

THE APPLICATION OF LATTICE GAS AUTOMATA FOR SIMULATING
POLYMER INJECTION IN POROUS MEDIA

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ABSTRAK

Penyelakuan daripada penyesaran polimer di dalam reserbor merupakan suatu teknik yang penting dalam kejuruteraan petroleum yang digunakan untuk meramalkan kesan pengeluaran minyak. Pemodelan aliran polimer menembusi media berliang kerap diterbitkan oleh pendekatan skala makroskopik. Untuk mendapat gambaran aliran polimer yang lebih baik, suatu model skala liang (skala meso) digunakan dalam tesis ini untuk menentukan sifat makroskopik. Tujuan penyelidikan ini adalah untuk mengembangkan model-model Frisch-Hasslacher-Pomeau (FHP) III dari kekisi gas automata kepada menyelakukan aliran polimer dan minyak secara mikroskopik untuk mengkaji sifat-sifat makroskopik bagi fenomena penjerapan, pembentukan gel dan penyesaran polimer. Pada penyelakuan aliran satu fasa, suatu cadangan peraturan perlanggaran daripada interaksi antara polimer dan benda pepejal untuk proses-proses penjerapan dan pembentukan gel telah dibuat. Hubungkait antara pelbagai sifat makroskopik, seperti penumpuan polimer, keliangan, panjang permukaan, lebar liang telah pun diperolehi. Pada amnya, penyelakuan-penyelakuan kekisi gas automata bersetuju dengan baik dengan kajian-kajian sebelumnya, dengan perbezaan antara mereka adalah berjulat dari 2.0% hingga 17.4%. Pada penyelakuan aliran dua fasa, mekanisme penyesaran untuk pelbagai nisbah mobiliti dan kadar penjerapan telah dianggarkan. Perubahan ketepuan dalam liang hujung-mati semasa penyesaran telah pun dianalisis. Hasil-hasil penyelakuan dua-fasa bersetuju dengan baik dengan hasil-hasil penyelidikan makmal, dengan perbezaan daripada seluruh parameter adalah berjulat dari 3.1% hingga 18.4%. Masa pengiraan adalah suatu faktor penting yang mempengaruhi kebolehlaksanaan penerapan model skala meso dalam penyelakuan media berliang yang bersaiz besar. Disebabkan sifat kekisi gas automata, penyelakuan boleh dilaksanakan menggunakan komputer-komputer selari secara efektif. Penggunaan komputer-komputer selari boleh mengurangkan masalah masa pengiraan. Dalam tesis ini, suatu teknik pengiraan selari dicadangkan untuk melarikan penyelakuan kekisi gas automata. Sistem gugusan dan komputer-komputer berdiri sendiri telah digunakan untuk menyelakukan media berliang aliran bersambung dan tak-bersambung, berturut-turut. Hasil penyelakuan-penyelakuan selari bersetuju dengan baik kepada hasil penyelakuan-penyelakuan tunggal, dengan perbezaan maksimum dari seluruh parameter adalah 3.93%. Masa pengiraan telah pun dikurangkan oleh suatu faktor yang berjulat dari 1.9083 hingga 14.3411.

ABSTRACT

The simulation of polymer displacement in a reservoir is one of the important techniques in petroleum engineering that is used to predict the performance of oil production. Modeling of polymer flow through a porous medium is often derived by a macroscopic scale approach. In order to gain better insight of the polymer flow, a pore scale (mesoscale) model is applied in this thesis to determine the macroscopic properties. The objectives of this research are to develop the Frisch-Hasslacher-Pomeau (FHP) III models of lattice gas automata to simulate microscopic polymer and oil flow for the study of macroscopic properties of adsorption, gelation and polymer displacement phenomena. In the single-phase flow simulation, collision rules of interactions between polymer and solid material for adsorption and gelation processes were proposed. Correlations between various macroscopic properties such as polymer concentration, porosity, surface length, pore width were obtained. In general, the lattice gas automata simulations were in good agreement with previous studies, where the differences between them were between 2.0% to 17.4%. In the two-phase flow simulation, the displacement mechanism for various mobility ratio and adsorption rate was estimated. The change of saturation in dead-end pores during the displacement was analyzed. The results of the two-phase flow simulations were in good agreement with those of laboratory experiments, where differences of all parameters were between 3.1% to 18.4%. The computation time is a crucial factor influencing the feasibility of a mesoscale model application in simulating large porous media. Due to the nature of lattice gas automata, the simulation can run using parallel computers effectively. The use of parallel computers is able to reduce the computation time problem. In this thesis, a parallel computation technique has been proposed to run the lattice gas automata simulation. A cluster system and standalone computers were used to simulate communicating and non-communicating flow in porous media, respectively. The results of the parallel simulations were in good agreement with those of single simulations, where maximum difference of all parameters was 3.93%. The computation time was reduced by a factor that ranged from 1.9083 to 14.3411.

