

Contents

List of Symbols	XV
Conversion Factors for the Main Parameters	XXIII
1 Hydrocarbon Reservoirs	
1.1 Conditions for the Existence of an Oil or Gas Reservoir	1
1.2 Sedimentology	1
1.3 The Generation of Hydrocarbons, and Their Migration	4
1.4 Hydrocarbon Traps.	5
1.5 Temperature and Pressure in the Reservoir.	8
References	12
Exercises	12
1.1 Analysis of RFT Pressure Gradients for Fluid Type and Contacts, p. 12. – 1.2 Investigation of Pressure Communication Between Wells, p. 14. – 1.3 Analysis of an Anomalous Temperature Profile Measured in a Well, p. 15	
2 Reservoir Fluids	
2.1 Composition	17
2.2 Phase Behaviour of Hydrocarbon Systems Under Reservoir Conditions.	17
2.3 Thermodynamic Properties of Reservoir Fluids	21
2.3.1 Volumetric Behaviour and Viscosity of Gases and Condensates. . .	22
2.3.1.1 Volumetric Behaviour	22
2.3.1.2 Viscosity	25
2.3.2 Volumetric Behaviour and Viscosity of Oil	27
2.3.2.1 Volumetric Behaviour	27
2.3.2.2 Correlations for the Estimation of R_{sf} , B_{of} , and c_o	30
2.3.2.3 Viscosity of Oil with Dissolved Gas	33
2.3.2.4 Gas/Oil Interfacial Tension	34
2.4 The Properties of Reservoir Water	34
References	38
Exercises	39
2.1 Calculation of Gas Properties Under Reservoir Conditions from Compositional Data, p. 39. – 2.2 Estimation of Reservoir Oil Properties Using Differential Liberation Data, p. 42. – 2.3 Estimation of Reservoir Oil Properties Using Production Test Data and Correlations, p. 44. – 2.4 Formation Water Properties Estimated Under Reservoir Conditions, p. 45.	
3 Reservoir Rocks	
3.1 Introduction	47
3.2 Cores and Logs: Their Characteristics and Relative Merits.	47

3.2.1	Cores	47
3.2.2	Logs	49
3.2.3	Relative Merits of Core and Log Measurements	51
3.3	Combined Use of Cores and Logs	51
3.4	Scalar Properties Dependent on Position	54
3.4.1	Porosity	54
3.4.2	Fluid Saturations	57
3.4.3	Compressibility	57
3.4.4	Wettability and Capillarity	61
3.4.4.1	Basic Concepts of Wettability	61
3.4.4.2	Basic Concepts of Capillarity	63
3.4.4.3	Drainage and Imbibition	64
3.4.4.4	Capillary Pressure Curves	66
3.4.4.5	Conversion of Laboratory Capillary Pressure Curves to Reservoir Conditions	68
3.4.4.6	Porosity as a Function of Pore Radius	69
3.4.4.7	Calculation of the Average Capillary Pressure Curve for a Reservoir – the Leverett J-Function	69
3.4.4.8	Determination of Preferential Wettability	71
3.5	Dynamic Properties	73
3.5.1	Permeability	73
3.5.1.1	Some Basics on the Concept of Potential	73
3.5.1.2	The Definition of Permeability	73
3.5.1.3	Sign Conventions	74
3.5.1.4	Horizontal Flow of an Incompressible Fluid	75
3.5.1.5	Steady State Horizontal Flow of Gas	76
3.5.1.6	The Klinkenberg Effect	77
3.5.1.7	Heterogeneity and Average Permeability in a Sedimentary Unit	79
3.5.1.8	Permeability-Porosity Correlations	82
3.5.2	Effective and Relative Permeability	83
3.5.2.1	The Concept of Potential – a Further Recap	83
3.5.2.2	Effective Permeability	83
3.5.2.3	Relative Permeability	84
3.5.2.4	Relative Permeability Curves for Oil/Water and Gas/Water (Imbibition)	84
3.5.2.5	Relative Permeability Curves for Gas/Oil (Drainage)	86
3.5.3	Comments on the Concept of Relative Permeability	86
3.5.4	Calculation of the Average Relative Permeability Curve in a Sedimentary Unit	89
3.5.5	Equations for the Calculation of Relative Permeability Curves	91
3.6	Reservoir Zonation	93
3.6.1	Quick Methods of Zonation	93
3.6.2	The Use of Statistical Analysis in Reservoir Zonation	94
3.6.3	Zonation Using Cluster Analysis	95
	References	98
	Exercises	99
3.1	Use of Laboratory Measurements to Estimate the Total and Interconnected Porosities of a Core Plug, p. 99. –	
3.2	Water Influx, Reduction in Thickness, and Subsidence of a Reservoir From Rock Mechanical Data, p. 100. –	
3.3	Calculation of Capillary Transition Zone Thicknesses Using the Leverett J-Function, p. 102. –	
3.4	Dimensional Analysis of the Permeability Parameter, p. 104. –	
3.5	Average Permeability of a Multi-Layered Reservoir, p. 106. –	
3.6	Completion Analysis – a Comparison of the Effects of Different Casing Diameters on Well Inflow Performance, p. 109. –	

