 250
10.2.4 Cycloaliphatics 250
10.2.5 Aromatics 250
10.2.6 Nonhydrocarbons in Reservoir Fluids 251
10.3 The Solid Components of Petroleum 251
10.3.1 Gas Hydrates 251
10.3.2 Waxes 252
10.3.3 Asphaltenes 252
10.3.4 Diamondoids 252
10.4 Classification of Reservoir Gases and Oils 252
10.4.1 Chemical Classification of Reservoir Oils or Crude Oils 253
10.4.2 Physical Classification of Crude Oils 253
10.5 Five Reservoir Fluids 254
10.6 Formation Waters 255
Reference 255

Chapter 11 Introduction to Phase Behavior 257

11.1 Introduction 257
11.2 Definition of Terms Used in Phase Behavior 258

11.2.1 Phase 258
11.2.2 Pressure, Temperature, and Intermolecular Forces 258
11.2.3 Equilibrium 258
11.2.4 Component and Composition 258
11.2.5 Distinction between Gases and Liquids 259
11.2.6 Types of Physical Properties 259
11.2.7 Phase Rule 259
11.3 Phase Behavior of a Pure Component 260
11.3.1 Phase Diagram of a Pure Component 260
11.3.1.1 Vapor Pressure Curve 260
11.3.1.2 Critical Point 261
11.3.1.3 Triple Point 262
11.3.1.4 Melting Point Curve 262
11.3.1.5 Sublimation–Pressure Curve 262
11.3.1.6 Conditions Outside the P_c–T_c Boundary 262
11.3.2 Pressure–Volume Diagram 263
11.3.3 Density–Temperature Behavior of a Pure Component 264
11.3.4 Determination of Vapor Pressure 265
11.4 Phase Behavior of Two-Component or Binary Systems 266
11.4.1 Phase Diagram of a Binary System 267
11.4.1.1 Critical Point 267
11.4.1.2 Bubble Point and Dew Point 268
11.4.1.3 Bubble-Point and Dew-Point Curves 268
11.4.1.4 Cricondenbar and Cricondentherm 269
11.4.1.5 Retrograde Dew Point and Condensation 269
11.4.1.6 Behavior of a Mixture in the Two-Phase Region 269
11.4.2 Effect of Changing the System Composition 272
11.5 Phase Behavior of Multicomponent Mixtures 274
11.6 Construction of Phase Envelopes 275
Problems 276
References 277

Chapter 12 Phase Behavior of Petroleum Reservoir Fluids 279

12.1 Introduction 279
12.2 Preamble to the Phase Behavior of Petroleum Reservoir Fluids 279
12.3 A Brief Description of the Plus Fraction 280
12.4 Classification and Identification of Fluid Type 281
12.5 Black Oils 281
12.6 Volatile Oils 282
12.7 Gas Condensates 285
12.8 Wet Gases 287
12.9 Dry Gases 288
12.10 Behavior of Petroleum Reservoir Fluids in the Two-Phase Region 288
Problems 291
References 292

Chapter 13 Sampling of Petroleum Reservoir Fluids....293

13.1 Introduction....293
13.2 Practical Considerations of Fluid Sampling....294
13.2.1 Well Conditioning....294
13.3 Methods of Fluid Sampling....296
13.3.1 Subsurface Sampling....296
13.3.2 Wellhead Sampling....296
13.3.3 Surface Sampling....297
13.4 Evaluating the Representativity of Fluid Samples: Quality Checks....298
13.5 Factors Affecting Sample Representativity....299
Problems....301
References....301

Chapter 14 Compositional Analysis of Petroleum Reservoir Fluids....303

14.1 Introduction....303
14.2 Strategy of Compositional Analysis....303
14.2.1 Surface Samples of Separator Gas and Liquid....304
14.2.2 Blow-Down Method....304
14.2.3 Direct Determination of Composition....304
14.3 Characteristics of Reservoir Fluid Composition....305
14.3.1 Well-Defined Components....306
14.3.2 Pseudo Fractions....306
14.3.3 Plus Fraction....306
14.4 Gas Chromatography....307
14.5 True Boiling-Point Distillation....309
14.5.1 Properties of TBP Cuts and Residue....310
14.5.2 Internal Consistency of TBP Data....311
14.5.3 Properties of TBP Cuts and Generalized Data....313
14.6 Characterization of Pseudo Fractions and Residue....314
14.7 Other Nonconventional Methods of Compositional Analysis....316
Problems....317
References....318

Chapter 15 PVT Analysis and Reservoir Fluid Properties....321

15.1 Introduction....321
15.2 Properties of Petroleum Reservoir Fluids....322
15.2.1 Gases and Liquids....323
15.2.2 Ideal Gases....323
15.2.2.1 Standard Volume....324
15.2.3 Real Gases....324
15.2.3.1 Gas Density....327
15.2.3.2 Specific Gravity....328
15.2.4 Mixtures of Gases....328
15.2.4.1 Apparent Molecular Weight....328