TABLE OF CONTENT

CHAPTER	TITLE	PAGE
	TITLE PAGE	i
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRAK	v
	ABSTRACT	vi
	TABLE OF CONTENT	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF SYMBOLS	xxi
	LIST OF APPENDICES	xxvii
1	INTRODUCTION	1
	1.1 Background	1
	1.2 Statement of Problem	4
	1.3 Objectives of the Research	4
	1.4 Scope of Work	5
	1.5 Summary	6
2	THEORY	7
	2.1 Introduction	7
	2.2 Types of Lattice	7
	2.3 Collision Rules	9

2.4	Evolution of Particles	11
2.5	Equations of the Lattice Gas Automata Method	13
2.5.1	Propagation and Collision Operators	13
2.5.2	Microscopic Properties	15
2.5.3	Coarse Graining	16
2.5.4	Macroscopic Properties	17
2.5.5	Pressure	18
2.5.6	Viscosity	19
2.5.7	Porosity	19
2.5.8	Pressure Gradient	21
2.5.9	Velocity	22
2.5.10	Flow Rate	23
2.5.11	Permeability	23
2.6	Initial Conditions	24
2.7	Boundary Conditions	25
2.8	Derivation of Navier-Stokes Equation from Lattice Gas Automata	28
2.9	Binary Fluid Model	33
2.9.1	Colour Model	34
2.9.2	Colour-Field Model	34
2.9.3	Measurement of Surface Tension	35
2.10	Reservoir Rock	36
2.10.1	Porosity	36
2.10.2	Saturation	37
2.10.3	Permeability	38
2.10.4	Relative Permeability	40
2.11	Polymer	42
2.11.1	Adsorption	43
2.11.2	Gelation	47
2.11.3	Measurements of Adsorption and Gelation	48
2.11.4	Polymer Properties	51
2.11.5	Polymer Displacement in Oil Reservoir	53
2.12	Summary	56
3	LITERATURE REVIEW	57

3.1	Introduction	57
3.2	Polymer Adsorption in Porous Media	57
3.3	Polymer Gelation in Porous Media	58
3.4	Immiscible Displacement Model	60
3.5	Parallel Computation for Lattice Boltzmann	64
3.6	Steady State Period	65
3.7	Relative Permeability	67
3.8	Summary	68
4	THE DEVELOPMENT OF LATTICE GAS AUTOMATA	70
4.1	Introduction	70
4.2	Modeling of Adsorption	70
4.3	Modeling of Gelation	72
4.4	Procedure of Simulator for Single-Phase Flow	74
4.5	Modeling of Polymer Displacement	75
4.5.1	Viscosity	77
4.5.2	Saturation	78
4.5.3	Velocity	79
4.5.4	Relative Permeability	80
4.5.5	Fractional Flow	81
4.5.6	Displacement Efficiency	82
4.6	Procedure of Simulator for Two-Phase Flow	82
4.7	Summary	84
5	VALIDATION OF LATTICE GAS AUTOMATA MODELS	85
5.1	Introduction	85

5.2	Laboratory Experiments	85
5.2.1	Polymer Adsorption in Continuous System	86
5.2.2	Polymer Displacement	87
5.3	Simulation Procedures	89
5.3.1	Polymer Adsorption in Continuous System	89
5.3.2	Polymer Adsorption in Batch System	91
5.3.3	Polymer Gelation	92
5.3.4	Polymer Displacement	92
5.4	Matching between the Experimental and Simulation Results	94
5.4.1	Polymer Adsorption in Continuous System	94
5.4.2	Polymer Adsorption in Batch System	97
5.4.3	Polymer Gelation	100
5.4.4	Polymer Displacement	101
5.5	Summary	104
6	SIMULATION OF ADSORPTION AND GELATION	105
6.1	Introduction	105
6.2	Velocity	105
6.3	Effects of Porosity and Surface Length on Adsorption Process	106
6.4	Effects of Adsorption on Permeability and Velocity	110
6.5	Polymer Adsorption in Batch System	113
6.6	Effects of Porosity, Surface Length and Pore Width on Gelation Process	115
6.7	Effects of Gelation on Permeability and Flow Rate	119
6.8	Summary	123
7	SIMULATION OF POLYMER DISPLACEMENT	124
7.1	Introduction	124
7.2	Relative Permeability	124

7.3	Mobility Ratio	127
7.4	Adsorption	131
7.5	Dead-End Pore	133
7.6	Summary	138
8	PARALLEL COMPUTATION	140
8.1	Introduction	140
8.2	Hardware and Software	140
8.3	Additional Collision Rules for Communicating Model	142
8.4	Formulations	144
8.5	Simulation Runs	147
8.5.1	Non-Communicating Flow System	148
8.5.2	Communicating Flow System	154
8.5.2.1	Liquid Flow in Porous Media	154
8.5.2.2	Polymer Adsorption	161
8.5.2.3	Polymer Gelation	164
8.5.2.4	Polymer Displacement	167
8.6	Summary	171
9	CONCLUSIONS AND RECOMMENDATIONS	173
9.1	Conclusions	173
9.2	Recommendations for Future Work	174
	REFERENCES	175
	APPENDICES A - J	185 - 264

