Contents

Introduction to polymer flooding

	1.1 1.2	Introduction Mobility ratio and polymer recovery mechanisms			
	1.3 1.4	Background and early experience Layout of this book	3		
2	Stru	Structure of the main polymers used in improved oil recovery (IOR)			
	2.1	Introduction	6		
	2.2	The structure of xanthan biopolymer	7		
		2.2.1 Primary chemical structure of xanthan	7		
		2.2.2 Conformation of the xanthan molecule	9		
		2.2.3 Molecular weight and molecular weight distribution (MWD) of xanthan 2.2.4 Order-disorder transition in xanthan	14 15		
		The structure of partially hydrolysed polyacrylamide (HPAM)	19		
		2.3.1 The chemical structure of HPAM	19		
		2.3.2 Molecular conformation of HPAM molecules in aqueous solution	21		
		2.3.3 Molecular weight and molecular weight distribution of HPAM	21		
	2.4	Methods of detection and assay for xanthan and HPAM	24		
		2.4.1 Xanthan assay	25		
		2.4.2 The chemical detection of polyacrylamide	25		
		2.4.3 Size exclusion chromatography determination of HPAM	27		
		Manufacture of polymers for improved oil recovery	27		
		2.5.1 Biopolymer production	28		
	26	2.5.2 Polyacrylamide production	29		
	2.6	New polymers for IOR application	32		
		2.6.1 New synthetic polymers 2.6.2 Improved biopolymers	33		
		2.0.2 Improved biopolymers	35		
3	Pro	perties of polymer solutions	37		
	3.1	Introduction	37		
	3.2	Solution viscosity of polymers	37		
		3.2.1 Viscosity and the generalised Navier-Stokes equations	38		
		3.2.2 How polymers viscosify	42		
	3.3	The molecular size of polymers in solution	43		
		3.3.1 The intrinsic viscosity: concentration and molecular weight relationships	43		
		3.3.2 Chain size and the molecular expansion factor3.3.3 Relationships for flexible coil polymers	47 48		
		3.3.4 Equations for less flexible molecules			
	3.4	Introduction to polymer rheology	50 52		
	J. 4	3.4.1 Steady shear flow of inelastic polymers	52 52		
		3.4.2 Viscoelastic polymers	56		
		3.4.3 Extensional flow	59		
		3.4.4 The viscosity of polyelectrolyte solutions	61		
		· · · · · · · · · · · · · · · · · · ·			

CONTENTS

		3.4.5 Salt, hardness and pH sensitivities of polyacrylamide and xanthan	62
		3.4.6 Molecular basis of polymer rheology	64
		3.4.7 Viscometry for polymer solutions	67
		3.4.8 Capillary flow of Newtonian and non-Newtonian fluids	69 74
		3.4.9 The Mooney-Weissenberg-Rabinowitsch equations	74 75
	3.5	Thermodynamics of polymer solutions	76
	36	Laboratory preparation and testing of polymer solutions 3.6.1 'Appropriate' laboratory solution preparation	77
		3.6.1 'Appropriate' laboratory solution preparation3.6.2 Removal of microgel	78
		3.6.3 Polymer dispersal in solution	78
		3.6.4 Screen factor measurements on polymer solutions	79
4	Poly	ymer stability	83
			01
	4.1	Introduction	83 85
	4.2 4.3	Chemical stability of polymers for IOR	102
	4.1	Mechanism of polymer chemical degradation 4.3.1 HPAM degradation mechanisms	102
		4.3.2 Xanthan degradation mechanisms	102
	4.4	Mechanical stability of polymers	114
	4.5	Biological degradation of polymers	124
5	Pol	ymer retention in porous media	126
		The Alexandra	126
	5.1	Introduction Polymer retention levels—units	120
	5.2 5.3	Polymer retention mechanisms in porous media	128
	1	5.3.1 Polymer adsorption	129
		5.3.2 Mechanical entrapment of polymer	130
		5.3.3 Hydrodynamic retention of polymer	133
		5.3.4 Remarks on retention mechanisms	135
	5.4	Polymer adsorption at the solid-liquid interface	136
	5.5	Experimental measurement of polymer retention in porous media	139
		5.5.1 Polymer retention from effluent analysis	139
		5.5.2 Experimental refinements in retention measurements	140
	5.6	Literature survey on polymer adsorption/retention	143
		5.6.1 Introductory overview of polymer adsorption in porous media	143 144
		5.6.2 Adsorption of HPAM and other flexible coil polymers 5.6.3 Adsorption of xanthan biopolymer in porous media	157
		5.6.4 Polymer adsorption on mineral surfaces	159
		5.6.5 Effect of adsorbed polymer on two-phase flow and relative	127
		permeabilities	161
	5.7	Concluding remarks	163
6	Po	ymer rheology in porous media	165
	6.1	Introduction	165
	6.2	Models of porous'media	166
	J.2	6.2.1 Experimental examination of pore structure	166
		6.2.2 Darcy flow in porous media and polymer apparent viscosity	168
		6.2.3 Capillary bundle models	169
	6.3	The flow of pseudoplastic fluids in porous media	171
		6.3.1 General approach to <i>in-situ</i> rheology	171
		6.3.2 Xanthan in-situ rheology: pseudoplastic behaviour	173
		6.3.3 Xanthan <i>in-situ</i> rheology: apparent slip effects	178
	<i>.</i>	6.3.4 Summary of experiments on the <i>in-situ</i> rheology of xanthan	182 183
	6.4	The in-situ rheology of viscoelastic fluids in porous media	103

