

การศึกษากระบวนการจัดน้ำสลัดกึ่งแข็งในแหล่งกักเก็บที่เหมาะสม
โดยใช้แบบจำลองที่คำนึงถึงองค์ประกอบ



นาย ชนินทร์ วงษ์ดนตรี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมปิโตรเลียม ภาควิชาวิศวกรรมเหมืองแร่และปิโตรเลียม
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2547
ISBN 974-17-6134-1
ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย

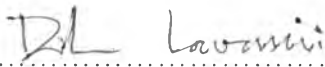
**OPTIMUM WATER ALTERNATING GAS INJECTION
USING COMPOSITIONAL RESERVOIR SIMULATION**

MR. Chanin Wongdontri

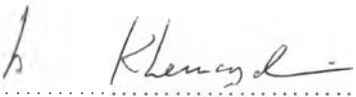
A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering in Petroleum Engineering
Department of Mining and Petroleum Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2004
ISBN: 974-17-6134-1
Copyright Chulalongkorn University


Thesis Title OPTIMUM WATER ALTERNATING GAS INJECTION
 USING COMPOSITIONAL RESERVOIR SIMULATION
By Chanin Wongdontri
Field of Study Petroleum Engineering
Thesis Advisor Suwat Athichanagorn, Ph.D.
Thesis Co-advisor Yothin Tongpenyai, Ph.D.

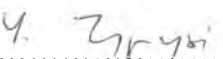
Accepted by the Faculty of Engineering, Chulalongkorn University in Partial
Fulfillment of the Requirements for the Master's Degree



..... Dean of the Faculty of Engineering
(Professor Direk Lavansiri, Ph.D.)

THESIS COMMITTEE


..... Chairman
(Associate Professor Yingyos Khemayodhin)


..... Thesis Advisor
(Suwat Athichanagorn, Ph.D.)


..... Thesis Co-advisor
(Yothin Tongpenyai, Ph.D.)


..... Member
(Jirawat Chewaroungroj, Ph.D.)

ชรินทร์ วงษ์ตันตรี: การศึกษากระบวนการอัดน้ำสลัดก๊าซลงในแหล่งกักเก็บที่เหมาะสมโดยใช้แบบจำลองที่คำนึงถึงองค์ประกอบ (OPTIMUM WATER ALTERNATING GAS INJECTION USING COMPOSITIONAL RESERVOIR SIMULATION) อาจารย์ที่ปรึกษา:

อ.ดร. สุวัฒน์ อธิษณากร, อาจารย์ที่ปรึกษาร่วม: ดร.โยธิน ทองเป็นใหญ่ จำนวนหน้า 114 หน้า, ISBN 974-17-6134-1

กระบวนการอัดน้ำสลัดก๊าซลงในแหล่งกักเก็บเป็นการเพิ่มการผลิตน้ำมันที่รวมเอาข้อดีของกระบวนการอัดน้ำและกระบวนการอัดก๊าซเข้าด้วยกัน ในวิทยานิพนธ์นี้ได้ทำการศึกษาค้นคว้า 2 ตัวแปรที่เหมาะสมนั้นคือ อัตราส่วนของน้ำต่อก๊าซที่ทำการอัดและขนาดต่อรอบของการอัดโดยใช้ทั้งแบบจำลองการไหลน้ำมันปกติและแบบจำลองการไหลที่คำนึงถึงองค์ประกอบ แหล่งกักเก็บที่ใช้จำลองเป็นแหล่งกักเก็บแบบที่มีค่าความสามารถในการซึมผ่านเท่ากันทั้งแหล่ง การศึกษาได้รวมถึงผลกระทบต่อภาวะการผลิตที่เหมาะสม เช่น ค่าความสามารถในการซึมผ่านในแนวนอน, อัตราส่วนของค่าความสามารถในการไหลในแนวตั้งต่อแนวนอน และตำแหน่งของหลุมผลิตและหลุมอัด นอกจากนี้ยังได้มีการศึกษาและเปรียบเทียบแบบจำลองฮิสเทรีซิส (hysteresis) ที่ใช้ในกระบวนการนี้ 2 แบบคือ แบบจำลองของคิลลาฟ และแบบจำลองของลาร์เซนและสกอร์ช