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Equations of velocity vectors for square and hexagonal lattice shapes	9
2.2	Bottle test gel strength codes (Sydansk, 1988)	51
3.1	Constants used in simulation studies of polyacrylamide/redox and biopolymer/Cr(III) systems (Khachatoorians, 2004)	59
5.1	Summary of experimental results of adsorption in a continuous system	95
5.2	Correlations between polymer concentration and probability factor P_{pg}	101
5.3	Summary of experimental results of polymer displacement	101
6.1	Properties of the porous media	108
6.2	Constants of the Langmuir and Freundlich equations	114
6.3	Data of LGA porous media	116
7.1	Viscosity data of polymer displacement simulation	128
8.1	Specification of the computer types	141
8.2	Simulation results of rock liquid properties for non-communicating flow	149
8.3	Speedup and efficiency of computer types	153
8.4	Average porosity for various division of porous medium	155
8.5	Average velocity for various division of porous medium	156
8.6	Average permeability for various division of porous medium	157
8.7	Speedup and efficiency of cluster system using computer type D	159
8.8	Simulation results of rock and liquid properties for polymer adsorption	162
8.9	Speedup and efficiency of cluster system for polymer adsorption simulation	163
8.10	Simulation results of rock and liquid properties for polymer gelation	165

8.11	Speedup and efficiency of cluster system for polymer gelation simulation	166
8.12	Simulation results of rock and liquid properties for polymer displacement	168
8.13	Speedup and efficiency for polymer displacement simulation	169
A.1	Lookup tables of collision rules	187
B.1	Development of lattice gas automata	189
D.1	Conversion factors between cgs units and LGA units	194
E.1	Absorbance level of xanthan	197
E.2	Data and results of experiment	199
F.1	Experiment data of commercial xanthan	201
F.2	Experiment data of xanthan from raw tapioca	201
F.3	Experiment data of xanthan from tapioca	202
F.4	Experiment data of xanthan from rice	202
F.5	Experiment data of xanthan from sago	203
F.6	Adsorption of commercial xanthan	203
F.7	Adsorption of xanthan from raw tapioca	204
F.8	Adsorption of xanthan from tapioca	204
F.9	Adsorption of xanthan from rice	205
F.10	Adsorption of xanthan from sago	205
H.1	Experiment data of polymer displacement	214
H.2	Experimental results of pore volume injected, produced oil and displacement efficiency during polymer flooding	215
H.3	Properties of xanthan solution with concentration 400 ppm	216

LIST OF FIGURES

NO. FIGURE	TITLE	PAGE
2.1	Square grid of a 2-dimensional lattice	8
2.2	Hexagonal grid of a 2-dimensional lattice	8
2.3	A set of collision rules for the FHP model (Buick, 1997)	10
2.4	Evolution of particles on an area of hexagonal lattice from time t to time $t+1$. The red arrows represent moving particles and rest particles are represented by the yellow circles	12
2.5	Coarse graining process. The small red arrows represent moving particles, rest particles are represented by the yellow circles, and the large black arrow represents resultant vector of particles in a region	17
2.6	Illustration of solid and void sites in LGA porous media	20
2.7	Illustration of solid, isolated void, and connected void sites in LGA porous media	21
2.8	Average velocity vector of the entire lattice region. The small red arrows represent moving particles, rest particles are represented by the yellow circles, and the large arrow represents resultant velocity vector	23
2.9	Flow passes through obstacles between boundary plates	25
2.10	No-slip boundary conditions at vertical and horizontal boundaries	26
2.11	Free-slip boundary conditions	27
2.12	Periodic boundary conditions. (a) Four particles impinge the boundaries at time step t . (b) The particles are reintroduced at corresponding positions at the opposite boundaries with the same velocity at time step $t+1$	27
2.13	Parallel flow in linear beds	39
2.14	Series flow in linear beds	40
2.15	Profile of relative permeability	42
2.16	Polymer adsorption at a solid-liquid interface (Sorbie, 1991)	44

2.17	Curve of isothermal adsorption	45
2.18	The BET model (Adamson, 1976)	45
2.19	Illustration of polymer solution rheology	52
2.20	The determination of flood front saturation	55
3.1	One-dimensional waterflood example (Jiao, 1996)	62
3.2	Saturation contours at 720 days in a five-spot waterflood with unfavorable mobility ratio for (a) a diagonal grid and (b) a parallel grid (Jiao, 1996)	63
3.3	Comparison of oil recovery curves computed for diagonal and parallel five-spot grids as pore volumes injected (Jiao, 1996)	63
3.4	Communication pattern of 2 X 2 processors (Cherba, 2002)	66
3.5	Velocity as a function of time step (Waite, 1998)	66
4.1	Collision rules for polymer adsorption process	71
4.2	Collision rules for polymer gelation process	73
4.3	Flow chart of the simulator for single-phase flow	76
4.4	Illustration of oil particles in void sites that are being displaced by injected polymer solution in lattice gas automata porous media	78
4.5	Flow chart of the simulator for two-phase flow	83
5.1	The schematic of the continuous system apparatus	86
5.2	The schematic of the polymer displacement experiment apparatus	88
5.3	Polymer adsorption in continuous system. (a) Initial condition of the system. (b) Adsorption process has taken place. Black areas represent solid, red areas represent polymer solution, and yellow dots represent adsorbed polymer	90
5.4	Polymer adsorption in batch system. (a) Initial condition of the system. (b) Adsorption process has taken place. Black areas represent solid, white areas represent void areas, arrows represent moving particles, and yellow layers represent adsorbed polymer	91
5.5	Polymer gelation in porous media. (a) Initial condition of a porous medium. (b) Gelation process has taken place. Black areas represent solid, red areas represent polymer solution, and yellow areas represent gel	93
5.6	Relationship between concentration and absorbed xanthan	94
5.7	Adsorption in LGA porous medium for concentration of commercial xanthan is 1000 ppm	96
5.8	Relationships between polymer concentration and probability factor P_{pa}	97

