CO_2-ASSISTED GRAVITY DRAINAGE EOR: NUMERICAL SIMULATION AND SCALING MODELS STUDY

A thesis

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in
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By

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ABSTRACT

Increasing demand of the oil and gas have given rise to surge in drilling and exploration activities to recover oil from other unexplored oil-bearing formations (such as offshore) as well as in the efforts to improve and/or modify the existing methods of the enhanced oil recovery to recover the residual oil left-behind by the applied EOR method. Nearly one-third volume of the original oil in place (OOIP) is left-behind by the current EOR technologies. Estimated 2 trillion barrels of this volume is lucrative to cater the energy needs of the respective countries. Gas injection EOR method is a major contending process in exploitation of this resource, and its application is on the rise since last decade. Continuous gas injection (CGI) and water-alternating gas (WAG) injection are the most notable and commonly field-implemented horizontal displacement type gas injection EOR processes. The limitations of CGI are the severe gravity segregation and poor sweep efficiencies. Although the reservoir sweep efficiencies are improved with the WAG, review of 59 field projects suggest that they yield only maximum of 10% incremental oil recoveries due to the detrimental effects of increased water saturation to diminish gas injectivity, reducing oil mobility, decreased oil relative permeability and oil bypassing due to gravity segregation. Conversely, vertical downward oil-displacement gas driven gravity drainage EOR methods uses the gravity forces to its advantage for enhancing the oil recovery. Gravity drainage EOR methods have been applied to dipping and reef type reservoirs in the field projects and reported to yield high incremental oil recoveries.

In this study, the CO_2-assisted gravity drainage EOR method is investigated in the non-dipping reservoir through the 3D reservoir simulations and scaling and the sensitivity analysis. Both the compositional and pseudomiscible black-oil numerical reservoir simulations are conducted in the 50 and 35 ^{o}API gravity oil-reservoirs respectively. Main objectives of this research are to (i) develop a better production strategy for the oil recovery optimization (ii) investigate the options to optimize oil recovery in the CO_2-assisted gravity drainage EOR process (numerical simulation studies) (iii) to develop a set of scaled models sufficient to completely scale the CO_2-assisted gravity drainage EOR process through the scaling and sensitivity studies.

Original contributions of this research are (i) First comprehensive demonstration of the CO_2-assisted gravity drainage EOR method application in 50 ^{o}API gravity oil-reservoir, (ii) Development and verification of a new hypothesis of the horizontal gas floodfront in the top-down CO_2-assisted gravity drainage EOR process, (iii) Development of a general process selection map for the preliminary choice between the immiscible and miscible process, (iv) Grid size effect studies: Changes in both the x and y grid-dimensions has no impact on the CO_2-assisted gravity drainage oil recovery, (v) Grid thickness effect studies: Thin layers, even in the upper layers, facilitates the optimum CO_2-assisted gravity drainage oil recovery (vi) Heterogeneity in permeability effect: Presence of heterogeneity in permeability (k_v / k_v = 0.001) improves the CO_2-assisted gravity drainage oil recovery performance (95.5% incremental oil recovery) thereby reducing the number of pore volumes and the operational time. It has been found that recovery further improves when the molecular diffusion effects are taken into account, (vii) Heterogeneity in porosity: Porosity values increasing downwards, such as in the overturned faults, promotes the CO_2-assisted gravity drainage mechanism to yield better oil recovery performance, (viii) Clear identification of the overall mechanisms and the supporting micro-mechanisms through the parametric analysis of the reservoir simulation results, (ix) Development of a new correlation (combination number, $N_{Jadhawar\ and\ Sarma}$) that encompasses the traditional process affecting multiphase operational parameters in the form of the dimensionless groups. It is further validated using the field projects including the data from the Oseberg field, Norway. Excellent logarithmic correlation match is obtained between the new combination number, $N_{Jadhawar\ and\ Sarma}$, and the oil recoveries from both the immiscible and miscible reservoir simulations as well as the field projects. New combination number, $N_{Jadhawar\ and\ Sarma}$, is a useful tool to predict CO_2-assisted gravity drainage oil recoveries, and (x) Development of a set of the additional scaled models sufficient to completely scale the CO_2-assisted gravity drainage EOR process are proposed and validated.

DEDICATION

I wholeheartedly dedicate this PhD research-work to my beloved brother Late Pravin, who will not be able to see the day of my memorable success for which we strived since our childhood. His unselfish character of offering the helping hand whenever needed, passionate and vibrant support to me and my family will be remembered until the last breath of my life.

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STATEMENT OF ORIGINALITY

The work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institutions and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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PUBLISHED PAPERS FROM THIS WORK

Journal Papers

1. Jadhawar, P.S. and Sarma, H.K., **2010**. *Improved Production Strategy for Enhancing the CO_2-Assisted Gravity Drainage Oil Recovery*, Journal of Petroleum Science and Engineering (JPSE) (Under review).

2. Jadhawar, P.S. and Sarma, H.K., **2010**. *Improved Production Strategy for Enhancing the CO_2-Assisted Gravity Drainage Oil Recovery*, SPE Reservoir Evaluation and Engineering (Under review).

3. Jadhawar, P.S. and Sarma, H.K., **2010**. *Numerical Simulation and Sensitivity Analysis of Gas-Oil Gravity Drainage Process of Enhanced Oil Recovery*, Journal of Canadian Petroleum Technology, Calgary, Canada; 49 (2), 64-70; February.

