
CONTENTS

Preface	xi
Acknowledgments	xiii
1 Setting the Stage	1
1.1 Introduction / 1	
1.2 Phases and Porous Media / 2	
1.3 Grain and Pore Size Distributions / 6	
1.4 The Concept of Saturation / 12	
1.5 The Concept of Pressure / 13	
1.6 Surface Tension Considerations / 16	
1.7 Concept of Concentration / 30	
1.8 Summary / 32	
1.9 Exercises / 32	
Bibliography / 33	
2 Mass Conservation Equations	35
2.1 Introduction / 35	
2.2 Microscale Mass Conservation / 38	
2.3 Integral Forms of Mass Conservation / 39	
2.4 Integral Theorems / 44	
2.4.1 Divergence Theorem / 45	
2.4.2 Transport Theorem / 45	
2.5 Point Forms of Mass Conservation / 46	
2.6 The Macroscale Perspective / 48	
2.6.1 The Representative Elementary Volume / 49	
2.6.2 Global and Local Coordinate Systems / 50	
2.6.3 Macroscopic Variables / 53	
2.6.4 Definitions of Macroscale Quantities / 56	
2.6.5 Summary of Macroscale Quantities / 62	
2.7 The Averaging Theorems / 63	
2.7.1 Spatial Averaging Theorem / 64	
2.7.2 Temporal Averaging Theorem / 66	
2.8 Macroscale Mass Conservation / 67	
2.8.1 Macroscale Point Forms / 67	
2.8.2 Integral Forms / 71	

- 2.9 Applications / 73
 - 2.9.1 Integral Analysis / 74
 - 2.9.2 Point Analysis / 76
- 2.10 Summary / 79
- 2.11 Exercises / 79
 - Bibliography / 81

3 Flow Equations

83

- 3.1 Introduction / 83
- 3.2 Darcy's Experiments / 85
- 3.3 Fluid Properties / 88
- 3.4 Equations of State for Fluids / 89
 - 3.4.1 Mass Fraction / 89
 - 3.4.2 Mass Density and Pressure / 90
 - 3.4.3 Fluid Viscosity / 92
- 3.5 Hydraulic Potential / 93
 - 3.5.1 Hydrostatic Force and Hydraulic Head / 93
 - 3.5.2 Derivatives of Hydraulic Head / 97
- 3.6 Single-Phase Fluid Flow / 98
 - 3.6.1 Darcy's Law / 99
 - 3.6.2 Hydraulic Conductivity and Permeability / 102
 - 3.6.3 Derivation of Groundwater Flow Equation / 106
 - 3.6.4 Recapitulation of the Derivation / 111
 - 3.6.5 Initial and Boundary Conditions / 113
 - 3.6.6 Two-Dimensional Flow / 116
- 3.7 Two-Phase Immiscible Flow / 121
 - 3.7.1 Derivation of Flow Equations / 121
 - 3.7.2 Observations on the p^c - s^w Relationship / 127
 - 3.7.3 Formulas for the p^c - s^w Relationship / 135
 - 3.7.4 Observations of the k_{rel}^α - s^w Relationship / 143
 - 3.7.5 Formulas for the k_{rel}^α - s^w Relation / 146
 - 3.7.6 Special Cases of Multiphase Flow / 149
- 3.8 The Buckley-Leverett Analysis / 155
 - 3.8.1 Fractional Flow / 155
 - 3.8.2 Derivation of the Buckley-Leverett Equation / 157
 - 3.8.3 Solution of the Buckley-Leverett Equation / 158
- 3.9 Summary / 160
- 3.10 Exercises / 161
 - Bibliography / 162

4 Mass Transport Equations

165

- 4.1 Introduction / 165
- 4.2 Velocity in the Species Transport Equations / 167
 - 4.2.1 Direct Approach / 168
 - 4.2.2 Rigorous Approach / 169

4.2.3	Distribution Approach / 172	
4.2.4	Summary / 175	
4.3	Closure Relations for the Dispersion Vector / 176	
4.4	Chemical Reaction Rates / 180	
4.5	Interphase Transfer Terms / 182	
4.5.1	Kinetic Formulation / 183	
4.5.2	Equilibrium Formulation / 187	
4.5.3	Summary: Kinetic vs. Equilibrium Formulations / 194	
4.6	Initial and Boundary Conditions / 195	
4.7	Conclusion / 196	
4.8	Exercises / 197	
	Bibliography / 198	
5	Simulation	199
5.1	1-D Simulation of Air-Water Flow / 199	
5.1.1	Drainage in a Homogeneous Soil / 201	
5.1.2	Drainage in a Heterogeneous Soil / 205	
5.1.3	Imbibition in Homogeneous Soil / 206	
5.2	1-D Simulation of DNAPL-Water Flow / 207	
5.2.1	Primary DNAPL Imbibition in Homogeneous Soil / 208	
5.2.2	Density Effect / 208	
5.2.3	DNAPL Drainage in Homogeneous Soil / 209	
5.2.4	Secondary Imbibition of DNAPL in Homogeneous Soil / 210	
5.2.5	Secondary Drainage in Homogeneous Soil / 211	
5.2.6	Primary Imbibition in Heterogeneous Soil / 212	
5.3	2-D Simulation of DNAPL-Water Flow / 213	
5.3.1	DNAPL Descent into a Water-Saturated Reservoir / 213	
5.4	Simulation of Multiphase Flow and Transport / 216	
5.4.1	1-D Two-Phase Flow and Transport / 217	
5.4.2	2-D Two-Phase Flow and Transport / 218	
5.5	2-D Single-Phase Flow and Transport / 224	
5.5.1	Base Case / 228	
5.5.2	Effect of Inflow / 228	
5.5.3	Impact of Well Discharge / 230	
5.5.4	Effect of Adsorption / 231	
5.5.5	Effect of a Low Transmissivity Region / 232	
5.5.6	Effect of a High Transmissivity Region / 234	
5.5.7	Effect of Rate of Reaction / 235	
5.6	3-D Single-Phase Flow and Transport / 236	
5.7	2-D Three-Phase Flow / 239	
5.8	Summary / 244	
	Bibliography / 245	
	Select Symbols	247
	Index	253