5.9	Simulation of polymer adsorption for the batch experiment after 5000 seconds. The concentration of polymer is 200 ppm	98
5.10	Cumulative number of adsorbed polymer particles on simulation of batch experiment for 3 hours	99
5.11	Comparisons of experiment and LGA simulation of adsorbed xanthan molecules for batch system	99
5.12	Arbitrary porous medium to represent sandpack A. Black areas represent solid, red areas represent polymer and yellow areas represent gel	100
5.13	Injected pore volume vs. displacement efficiency for validation	102
5.14	LGA porous medium for validation. Black areas represent solid, purple areas represent polymer, red areas represent oil, and yellow dots represent adsorbed polymer	102
5.15	Relative permeability curves for validation	103
6.1	Comparison of velocity profile of plane Couette flow	106
6.2	Polymer adsorption in the porous medium 1 after ten days. Concentration of polymer is 2457 ppm	107
6.3	Polymer adsorption in the porous medium 2 after ten days. Concentration of polymer is 2457 ppm	107
6.4	Polymer adsorption in the porous medium 3 after ten days. Concentration of polymer is 2457 ppm	108
6.5	Polymer adsorption in the porous medium 4 after ten days. Concentration of polymer is 2457 ppm	108
6.6	Effect of polymer concentration to number of adsorbed polymer particles in the porous medium 1 during 20 days	109
6.7	Number of adsorbed polymer particles as a function of time in the four porous media for concentration 23962 ppm during 20 days	110
6.8	The effect of polymer concentration to fluid velocity reduction in the porous medium 3 during 20 days	111
6.9	The effect of polymer concentration to permeability reduction in the porous medium 3 during 20 days	112
6.10	Reduction of ratio permeability due to adsorption process	113
6.11	Comparisons of theoretical and LGA simulation curves of adsorbed xanthan molecules for batch experiment	114
6.12	Gelation in porous medium A. Black areas represent solid, red areas represent polymer, and yellow areas represent gel	115
6.13	Gelation in Porous medium B	115
6.14	Gelation in porous medium C	116
6.15	Gelation in Porous medium D	116

6.16	Effect of porosity, surface length (L_s) and pore width (w_p) on gelation process in the four porous media for xanthan concentration 6483 ppm during 1500 minutes	117
6.17	Effect of porosity and surface length (L_s) on gelation process in the four porous media for xanthan concentration 1523 ppm during 1500 minutes	118
6.18	Effect of pore width (w_p) on gelation process for various xanthan concentrations	119
6.19	Final permeability of porous medium A for various concentrations of polyacrylamide and xanthan	120
6.20	Final permeability of porous media for various xanthan concentrations	120
6.21	Flow rate of fluid for various xanthan concentrations after gelation process	121
6.22	Reduction of permeability ratio due to gelation process	122
7.1	Simulation of polymer displacement on a 5 cm by 2 cm porous medium after 200 seconds. Black areas represent solid, red areas represent oil, purple areas represent polymer solution, purple dots represent water and yellow dots represent adsorbed polymer	125
7.2	Comparisons of relative permeability curves among simulation results and unsteady-state correlations	126
7.3	Comparisons of relative permeability curves among simulation results, imbibition process and standstone correlations	126
7.4	Porous medium for investigating the effect of mobility ratio	128
7.5	Effect of mobility ratio on relative permeability	129
7.6	Effect of mobility ratio on displacement efficiency	130
7.7	Effect of mobility ratio on fractional flow	130
7.8	Effect of adsorption on relative permeability	132
7.9	Effect of adsorption on displacement efficiency	132
7.10	Polymer displacement in porous media with various neck width sizes of dead-end pore after 260 seconds. Black areas represent solid, purple areas represent polymer, and red areas represent oil	134
7.11	Polymer displacement in porous media with various areas of dead-end pore body after 260 seconds	135
7.12	Polymer displacement in porous media with various neck positions of dead-end pores after 260 seconds	136
7.13	Dead-end pore pressure as a function of time and various neck width sizes of dead-end pore	136
7.14	Dead-end pore pressure as a function of time and various dead-end pore areas	137
7.15	Polymer saturation in dead-end pore as a function of time and	