จากผลการศึกษาพบว่ากระบวนการอัดน้ำสลัดก๊าซให้สัดส่วนการผลิตน้ำมันที่ดีกว่าการอัดน้ำอย่างเดียวในหลายๆกรณี อิทธิพลของก๊าซที่ถูกอัดในแบบจำลองที่คำนึงถึงองค์ประกอบมีมากกว่าในแบบจำลองปกติ ผลการศึกษาบ่งชี้ว่าสัดส่วนการผลิตน้ำมันจะเพิ่มขึ้นเมื่อขนาดต่อรอบการอัดลดลงและอัตราส่วนของน้ำต่อก๊าซที่ทำการอัดเป็น 0.25 ค่าความสามารถในการซึมผ่านในแนวนอน, อัตราส่วนของค่าความสามารถในการซึมผ่านในแนวตั้งต่อแนวนอน และตำแหน่งของหลุมผลิตและหลุมอัดไม่มีผลต่อตัวแปรที่เหมาะสมแม้ว่าจะมีผลต่อค่าสัดส่วนการผลิตในแต่ละกรณี นอกจากนี้ยังพบว่าการใช้แบบจำลองฮิสเทรีซิสที่ต่างกันจะมีผลต่อค่าความสามารถในการซึมผ่านสัมพัทธ์ทำให้ได้ค่าสัดส่วนการผลิตที่ต่างกัน

ภาควิชาวิศวกรรมเหมืองแร่และปิโตรเลียม

สาขาวิชาวิศวกรรมปิโตรเลียม

ปีการศึกษา 2547

ลายมือชื่อนิติ.....
ลายมือชื่ออาจารย์ที่ปรึกษา.....*Sumat Attichonngorn*
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม.....*N - WJ*

4571604321 : MAJOR PETROLEUM ENGINEERING

KEY WORD : COMPOSITIONAL/ RESERVOIR SIMULATION/WATER ALTERNATING GAS

CHANIN WONGDONTRI. THESIS TITLE: OPTIMUM WATER ALTERNATING GAS INJECTION USING COMPOSITIONAL RESERVOIR SIMULATION. THESIS ADVISOR: DR. SUWAT ATHICHANAGORN, THESIS CO-ADVISOR: DR. YOTHIN TONGPENYAI, 114 pp.
ISBN 974-17-6134-1

Water alternating gas (WAG) injection is an enhanced oil recovery method that combines effect of water and gas flooding. This study is conducted to find the most suitable water-gas ratio and cycle size that yield optimal recovery. Black oil and compositional reservoir simulations for a synthetic homogeneous reservoir are used for this purpose. The effects of horizontal permeability, vertical to horizontal permeability ratio, and distance between production and injection wells were also investigated. In this study, three phase Larsen and Skauge relative permeability hysteresis model was compared with the standard two-phase Killough hysteresis model.

The results of the study show that WAG process, when appropriately implemented can yield higher recovery factor than waterflood. The impact of injected gas on increasing recovery efficiency was more evident in the compositional model than that in the black oil model. The results from the compositional model indicate that the smaller the cycle size, the higher the recovery factor will be and the water-gas ratio of 0.25 provides the highest recovery. Horizontal permeability, vertical to horizontal permeability ratio, and distance between producer and injector do not have an effect on optimal values of water-gas ratio and cycle size although they affect the absolute values of the recovery factor. The impact of using different relative permeability hysteresis was also found.

Department of Mining and Petroleum Engineering
Field of study: Petroleum Engineering
Academic year: 2004

Student's signature.....

Advisor's signature.....*Suwat Athichanagorn*

Co-advisor's signature.....

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor Dr. Suwat Athichanagorn and co-advisor Dr. Yothin Tongpenyai for their valuable guidance and enlightenment during the work of this thesis.

Thanks is also due to my colleague Manisa Rangpolsumrit for providing technical guideline on reservoir simulation.

I also wish to express my appreciation to Sarun Chaiworawitgul for his useful knowledge of computer and allowing me to use some of his facilities.

To my parents, for the tireless encouragement and for being there always, my gratitude is beyond description.

CONTENTS

	page
ABSTRACT (IN THAI).....	iv
ABSTRACT (IN ENGLISH).....	v
ACKNOWLEDGEMENTS.....	vi
CONTENTS.....	vii
LIST OF TABLES.....	ix
LIST OF FIGURES.....	x
NOMENCLATURE.....	xvi
CHAPTER	
1 INTRODUCTION.....	1
2 LITERATURE REVIEW.....	3
3 THEORY.....	7
3.1 WAG process overview.....	7
3.1.1 Problem in WAG process.....	11
3.2 Recovery factor relation.....	12
3.2.1 Horizontal displacement efficiency.....	12
3.2.2 Vertical sweep efficiency.....	13
3.3 Reservoir Simulation.....	14
3.3.1 Peng-Robinson Equation of State.....	18
3.3.2 Flash calculation.....	20
3.4 Relative permeability hysteresis model.....	21
3.4.1 Killough model.....	21
3.4.2 Larsen and Skauge model.....	22
3.4.2.1 Hysteresis of gas relative permeability.....	22
3.4.2.2 Hysteresis of water relative permeability.....	25
3.5 Parametric study.....	27
3.5.1 Water-gas ratio.....	27