3.7 Evaluation of the Increase in Productivity after a Matrix Acid Treatment, p. 110. – 3.8 The Rate of Influx of Water into a Reservoir from a Surface-Fed Aquifer, p. 111. – 3.9 Relative Permeability Curves for Imbibition, Derived Through Correlations, p. 113. – 3.10 Statistical Analysis of a Large Number of Cores From Wells in the Same Depositional Unit to Establish the Mean Permeability and its Variance, p. 115.

4 The Evaluation of Oil and Gas Reserves

4.1	Introduction	117
4.2	Reserves.	117
4.2.1	Proven Reserves.	118
4.2.2	Non-Proven Reserves.	119
4.2.2.1	Probable Reserves.	119
4.2.2.2	Possible Reserves	120
4.2.3	Classification of Reserves According to Production Status	120
4.2.3.1	Developed Reserves.	120
4.2.3.2	Non-Developed Reserves.	121
4.3	Basic Data for the Volumetric Calculation of Reserves	121
4.3.1	Equations Used	121
4.3.2	Reservoir Area, A	122
4.3.3	Net Pay Thickness	122
4.3.4	Porosity ϕ , and Average Porosity $\bar{\phi}$	124
4.3.5	Calculation of the Water Saturation, S_w , and Mean $\bar{S}_w$	126
4.3.6	Calculation of the Volume Factors of Oil (B_o) and Gas (B_g).	126
4.3.7	Recovery Factor E_R	127
4.4	Volumetric Method for the Evaluation of Reserves	129
4.4.1	Deterministic Method	130
4.4.1.1	Method of Mean Values	130
4.4.1.2	Equivalent Hydrocarbon Column	130
4.4.2	Probabilistic, or Monte Carlo, Method	131
4.5	Classification of Fields in Terms of Hydrocarbon Volume	132
	References	134
	Exercises	135
	4.1 Reserves Analysis of an Oil Reservoir for Solution Gas Drive, and for Pressure Maintenance by Water Injection, p. 135. –	
	4.2 Reserves Analysis of a Gas Reservoir for Gas Expansion Drive, and for Water Drive (Total and Partial Sweep), p. 136.	

5 Radial Flow Through Porous Media: Slightly Compressible Fluids

5.1	Introduction	139
5.2	Equation for Single Phase Radial Flow	139
5.3	Linearisation of the Diffusivity Equation for Horizontal Radial Flow – Case Where the Rock-Fluid Diffusivity is Independent of the Pressure	141
5.4	Dimensionless Form of the Radial Diffusivity Equation	142
5.5	Behaviour with Time Under Flowing Conditions	143
5.6	Solutions to the Radial Diffusivity Equation for a Fluid of Constant Compressibility	146
5.6.1	Transient Flow	146
5.6.1.1	Treatment for an Ideal Well.	146
5.6.1.2	Treatment for a Real Well – Skin Effect.	150