	the distance of neck of dead-end pore from the left side	138
8.1	Flow diagram of cluster system	142
8.2	Propagations of particles cross the borderline	143
8.3	Porous medium with non-communicating flow. Black areas represent solid material and purple areas represent liquid	148
8.4	Average velocity of non-communicating flow system	150
8.5	Average permeability results for liquid flow in porous medium with non-communicating channels	151
8.6	Computation time for various computer types	151
8.7	Computation time for various numbers of processors	152
8.8	Fluid flow in a 10 cm x 8 cm porous medium. Black areas represent solid material and purple areas represent liquid	154
8.9	Average velocity results for various divisions of a porous medium	155
8.10	Average permeability results for various division of a porous medium	157
8.11	Computation time for various numbers of processors	158
8.12	Speedup for various numbers of processors	159
8.13	Communication pattern based on the algorithm	160
8.14	Polymer flow with adsorption process in a 5 cm by 4 cm porous medium after 2000 seconds. Black areas represent solid, red areas represent polymer solution, and yellow dots represent adsorbed polymer	161
8.15	Computation time of various numbers of processors for polymer adsorption in porous media with communicating flow	163
8.16	Polymer flow with gelation process in a 5.5 cm by 4 cm porous medium. Black areas represent solid, red areas represent polymer solution, and yellow areas represent gel	164
8.17	Computation time of various numbers of processors for polymer gelation in porous media with communicating flow	166
8.18	Polymer displacement in a 5 cm by 4 cm porous medium. Black regions represent solid materials; red regions represent displaced oil; purple regions represent displacing polymer solution, and yellow dots represent adsorbed polymer particles on solid surface	167
8.19	Comparisons of displacement efficiency for porous medium with communicating flow	169
8.20	Computation time of various computer numbers for polymer displacement in porous media with communicating flow	170

C.1	Plane Couette flow	191
C.2	Plane Couette flow in case plates move in opposite direction	191
F.1	Relationship between concentration and absorbed polymer for commercial xanthan	201
F.2	Relationship between concentration and absorbed polymer for xanthan from raw tapioca	202
F.3	Relationship between concentration and absorbed polymer for xanthan from tapioca	203
F.4	Relationship between concentration and absorbed polymer for xanthan from rice	204
F.5	Relationship between concentration and absorbed polymer for xanthan from sago	205
F.6	LGA porous medium for commercial xanthan with concentration of 1000 ppm	206
F.7	LGA porous medium for commercial xanthan with concentration of 3000 ppm	206
F.8	LGA porous medium for commercial xanthan with concentration of 5000 ppm	207
F.9	LGA porous medium for xanthan from raw tapioca with concentration of 1000 ppm	207
F.10	LGA porous medium for xanthan from raw tapioca with concentration of 3000 ppm	207
F.11	LGA porous medium for xanthan from raw tapioca with concentration of 5000 ppm	208
F.12	LGA porous medium for xanthan from tapioca with concentration of 1000 ppm	208
F.13	LGA porous medium for xanthan from tapioca with concentration of 3000 ppm	208
F.14	LGA porous medium for xanthan from tapioca with concentration of 5000 ppm	209
F.15	LGA porous medium for xanthan from rice with concentration of 1000 ppm	209
F.16	LGA porous medium for xanthan from rice with concentration of 3000 ppm	209
F.17	LGA porous medium for xanthan from rice with concentration of 5000 ppm	210
F.18	LGA porous medium for xanthan from sago with concentration of 1000 ppm	210

F.19	LGA porous medium for xanthan from sago with concentration of 3000 ppm	210
F.20	LGA porous medium for xanthan from sago with concentration of 5000 ppm	211
G.1	Arbitrary porous medium to represent sandpack A	212
G.2	Arbitrary porous medium to represent sandpack B	212
G.3	Arbitrary porous medium to represent sandpack C	213
G.4	Arbitrary porous medium to represent sandpack D	213
H.1	Flow curve of a xanthan solution used in polymer displacement in sand pack	217
I.1	Flow diagram for parallel simulation	220

LIST OF SYMBOLS

A	–	surface area
B_o	–	oil formation volume factor
B_{oi}	–	oil formation volume factor at start of project
C	–	concentration (ppm)
c	–	particle velocity
C'	–	collision operator
$C_{a(ref)}$	–	injected polymer concentration (Chapter 4)
$C_e(r,t)$	–	colour density
C_f	–	polymer concentration after adsorption, (ppm)
C_{fa}	–	factor by which the retained polymer deposit compacts when deposited
C_i	–	initial polymer concentration (ppm)
C_s	–	speed of sound
d	–	mean density per link
D_{eff}	–	displacement efficiency, %
d_g	–	diameter of grain
d_o	–	the mean oil density per link
D_p	–	polymer retention factor
d_p	–	the mean polymer density per link
$d\sigma/dt$	–	rate component a is removed from solution by filtration
E_p	–	side of polygon
$E(P,N)$	–	parallel efficiency
F	–	non-linear filtration
f_{lc}	–	local colour flux
f_p	–	fractional flow of polymer solution, fraction
f_w	–	fraction flow of water, fraction
f_w^*	–	fraction flow of water at flood front, fraction