CONTENTS (continued)

CHAPTER	page
3.5.2 Slug size or cycle-size.....	28
4 RESERVOIR MODEL DESCRIPTION.....	29
4.1 Black oil reservoir model.....	30
4.2 Compositional reservoir model.....	33
4.3 Production and injection strategy for base case model.....	35
5 RESULTS AND DISCUSSIONS.....	36
5.1 Optimum WAG process using Black oil model.....	36
5.1.1 Results of base case model.....	36
5.1.2 Optimization study.....	45
5.1.2.1 Effect of horizontal permeability.....	45
5.1.2.2 Effect of vertical to horizontal permeability ratio.....	59
5.1.2.3 Effect of location of producer and injector.....	61
5.2 Optimum WAG process using Compositional model.....	68
5.2.1 Results of base case model.....	68
5.2.2 Optimization study.....	77
5.2.2.1 Effect of horizontal permeability.....	77
5.2.2.2 Effect of vertical to horizontal permeability ratio.....	85
5.2.2.3 Effect of location of producer and injector.....	91
5.3 Relative permeability hysteresis model.....	95
6 CONCLUSION AND RECOMMENDATION.....	108
REFERENCES.....	111
VITAE.....	114

LIST OF TABLES

TABLE	page
3.1	Summary of WAG field case.....8
3.2	Summary of incremental oil recovery of WAG field case..... 9
4.1	PVT properties of oil and gas used in reservoir model.....31
4.2	Relative permeability to oil, water, and gas used in drainage process...32
4.3	Relative permeability to oil, water, and gas used in imbibition process.32
4.4	Reservoir fluid and injected gas composition.....33
4.5	Peng-Robinson fluid description for compositional reservoir model....34
4.6	Binary interaction coefficients (δ) for compositional reservoir model...34
5.1	Summary of optimum WAG cases for each horizontal permeability....50
5.2	Results of WAG cases with 2-year cycle size $k_h = 200$ md and $k_v = 2$ md terminated by oil rate = 200 STB/day and water cut= 0.7.....53
5.3	Scenario for studying the effect of location of producer and injector..... 62
5.4	Water breakthrough time for WAG cases with water-gas ratio = 1 and 3 month-cycle size.....63
5.5	Summary of cases used to investigate the effect of relative permeability hysteresis model..... 95
5.6	Recovery factor of three cases.....105
5.7	Recovery factors of cases 1 and 2 when varying trapped gas saturation (a)..... 105
5.8	Recovery factors of case 3 when varying Land 's constant (C)..... 106
5.9	Recovery factors of case 3 when varying reduction factor (a)..... 106

LIST OF FIGURES

FIGURE	page
3.1 Procedure of the fully implicit solution method.....	17
3.2 Killough model for non-wetting phase hysteresis.....	21
3.3 Larsen and Skauge gas hysteresis (3D projection).....	23
3.4 Larsen and Skauge hysteresis (2D projection).....	23
3.5 Water relative permeability hysteresis.....	26
4.1 Reservoir model configuration.....	30
5.1 Oil production rate vs. producing time for base case model.....	37
5.2 Oil recovery factor vs. producing time.....	37
5.3 Gas production rate vs. producing time.....	38
5.4 Gas-oil ratio vs. producing time.....	38
5.5 Water cut vs. producing time.....	39
5.6 Reservoir pressure vs. producing time.....	40
5.7 Bottom hole pressure of production well vs. producing time.....	40
5.8 Bottom hole pressure of injection well vs. time.....	41
5.9 Oil saturation of one of injection blocks vs. time.....	42
5.10 Oil relative permeability of one of injection well blocks vs. time.....	42
5.11 Water saturation of one of injection well blocks vs. time.....	43
5.12 Water relative permeability of one of injection well blocks vs. time...	43
5.13 Gas saturation of one of injection well blocks vs. time.....	44
5.14 Gas relative permeability of one of injection well blocks vs. time.....	44
5.15 Recovery factor of WAG process with water-gas ratio = 0.25 when varying horizontal permeability.....	46
5.16 Recovery factor of WAG process with water-gas ratio = 0.5 when varying horizontal permeability.....	46
5.17 Recovery factor of WAG process with water-gas ratio = 1 when varying horizontal permeability.....	47
5.18 Recovery factor of WAG process with water-gas ratio = 2 when varying horizontal permeability.....	47
5.19 Recovery factor of WAG process with water-gas ratio = 4 when varying horizontal permeability.....	48