5.6.2	Pseudo-Steady State Flow	152
5.6.3	Steady State Flow	156
5.7	The Principle of Superposition Applied to the Solution of the Diffusivity Equation	157
5.8	Testing Production and Injection Wells	159
	References	160
	Exercises	160
	5.1 Investigation of the Infinite Acting Radial Flowing Response in an Oil Well, p. 160. – 5.2 Design of an Interference Test Between Two Oil Wells to Investigate Hydraulic Communication Through the Reservoir, p. 163. – 5.3 Calculation of the Productivity Index (PI), Completion Factor (CF) and Damage Ratio (F_s) of an Oil Well in a Drainage Area, p. 164.	
6	The Interpretation of Production Tests in Oil Wells	
6.1	Introduction.	167
6.2	Measurement of Flow Rate and Pressure.	167
6.3	The Problem of Non-Uniqueness	169
6.4	Calculation of the $p_D(t_D)$ Function for Non-Circular Geometries. . .	171
6.5	The Interpretation of Pressure Drawdown Tests	176
6.5.1	Overview.	176
6.5.2	Constant Rate Drawdown Tests	178
6.5.3	Drawdown Tests with Slowly Varying Flow Rates	181
6.5.4	Multi-Rate Pressure Drawdown Tests	184
6.6	Interpretation of Pressure Buildup Tests	188
6.6.1	Overview.	188
6.6.2	Well with a Constant Rate History	188
6.6.3	Well with a Variable Rate History.	191
6.7	The Derivative of Pressure with Respect to Time	195
6.8	Using Type–Curves	196
6.9	The Influence of Reservoir Heterogeneity on Bottom–Hole Pressure Behaviour.	199
6.9.1	Skin Effect Due to Well Geometry	200
6.9.2	Layered Reservoir or Reservoir with an Underlying Aquifer	201
6.9.3	The Presence of a Permeability Barrier in the Drainage Area.	203
6.10	Comments on the Interpretation of Injection Tests	205
6.11	Interference Testing Between Wells	210
6.12	Pulse Testing	214
	References	217
	Exercises	219
	6.1 Calculation of the $p_D(t_{DA})$ Function for a Well in Different Drainage Area Geometries, p. 219. – 6.2 Analysis of an Extended Drawdown Test to Obtain Well and Reservoir Characteristics, Including Volume of Oil in Place, and Size and Shape of the Reservoir, p. 222. – 6.3 Analysis of a Pressure Buildup Test Following an Extended Production Period, p. 227.	
7	The Interpretation of Production Tests in Gas Wells	
7.1	Introduction.	233
7.2	The Real Gas Pseudo-Pressure – $m(p)$	233
7.3	Linearisation of the Diffusivity Equation for a Real Gas Using the $m(p)$ Function	234

7.4	Dimensionless Form of the Diffusivity Equation for a Gas	236
7.5	Non-Darcy Flow	237
7.6	The Radial Horizontal Flow of Gas Towards the Well	241
7.6.1	Transient Flow	241
7.6.2	Pseudo-Steady State Flow	242
7.6.3	Steady State Flow	242
7.6.4	General Solution to the Diffusivity Equation for a Gas	243
7.7	A Comparison Between the $m(p)$ and p^2 Solutions to the Gas Flow Equation	243
7.8	Gas Well Deliverability Testing	248
7.8.1	Introduction.	248
7.8.2	Tests Conducted in Pseudo-Steady State Flow	248
7.8.2.1	The Empirical “Back Pressure Test” (US Bureau of Mines).	249
7.8.2.2	Rigorous Interpretation of Flow-After-Flow Tests	251
7.8.3	Transient Gas Well Tests	252
7.8.3.1	The Isochronal Test	252
7.8.3.2	Multi-Rate Pressure Drawdown Tests	256
7.9	The Interpretation of Pressure Buildup Tests	258
7.10	Final Considerations.	261
	References	261
	Exercises	261
	7.1 Investigation of the Properties of Methane, and Calculation of the Pseudo-Pressure $m(p)$, p. 261. – 7.2 Analysis of a Flow-After- Flow Test in a Gas Well, Using the “Back Pressure” and “Quadratic” Methods to Estimate the AOF, p. 266. – 7.3 Analysis of an Isochronal Test with an Extended Final Flowing Period in a Gas Well to Obtain Well and Reservoir Characteristics and AOF, p. 268. – 7.4 Analysis of Two Pressure Buildup Tests Following Short Flowing Periods to Evaluate Permeability and Darcy and Non-Darcy Skins, p. 274.	
8	Downhole Measurements for the Monitoring of Reservoir Behaviour	
8.1	Introduction.	279
8.2	Selective Formation Testing (RFT)	280
8.3	Production Logs	283
8.3.1	The Measurement of Fluid Velocity in the Wellbore	283
8.3.2	Measurement of Wellbore Fluid Density	287
8.3.2.1	The Gradiomanometer (GM).	287
8.3.2.2	Nuclear-Fluid Densimeter (NFD)	289
8.3.3	Measurement of the Fluid Capacitance.	289
8.3.4	Measurement of the Photoelectric Properties of the Wellbore Fluid	290
8.3.5	The Measurement of Temperature and Pressure	292
8.3.6	Auxiliary Measurements.	293
8.3.7	The Recording of Production Logs	294
8.4	Criteria for the Interpretation of Production Logs	295
8.4.1	Production Log Diagnosis in Oil Wells.	296
8.4.2	Production Log Diagnosis in Gas Wells	297
8.4.3	Production Log Diagnosis in Water Injection Wells	298
8.5	Nuclear Logs	299
8.5.1	Overview.	299
8.5.2	Some Fundamentals of Radioactivity	301
8.5.3	The Interaction of Gamma Rays with Matter	303
8.5.4	The Interactions of Neutrons with Matter	305
8.5.4.1	Inelastic Collisions	306