f_{wl}	–	fraction flow of water at oil bank, fraction
f_{wp}^*	–	fraction flow of polymer at flood front, fraction
G	–	absorbance
$g(\rho)$	–	Galilean invariance term
H	–	power law coefficient
h	–	thickness of porous medium
k_a	–	absolute permeability
k_{arith}	–	arithmetic average permeability
k_f	–	final permeability
k_i	–	initial permeability
K_l	–	longitudinal dispersion constant
k_o	–	permeability of oil
k_p	–	permeability of polymer solution
k_t	–	permeability at time t
k_{recip}	–	reciprocal average permeability
k_{ro}	–	relative permeability of oil
k_{row}	–	relative permeability of oil with respect to water
k_{ro}^o	–	end point of oil relative permeability
k_{rp}	–	relative permeability of polymer solution
k_{rp}^o	–	end point of polymer relative permeability
k_{rw}	–	relative permeability of water
k_{rw}^o	–	end point of water relative permeability
k_{rwp}	–	relative permeability of wetting phase
k_w	–	permeability of water
k_x	–	permeability in x direction
L		length of medium
L_i	–	length of bed i
L_s	–	surface length
M	–	mobility ratio
m	–	momentum
M_p	–	mobility ratio of polymer flooding
m_s	–	the mass of sand particles, gr
n	–	power law exponent
n_{be}	–	occupation numbers of link e of blue particle

N_e	–	mean population of link e
n_e	–	occupation numbers of link e
N_g	–	number of grain
N_M		mach number
$N_{oe}(r,t)$	–	mean population of oil particles
N_p	–	produced oil
N_{pa}	–	total value of adsorbed particle
$N_{pe}(r,t)$	–	mean population of polymer particles
N_{pg}	–	total value of gelled particle
n_{re}	–	occupation numbers of link e of red particle
$N_{we}(r,t)$	–	mean population of water particles
N_y	–	Number of particles in y direction
O	–	origin
P	–	processors
p	–	pressure
p_c	–	capillary pressure
p_{inner}	–	the pressure inside of the bubble
p_l	–	local pressure
p_{outer}	–	the pressure outside of the bubble
p_p	–	pore pressure
P_{pa}	–	probability factor of polymer adsorption occurrence, fraction
P_{pg}	–	probability factor of polymer gelation occurrence, fraction
q	–	flow rate
Q	–	amount of adsorbed polymer
Q_e	–	amount of adsorbed polymer at equilibrium condition
q_o	–	oil flow rate
q_t	–	total flow rate
R	–	resistance factor
R_l	–	dumping resistance
r	–	bubble radius
r	–	site
Re	–	Reynolds number
R_a	–	concentration change rate of component a chemical reactions

S	–	Saturation
S'	–	streaming (propagation) operator
s	–	in-state of a collision
s'	–	out-state of a collision
S_{btp}	–	saturation of displacing polymer at breakthrough
S_l	–	local saturation
S_o	–	oil saturation
S_{oi}	–	initial oil saturation
S_{or}	–	residual oil saturation
S_{orw}	–	residual oil saturation in oil-water system
S_p	–	polymer solution saturation
S_{p2}	–	polymer solution saturation in dead-end pore
$S(P,N)$	–	speedup
S_w	–	water saturation
S_w^*	–	water saturation at flood front
S_{w1}	–	water saturation at oil bank
S_{wc}	–	connate water saturation
S_{wi}	–	initial water saturation
$s(\mathbf{r})$	–	site
$s_{cv}(\mathbf{r})$	–	connected void site
$s_{iv}(\mathbf{r})$	–	isolated void site
$s_s(\mathbf{r})$	–	solid site
$s_v(\mathbf{r})$	–	void site
t	–	time
t_D	–	dimensionless time
t_{dis}	–	displacement time
$T(P,N)$	–	time required for a given algorithm to solve problem of size N on P processors
u	–	flow rate per unit area
V	–	volume
v	–	velocity
v_D	–	Darcy velocity
v_D^*	–	velocity of polymer front
v_l	–	local velocity
V_p	–	pore volume

W	–	work
w	–	reservoir width
w_p	–	reservoir width
X	–	length of lattice in x direction
x_D	–	dimensionless distance
Y	–	width of lattice in y direction
Z_a	–	rate of concentration change of component “a” due to chemical reaction

Greek

Δ_e	–	collision function for link e
ε	–	evolution operator
ϕ	–	porosity
ϕ_{abs}	–	absolute porosity
ϕ_{eff}	–	effective porosity
ϕ_{IPV}	–	porosity that is not accessible to polymer
ϕ_o	–	initial unclogged porosity
γ	–	shear rate
η	–	true density
λ_l	–	local mobility
λ_o	–	mobility of oil
λ_p	–	mobility of polymer
μ	–	dynamic viscosity
μ_a	–	apparent viscosity
μ_o	–	oil viscosity
μ_p	–	viscosity of polymer solution
μ_{pN}	–	viscosity in the lower Newtonian region
μ_w	–	water viscosity
μ_∞	–	viscosity at very high shear rates
ν	–	kinematic viscosity
$\Pi_{\alpha\beta}$	–	momentum flux tensor

ρ	–	bulk density
σ	–	surface tension
τ	–	shear stress
τ_r	–	shear stress at intersection of the lines extrapolated from the Newtonian and the power law region
$\xi_{r,t}$	–	a time and site dependent Boolean variable
Ω	–	collision function
\int_x	–	the average change in the x component of momentum at a single point on the boundary $x = 0$