viii

	CONTENTS	ix
6.5	Theoretical analysis of polymer rheology in porous media 6.5.1 Summary of approaches to modelling <i>in-situ</i> rheology	192 193
	6.5.2 Network modelling of non-Newtonian fluids in porous media 6.5.3 Rheological effects in the presence of depleted layers	195
6.6	6.5.3 Rheological effects in the presence of depleted layers Concluding remarks on polymer <i>in-situ</i> rheology	202 206
	mer transport in porous media	208
I UIY	met transport in porous meura	200
	Introduction	208
	Tracer and polymer flow equations in a 1-D core 7.2.1 The convection-dispersion equation for tracer and polymer transport	209 210
	7.2.1 Non-equilibrium effects in the CD equation	210
	Polymer and tracer dispersion in porous media	216
	7.3.1 Magnitude of polymer and tracer dispersion coefficients	216
	7.3.2 Modelling of polymer and tracer dispersion	219
	7.3.3 Non-equilibrium effects in polymer transport	224
7.4	Excluded/inaccessible pore volume effects in polymer transport through porous media	224
	7.4.1 Interpretation of velocity enhancement in polymer transport through porous media	224
	7.4.2 Underlying assumptions in the formulation of the transport equation	
	in the presence of inaccessible/excluded pore volume effects	227
	Equilibrium and non-equilibrium adsorption 7.5.1 The effect of adsorption/retention on polymer effluent profiles	230 230
	7.5.2 Non-linear adsorption of polymer	230
	7.5.3 Non-equilibrium polymer adsorption	234
	Viscous fingering in polymer flooding	237
	7.6.1 Inclusion of viscous fingering in the macroscopic flow equations	237
	7.6.2 Graded viscosity banks	241
7.7 7 R	Polydispersity effects in polymer transport through porous media Concluding remarks	242 244
	-	
Oil	displacement using polymers	246
8.1	Introduction	246
8.2	Overview of the main oil displacement mechanisms	247
8.3	'Incremental' oil in polymer flooding	250
8.4	One-dimensional polymer flooding	251
	8.4.1 Extended fractional flow theory for 1-D polymer flooding8.4.2 Oil displacement by polymers in linear cores	252 258
8.5	Multiphase flow equations for polymer flooding	260
0.5	8.5.1 Overview of polymer simulation models	260
	8.5.2 The two-phase flow/polymer transport equations	261
	8.5.3 A simple finite difference strategy	262
	8.5.4 Application of numerical scheme and comparison with 1-D analytical solution	266
	8.5.5 The 3-D, two-phase polymer and heat transport equations	267
8.6	Improvement in areal sweep efficiency	270
8.7	Polymer recovery mechanisms in simple stratified systems	274
	8.7.1 Description of basic flow mechanisms	275
	8.7.2 The two-layer numerical model	277
	8.7.3 Effects of vertical permeability on cross-flow	278
	8.7.4 Ratio of horizontal permeability and layer thicknesses	280 281
	8.7.5 Fluid mobilities8.7.6 Effects of vertical permeability on oil production	/**
	8.7.7 Conclusions on polymer recovery mechanisms for a simple two-layer	
	reservoir	784

8

CONTENTS

	8.8 × 8.9 8.10	The effects of polymer in real-field cross-sections 8:8.1 A simulation case study—the Brent Sands 8:8.2 Eight-layer cross-sectional model Adsorption and degradation in field scale polymer floods 8:9.1 Polymer adsorption models in field calculations	285 287 292 297 297 299 300 304 306 308 310	
9	App	lication and planning of field polymer floods	312	
	9.2 9.3 9.4	 Preliminary screening of candidate reservoirs for polymer flooding application 9.2.1 Background to the development of screening rules 9.2.2 Reservoir screening criteria for polymer flooding 9.2.3 Rapid polymer screening calculations Design work for planning a field polymer flood pilot 9.3.1 Field studies 9.3.2 Laboratory tests 9.3.3 Computer simulations Concluding remarks 	313 313 315 319 320 321 324 332 340	
Re	feren	ces	341	
Index				

х