8.5.4.2	Elastic Collisions	307
8.5.4.3	Thermal Neutron Capture	308
8.5.4.4	Thermal Neutron Decay	310
8.5.5	Neutron Logging Tools	313
8.6	Identification of Gas-Bearing Intervals	314
8.6.1	Newly Drilled or Recently Completed Wells	314
8.6.2	Producing Wells	315
8.7	Identification of Water Flooded Zones ($S_w > S_{iw}$)	318
8.7.1	Chlorine Log	318
8.7.2	Thermal Decay Time Log (TDT)	319
8.7.3	The Carbon/Oxygen Ratio, COR	322
	References	324

9 The Influx of Water into the Reservoir

9.1	Introduction	327
9.2	Empirical Equations for the Calculation of $W_e(t)$	329
9.2.1	The Schilthuis Equation (1936)	329
9.2.2	Hurst's Equation (1943)	331
9.3	A Global Equation for the Calculation of $W_e(t)$	332
9.4	Calculation of W_e Using the Solution to the Diffusivity Equation for Fluids of Constant Compressibility	333
9.5	Aquifer Influence Functions – Their Calculation from Reservoir History and Their Use in Predicting $W_e(t)$	339
9.5.1	Calculation of $W_e(t)$ from the Constant Rate $p_D(t_D)$ Solution	339
9.5.2	Aquifer “Influence Functions”	342
9.6	The Fetkovich Method for Finite Aquifers	345
9.7	Final Considerations	349
	References	350
	Exercises	351
	9.1 Calculation of the Maximum Possible Water Influx into an Oil Reservoir, Based on Production Data, p. 351. – 9.2 Estimation of Water Influx into an Oil Reservoir at Different Times for Three Different Aquifer Permeabilities by the van Everdingen and Hurst Method, p. 352. – 9.3 Estimation of Water Influx into an Oil Reservoir at Different Times for Three Different Aquifer Permeabilities by the Fetkovich Method, p. 355.	

10 The Material Balance Equation

10.1	Introduction	359
10.2	Average Reservoir Pressure	362
10.3	Dry Gas Reservoirs	365
10.3.1	Closed Reservoir	365
10.3.1.1	Material Balance Equation	365
10.3.1.2	Prediction of the Gas Production Rate as a Function of Time	367
10.3.2	Reservoir in Contact with an Aquifer	369
10.3.2.1	Material Balance Equation	369
10.3.2.2	Prediction of the Gas Production Rate as a Function of Time	372
10.3.2.3	Prediction of the Reservoir Pressure Behaviour	373
10.4	Gas Condensate Reservoirs	376
10.4.1	Introduction	376
10.4.2	Pressure Maintenance by Water Injection or Gas Recycling	377
10.4.3	Closed Reservoir	379

10.4.4	Reservoir in Contact with an Aquifer	380
10.4.4.1	Calculation of the Volumetric and Phase Behaviour of a Condensate Gas Using an EOS	380
10.4.4.2	Prediction of Reservoir Behaviour.	385
10.5	Oil Reservoirs	387
10.5.1	General Material Balance Equation for Oil Reservoirs.	387
10.5.2	Drive Indices	391
10.5.3	Special Cases	393
10.5.3.1	Undersaturated Oil Reservoir at Pressures Above Bubble Point . . .	393
10.5.3.2	Saturated Oil Reservoirs, Without Gas Cap or Aquifer	394
10.5.3.3	Oil Reservoir with a Gas Cap, Not in Communication with an Aquifer	395
	References	396
	Exercises	397
	10.1 Material Balance Equation: Planning the Development of a Dry Gas Reservoir to Maintain Steady Production for as Long as Possible given Certain Operating Constraints, p. 397. –	
	10.2 Material Balance Equation: Estimation of Initial Gas Reserves in Communication with an Aquifer, p. 400. –	
	10.3 Calculation of Drive Indices and Water Influx for an Oil Reservoir with Gas Cap and Aquifer, p. 401. – 10.4 Calculation of Oil Production for an Oil Reservoir not in Contact with an Aquifer, p. 402.	
	Author Index	405
	Subject Index	407