Subscripts and Superscripts

a	–	component a
e	–	link
f	–	final
g	–	grain
i	–	initial
j	–	grid location
l	–	local
n	–	current time level
o	–	oil
p	–	polymer
t	–	total
w	–	water
x	–	x direction
y	–	y direction
*	–	normalized value

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	COLLISION RULES OF FHP-III	185
B	DEVELOPMENT HISTORY OF LATTICE GAS AUTOMATA	189
C	PLANE COUETTE FLOW	190
D	CONVERSION CORRELATIONS	192
E	EXPERIMENTS OF ADSORPTION IN BATCH SYSTEM AND GELATION	196
F	EXPERIMENTAL AND SIMULATION RESULTS OF POLYMER ADSORPTION	200
G	SIMULATION RESULTS OF POLYMER GELA- TION	212
H	EXPERIMENTAL AND SIMULATION RESULTS OF POLYMER DISPLACEMENT	214
I	PARALLEL VIRTUAL MACHINE	219
J	PAPERS	262

CHAPTER 1

INTRODUCTION

This chapter presents the background of simulation of polymer flow in porous media and the applications of lattice gas automata method in the first section. The background brings out and concludes statements of problem for conducting the research ideas that are written in the second section. The objectives of the research are based on the problem statement, whereas the scope of work is planned to achieve the objectives. They are described in the next two sections. In the last section, a preview of the chapters in this thesis is presented.

1.1 Background

Polymer injection into reservoir rock is one of extensively used methods in enhancing oil recovery (Chauveteau and Sorbie, 1991). Many aspects of polymer injection have been simulated for a long period of time. Two phenomena that usually happened during polymer injection were adsorption and gelation. These phenomena played important roles, because they affected several rock and fluid properties.

The presence of the adsorbed or gelled polymer layers reduces the cross sectional area in pore throats. Since the pore size becomes closer to macromolecular length, the fluid flow in the medium is more difficult than at original condition. This means that the permeability of the rock reduces. The change of the permeability reduces the mobility of any fluid. On the other hand, adsorption and gelation reduce the density and viscosity of polymer solution because part of polymer particles is

linked and excluded from solution. The change of the viscosity affects the relative permeability, while the combination of permeability and polymer viscosity reductions affects the mobility ratio of a polymer displacement. Finally, the change of mobility ratio results in the change of the displacement efficiency (Zaitoun and Kohler, 1987; Ghazali and Willhite, 1985; Chauveteau and Sorbie, 1991).

Previous researchers (Liu, 2002; Khachatoorians, 2004) developed polymer flow in porous media models to study the phenomena of adsorption and gelation. However, the models were developed using macroscale approach. Several macroscale models were also developed for polymer displacement simulation (Bondor *et al*, 1972; Todd and Chase, 1979; Mattax and Dalton, 1990; Lecourtier *et al*, 1992; Dakhli, 1995; Wu, 1996; Shirif, 1998). The models usually assume that the levels of adsorption and gelation are same everywhere. In addition, the polymer front is assumed to be like a piston. In reality, the polymer front is not flat and the thickness of adsorption and gelation are not the same. The distribution and rate of adsorption and gelation processes are affected by local properties of a site in porous media such as pore size and mineralogy. An appropriate way to overcome these difficulties is the application of mesoscale model instead of macroscale model. The mesoscale model is able to accommodate to the realities.

In macroscale approach, a porous medium system area is usually assumed to possess homogeneous properties, whereas, in reality a reservoir rock is consist of various fluid saturations and various size and shape of rock granule. The assumption is usually tolerated in predicting macroscale properties. However, the pertinence of the methods is questionable when the phenomena are very much depending on heterogeneity of the rock such as adsorption and gelation of polymer. It is obvious that the phenomena must be viewed at mesoscale. The mesoscale approach is needed to model the heterogeneity of the porous medium.

Several molecular automaton methods based on the mesoscale approach have been developed. A classic comprehensive solution for the system can be obtained by using molecular dynamics. The method models all individual molecules. Inter-molecule interactions are modeled to behave as a fluid. The position, velocity and direction of the molecules are calculated. Successive calculations of the interaction

would build up the macroscopic flow. Unfortunately, calculations of molecular dynamics become so large and spend much time even for very small system. An appropriate way to overcome this difficulty is the application of cellular automata method. The cellular automata method is discrete analogues of molecular dynamics, in which particles with discrete velocities populate the links of a fixed array of sites (Wolfram, 1986). Cellular automata method has been developed into some classes. One of the cellular automata methods that seems suitable for polymer injection in porous media is lattice gas automata (LGA) since the method has been developed for simulating immiscible fluids (Rothman and Keller 1988).

Lattice gas automata method was introduced by Hardy *et al* (1973), and was completed by Frisch *et al* (1986) by introducing the hexagonal lattice to satisfy Navier-Stokes equation. The method was capable to model a complex system accurately. In 1988, Rothman applied lattice gas automata method to study the fluid flow in porous media.

One of LGA advantages is that the method replaces floating-point calculation with fewer Boolean and/or table-lookup operations (Biggs and Humby, 1998). The boundary conditions for complex geometries can be easily implemented (Frisch *et al*, 1986). In addition, the coding of fluid and solid sites is simple (Lee and Chung, 1993). The lattice gas automata simulation can also be run using parallel computers (Buick, 1997).