LIST OF FIGURES (continued)

FIGURE	page
5.20	Recovery factor of WAG process with $k_h = 50$ md when varying water-gas ratio..... 49
5.21	Recovery factor WAG process with $k_h = 100$ md when varying water-gas ratio..... 49
5.22	Recovery factor of WAG process with $k_h = 200$ md when varying water-gas ratio..... 50
5.23	Recovery factor of WAG process with $k_h = 500$ md when varying water-gas ratio..... 50
5.24	Recovery factor of WAG process with $k_h = 1,000$ md when varying water-gas ratio..... 51
5.25	Effect of horizontal permeability on period of plateau rate for WAG cases with 24 months cycle size..... 52
5.26	Effect of horizontal permeability on water breakthrough time for WAG cases with 24 months cycle size..... 53
5.27	Recovery factor of WAG process with $k_h = 200$ md when varying water- gas ratio using only oil rate as an economic limit..... 55
5.28	Recovery factor of WAG cases with water-gas ratio = 1 for investigating the effect of cycle size..... 56
5.29	Production profile for WAG case with water-gas ratio = 1 for case with 35 month -cycle size..... 56
5.30	Production profile for WAG case with water-gas ratio = 1 for case with 36 month -cycle size..... 57
5.31	Production profile for WAG case with water-gas ratio = 1 for case with 38 month -cycle size..... 57
5.32	Production profile for WAG case with water-gas ratio = 1 for case with 40 month -cycle size..... 58
5.33	Production profile for WAG case with water-gas ratio = 1 for case with 42 month -cycle size..... 58
5.34	Recovery factor of WAG process with $k_h = 200$ md stop producing at 6 years..... 59

LIST OF FIGURES (continued)

FIGURE	page
5.35	Effect of k_v/k_h on WAG cases with water-gas ratio = 0.25, $k_h = 200$ md..... 60
5.36	Effect of k_v/k_h on WAG cases with water-gas ratio = 0.5, $k_h = 200$ md..... 61
5.37	Effect of k_v/k_h on WAG cases with water-gas ratio = 1, $k_h = 200$ md..... 61
5.38	Effect of k_v/k_h on WAG cases with water-gas ratio = 2, $k_h = 200$ md..... 61
5.39	Effect of k_v/k_h on WAG cases with water-gas ratio = 4, $k_h = 200$ md..... 62
5.40	Effect of k_v/k_h on WAG cases with injection rate = 500 and 10000 barrel/day..... 62
5.41	Configuration of three different well location..... 63
5.42	Recovery factor of WAG process when varying water-gas ratio for cases with scenario 1..... 64
5.43	Recovery factor of WAG process when varying water-gas ratio for cases with scenario 2..... 64
5.44	Recovery factor of WAG process when varying water-gas ratio for cases with scenario 3..... 65
5.45	Production profile of scenario 1..... 65
5.46	Production profile of scenario 2..... 66
5.47	Production profile of scenario 3..... 66
5.48	Oil production profile..... 68
5.49	Cumulative oil production profile..... 68
5.50	Oil viscosity profile of block (20, 11, 5) from compositional model..... 69
5.51	Oil viscosity of block (20, 11, 5) from black oil model..... 69
5.52	Gas production profile..... 70
5.53	Gas-oil ratio profile..... 70
5.54	Water production profile..... 71

LIST OF FIGURES (continued)