15.2.4.2 Critical Pressure and Temperature of Gas Mixtures 329
15.2.4.3 Determination of Compressibility Factor of Gas Mixtures....332
15.2.4.4 Determination of Density of Gas Mixtures....334
15.2.5 Dry Gases....334
15.2.5.1 Formation Volume Factor....334
15.2.5.2 Coefficient of Isothermal Compressibility....336
15.2.5.3 Viscosity....336
15.2.6 Wet Gases....338
15.2.6.1 Recombination Cases....338
15.2.6.2 Formation Volume Factor....342
15.2.7 Gas Condensates....343
15.2.8 Black Oils and Volatile Oils....343
15.2.8.1 Formation Volume Factor....344
15.2.8.2 Solution Gas–Oil Ratio or Gas Solubility....345
15.2.8.3 Total Formation Volume Vactor....345
15.2.8.4 Coefficient of Isothermal Compressibility....347
15.2.8.5 Viscosity....348
15.2.8.6 Surface Tension....349
15.2.8.7 Volatile Oils....351
15.3 Laboratory Tests....351
15.3.1 PVT Equipment....352
15.3.2 Constant Composition Expansion....354
15.3.3 Differential Liberation....356
15.3.4 Constant Volume Depletion....359
15.3.4.1 Liquid Drop Out....361
15.3.4.2 Material Balance for Condensate Composition....361
15.3.4.3 Two-Phase Compressibility Factor....365
15.3.5 Separator Tests....365
15.3.5.1 Optimum Separator Conditions....367
15.4 Adjustment of Black Oil Laboratory Data....367
15.4.1 Combination Equations....370
15.4.1.1 Formation Volume Factor of Oil....371
15.4.1.2 Solution Gas–Oil Ratio....372
15.4.1.3 Formation Volume Factor of Gas....373
15.4.1.4 Total Formation Volume Factor....374
15.4.1.5 Coefficient of Isothermal Compressibility of Oil....374
15.4.2 Composite Liberation....374
15.5 Other Sources of Obtaining the Properties of Petroleum Reservoir Fluids....375
15.5.1 Empirical Correlations....375
15.5.1.1 Standing's Empirical Correlations....376
15.5.2 Prediction of Viscosity from Compositional Data....378
15.5.3 Prediction of Surface Tension....380
Problems....381
References....387

Chapter 16 Vapor-Liquid Equilibria 389

16.1 Introduction 389
16.2 Ideal Solution Principle 390
16.2.1 Raoult's Law 390
16.2.2 Dalton's Law 390
16.2.3 Equilibrium Ratio 391
16.2.4 Concept of PT Flash 391
16.2.5 Calculation of Bubble-Point Pressure 393
16.2.6 Calculation of Dew-Point Pressure 393
16.2.7 Drawbacks of the Ideal Solution Principle 394
16.3 Empirical Correlations for Calculating Equilibrium Ratios for Real Solutions 395
16.3.1 Wilson Equation 395
16.3.2 Methods Based on the Concept of Convergence Pressure 396
16.3.2.1 *K*-Value Charts 399
16.3.2.2 Whitson–Torp Correlation 403
16.4 Equations-Of-State (EOS) Models 404
16.4.1 Description of EOS Models 405
16.4.1.1 van der Waals Equation of State 405
16.4.1.2 Redlich–Kwong Equation of State 409
16.4.1.3 Soave–Redlich–Kwong Equation of State 410
16.4.1.4 Peng–Robinson Equation of State 411
16.4.2 Concept of Fugacity 411
16.4.3 Application of Equations of State to Pure Components 412
16.4.4 Extension of EOS Models to Mixtures 413
16.4.4.1 Determination of Equilibrium Ratios from EOS Models 416
16.4.5 VLE Calculations Using EOS Models 418
16.4.5.1 Calculation of Bubble-Point Pressure 418
16.4.5.2 Calculation of Dew-Point Pressure 421
16.4.5.3 PT Flash Calculations 421
16.4.5.4 Separator Calculations 424
16.4.5.5 A Note About the Application of EOS Models to Real Reservoir Fluids 428
16.5 Use of EOS Models in PVT Packages 429
Problems 430
References 431

Chapter 17 Properties of Formation Waters 433

17.1 Introduction 433
17.2 Compositional Characteristics of Formation Water 434
17.3 Bubble-Point Pressure of Formation Water 435
17.4 Formation Volume Factor of Formation Water 435
17.5 Density of Formation Water 437

17.6 Viscosity of Formation Water 437
17.7 Solubility of Hydrocarbons in Formation Water 438
17.8 Solubility of Formation Water in Hydrocarbons 440
17.8.1 Water Content of Gaseous Hydrocarbons 441
17.8.2 Water Content of Liquid Hydrocarbons 441
17.9 Compressibility of Formation Water 442
Problems 443
References 444

Author Index 445

Subject Index 449