On the other hand, lattice gas automata method has some drawbacks. In LGA method, the density is independent of pressure. Conversely, the pressure is a function of the density. Consequently, the method is only applicable for incompressible fluid. LGA method is a pore-length scale approach (Lee and Chung, 1993). However, the limitation is not a problem for this research, since the fluids used were incompressible.

It is impractical to model the whole reservoir by LGA. One cubic centimeter of reservoir sandstone may have 200,000 pores bodies. If an oilfield inter-well spacing is 100 meters, one needs about 2×10^{17} sites to simulate the porous medium, (Patzek, 2000). Thus, much time for simulating the large porous media is needed for

the LGA model. Computer with high performance is required to reduce the computation time problem. Nowadays, massively parallel processors (MPPs) are the most powerful computer in the world. However, the operating or maintenance costs of the MPPs are usually expensive. Parallel computation can be a potential alternative in accelerating the simulation rate (Al Geist *et al*, 1994a). Previous researchers recognized the necessity of parallel computation for LGA simulation (Frisch *et al*, 1986; Rothman, 1988; Chen S. *et al*, 1991; Starr *et al*, 1996). However, the computation time reduction for LGA using parallel computer has not been reported yet.

1.2 Statement of Problem

Based on the above mentioned background, some problems exist, that are:

1. The adsorption and gelation should be simulated at pore scale. A mesoscale method is expected to gain a better insight of the microscopic phenomena than a macroscale method. One of the possible mesoscale methods is lattice gas automata. Can lattice gas automata method be used to simulate the phenomena?
2. LGA method has been developed for modeling two-phase flow in porous media. As an extended application of the adsorption modeling, can the LGA method be applied for modeling polymer displacement?
3. In general, a mesoscale method is time consuming if it is applied to simulate fluid flow in laboratory or larger scales. This may cause the method to be unfeasible. Can parallel computation be applied on lattice gas simulation to reduce the computation time?

1.3 Objectives of the Research

In order to solve the above-mentioned problems, the objectives of the research are listed as follows:

1. To model adsorption, gelation and polymer displacement processes.

2. To conduct laboratory experiments for validating the models.
3. To conduct parallel computation in simulating the models in order to reduce the computation time.
4. To study the effects of porosity and surface length on polymer adsorption as well as the effects of polymer adsorption on rock and fluid properties.
5. To study the effects of porosity, surface length and pore diameter on gelation process and the effects of polymer concentration on permeability reduction in the simulation of gelation.
6. To study the effects of mobility ratio, adsorption and dead-end pore on polymer displacement performance, such as displacement efficiency, relative permeability and fractional flow.

1.4 Scope of Work

In order to achieve the objectives, the scope of work should be identified. The scope of work of the research covers:

1. Conducting laboratory experiments on a single-phase and a two-phase flow in porous media.
2. Modeling adsorption, gelation and polymer displacement in porous media.
3. Modeling lattice gas automata for parallel computation.
4. Writing simulators for adsorption, gelation and polymer displacement.
5. Validating the simulators with the laboratory displacement experiments.
6. Running parallel computation for the lattice gas automata models.
7. Investigating and analyzing several parameters of rock and fluid during polymer injection process such as velocity, viscosity, and permeability.

The design of the experiments and methods used resulted in several limitations. The porous media used were the compacted loose sand grains (sandpacks) where the porosity of the media ranged from 0.31% to 0.52%. The use of the porous media type instead of sandstone cores was aimed to reduce the non-accessible pores by polymer and allow the adsorption process to occur on the entire pore surface. This was due to the models being assumed that that all polymer

particles retained in porous media were caused by adsorption, while hydrodynamics retention and mechanical entrapment of polymer were not taken into account. Besides that, kerosene (a light fuel oil) was used as displaced liquid in the polymer displacement experiment. Several limitations were also associated with the adsorption and gelation processes where temperature was constant and the processes were irreversible during simulation.

1.5 Summary

Simulation of polymer flow in porous media has been developed for a long time especially in predicting macroscopic phenomena. Since natural porous rock system is generally heterogeneous, microscopic phenomena that arrange the macroscopic phenomena are important. The application of lattice gas automata method as a mesoscale approach is an alternative in simulating the phenomena deeper.

This thesis is organized as follows: an introduction followed by the problem statement, the objectives and the scope of work as presented in this chapter. Chapter 2 outlines the basic theory of the lattice gas automata along with reservoir fluid and polymer flow behavior. Chapter 3 reviews the previous studies that are relevant to this research. Chapter 4 presents the development of lattice gas automata for adsorption, gelation and polymer displacement. Chapter 5 discusses the validation of lattice gas automata models both for static and dynamic polymer solution and polymer displacement in porous media. Chapter 6 presents the simulation results and discussion of adsorption and gelation. The simulation results and discussion of polymer displacement are provided in Chapter 7. The development of lattice gas automata for parallel computation along with result and discussion are provided in Chapter 8. Finally, Chapter 9 concludes this study and provides the recommendations for further researches.

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