FIGURE	page
5.55	Water cut profile..... 71
5.56	Reservoir pressure profile.....72
5.57	Bottom hole pressure profile of injection well.....72
5.58	Bottom hole pressure profile of production well.....73
5.59	Oil saturation profile of one of injection well blocks.....74
5.60	Oil relative permeability profile of one of injection well blocks.....74
5.61	Gas saturation profile of one of injection well block.....75
5.62	Gas relative permeability profile of one of injection well blocks.....75
5.63	Water saturation profile of one of injection well blocks..... 76
5.64	Water relative permeability profile of one of injection well blocks....76
5.65	Recovery factor of WAG process when varying horizontal permeability for cases with water-gas ratio = 0.25.....77
5.66	Recovery factor of WAG process when varying horizontal permeability for cases with water-gas ratio = 0.5.....78
5.67	Recovery factor of WAG process when varying horizontal permeability for cases with water-gas ratio = 1..... 78
5.68	Recovery factor of WAG process when varying horizontal permeability for cases with water-gas ratio = 2.....79
5.69	Recovery factor of WAG process when varying horizontal permeability for cases with water-gas ratio = 4.....79
5.70	Recovery factor of WAG process when varying water-gas ratio for cases with $k_h = 50$ md.....80
5.71	Recovery factor of WAG process when varying water-gas ratio for cases with $k_h = 100$ md..... 80
5.72	Recovery factor of WAG process when varying water-gas ratio for cases with $k_h = 200$ md..... 81
5.73	Recovery factor of WAG process when varying water-gas ratio for cases with $k_h = 500$ md..... 81

LIST OF FIGURES (continued)

FIGURE	page
5.74	Recovery factor of WAG process when varying water-gas ratio for cases with $k_h = 1,000$ md.....82
5.75	Effect of horizontal permeability on the period of plateau rate for WAG cases with 24 months cycle size..... 83
5.76	Effect horizontal permeability on water breakthrough time for WAG cases with 24 months cycle size..... 84
5.77	Recovery factor of WAG process when varying water-gas ratio for cases with $k_h = 200$ md cut by oil rate.....85
5.78	Effect of k_v/k_h on WAG cases with water-gas ratio = 0.25, $k_h = 200$ md..... 86
5.79	Effect of k_v/k_h on WAG cases with water-gas ratio = 0.5, $k_h = 200$ md..... 86
5.80	Effect of k_v/k_h on WAG cases with water-gas ratio = 1, $k_h = 200$ md..... 87
5.81	Effect of k_v/k_h on WAG cases with water-gas ratio = 2, $k_h = 200$ md..... 87
5.82	Effect of k_v/k_h on WAG cases with water-gas ratio = 4, $k_h = 200$ md..... 88
5.83	Recovery factor of WAG process when varying water-gas ratio for cases with $k_v/k_h = 0.1$89
5.84	Recovery factor of WAG process when varying water-gas ratio for cases with $k_v/k_h = 0.5$89
5.85	Recovery factor of WAG process when varying water-gas ratio for cases with $k_v/k_h = 1$90
5.86	Recovery factor of WAG process when varying water-gas ratio for cases with scenario 1..... 91
5.87	Recovery factor of WAG process when varying water-gas ratio for cases with scenario 2.....92

LIST OF FIGURES (continued)

FIGURE	page
5.88	Recovery factor of WAG process when varying water-gas ratio for cases with scenario 3..... 92
5.89	Production profile for scenario 1..... 93
5.90	Production profile for scenario 2..... 94
5.91	Production profile for scenario 3..... 94
5.92	Plot of gas relative permeability vs. gas saturation of case 1..... 97
5.90	Plot of water relative permeability vs. water saturation of case 1..... 98
5.91	Plot of gas relative permeability vs. gas saturation of case 2.....100
5.92	Plot of water relative permeability vs. water saturation of case 2.....101
5.93	Plot of gas relative permeability vs. gas saturation of case 3.....103
5.94	Plot of water relative permeability vs. water saturation of case 3.....104

NOMENCLATURE

a	Input constant for Killough hysteresis model
B	Formation volume factor, RB/STB
C	Land's constant
E_h	Horizontal sweep efficiency
E_m	Microscopic displacement efficiency
E_v	Vertical sweep efficiency
g	Gravitational acceleration, ft/s ²
h	Height of displacement zone, ft
H	Reservoir thickness, ft
k_h	Horizontal permeability, md
K_i	Equilibrium ratio of component i
k_o	Permeability to oil, md
k_{rg}	Gas relative permeability
k_{ro}	Oil relative permeability
k_{rw}	Water relative permeability
k_v	Vertical permeability, md
L	Distance between producer and injector, ft
M	Mobility ratio
p	Pressure, psia
p_{cog}	Capillary pressure for oil-gas system, psia
p_{cow}	Capillary pressure for oil-water system, psia
p_{ri}	Pseudoreduced pressure of component i
q_{sc}	Flow rate, STB/day
R	Gas constant
REC	Oil recovery factor
R_s	Solution gas-oil ratio, SCF/STB
$R_{v/g}$	Viscous to gravity ratio
S	Saturation
S'	Inverse of the slope of capillary pressure-saturation curve
S_{gi}	Initial gas saturation