Conference Presentations

4. Jadhawar, P.S. and Sarma, H.K., **2010**. *Improved Production Strategy for Enhancing the Immiscible and Miscible CO_2-Assisted Gravity Drainage Oil Recovery*, to be presented at the SPE 2010 International Oil and Gas Conference and Exhibition China (IOGCEC), Beijing, China, June 8-10.

5. Jadhawar, P.S. and Sarma, H.K., 2008a. *CO_2-Assisted Gravity Drainage Enhanced Oil Recovery (GAGD-EOR) in Australian Reservoirs: Reservoir Simulation and Scaled Model Studies*, 2008 AIE Postgraduate Student Energy Awards Sydney, Australia; Nov 18.

6. Jadhawar P.S., Sarma H.K. 2008. *Scaling and Sensitivity Analysis of Gas-Oil Gravity-Drainage EOR*. Presented at the 2008 SPE Asia Pacific Oil & Gas Conference and Exhibition Perth, Australia, 20–22 October.

7. Jadhawar P.S., Sarma H.K. 2008. *Numerical Simulation and Sensitivity Analysis of Gas-Oil Gravity Drainage Process of Enhanced Oil Recovery*, Canadian International Petroleum Conference, Calgary, Canada, June 17-19.

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NOMENCLATURE

Nomenclature and units used throughout this thesis are as follows:

ENGLISH

Symbol	**Description**
B_o	Formation Volume Factor of the oil, Res bbl/STB, $[L^3/L^3]$
B_g	Formation Volume Factor of the gas, SCF/STB, $[L^3/L^3]$
$B_{solvent}$	Formation Volume Factor of the solvent $[L^3/L^3]$
g	Acceleration due to gravity, ft/s^2 $[L/T^2]$
H	Thickness of the reservoir, ft [L]
i_g	Rate of gas injection, SCFD
k_v	Vertical permeability, mD, psia $[L^2]$
k_h	Horizontal permeability within the reservoir, mD, psia $[L^2]$
k_{ro}	Permeability to oil of the porous medium, mD, psia $[L^2]$
k_{rg}	Permeability to gas of the porous medium, mD, psia $[L^2]$
k_{rw}	Permeability to water of the porous medium, mD, psia $[L^2]$
L	Characteristic length of reservoir or Well spacing, ft [L]
M	Mobility ratio
M_{wo}	Water-oil mobility ratio, bbls $[L^3]$
M_{go}	Gas-oil mobility ratio, bbls $[L^3]$
N_B	Bond number, dimensionless
N_B	Capillary number, dimensionless
N_G	Gravity number, dimensionless
$N_{Kulkarni}$	Kulkarni number, dimensionless
$N_{Rostami}$	Dimensionless number of Rostami et al.
$N_{Jadhawar\ and\ Sarma}$	Capillary number, dimensionless
N_p	Cumulative oil production, bbls $[L^3]$
N_{gI}	Gravity number based on the gas injection rate, dimensionless
N_{gP}	Gravity number based on the pressure difference between the gas injection and oil production wells, dimensionless
P_{avg}	Average reservoir pressure, psia $[M/LT^2]$
P_c	Capillary pressure, psia $[M/LT^2]$
P_{inj}	Gas injection pressure, psia $[M/LT^2]$
P_{prod}	Oil recovery (producing) pressure, psia $[M/LT^2]$
P_{MM}	Minimum miscibility pressure, psia $[M/LT^2]$

ΔP	Difference of pressure between the gas injection pressure and oil recovery pressure, psia $[M/LT^2]$
ΔP_R	Change in the reservoir pressure, psia $[M/LT^2]$
PV_{CO2inj}	Pore volume of the CO_2 injected, psia $[M/LT^2]$
q_o	Rate of the oil production, bpd, $[L^3/T]$
R_L	Effective Aspect ratio, dimensionless
R_s	Solution gas-oil ratio
R_D	Dimensionless recovery
S_o	Spreading Coefficient
S_{orw}	Residual oil saturation to water (water-oil system)
S_{org}	Residual oil saturation to gas (gas-oil system)
S_{WC}	Connate water saturation
t	Time [T]
t_D	Dimensionless time
T	Temperature, ^oF $[\theta]$
u_c	Critical Velocity, ft/D, [L/T]
u_T	Average superficial velocity, ft/s, [L/T]
W	Width (diameter of core) of the reservoir, ft [L]

GREEK

ρ_o	Density of reservoir fluid (oil), lb/ $ft^3 [M/L^3]$
ρ_g	Density of the gas, lb/ $ft^3 [M/L^3]$
$\Delta\rho$	Difference of the density between the reservoir fluid (oil) and the injected gas, lb/ ft^3 $[M/L^3]$
λ_{ro}	Mobility of oil within the porous medium
λ_{rg}	Mobility of gas within the porous medium
λ_{rw}	Mobility of water within the porous medium
ϕ	Porosity, fraction
α	Angle of dip (tilt) of a particular reservoir section with respect to the horizontal
μ_o	Viscosity of the oil, cP [M/LT]
μ_g	Viscosity of the gas, cP [M/LT]
$\mu_{solvent}$	Viscosity of the solvent, cP [M/LT]
σ_{wg}	Water-gas interfacial tension, dyne/cm, $[M/T^2]$
σ_{go}	Gas-oil interfacial tension, dyne/cm, $[M/T^2]$
σ_{ow}	Oil-water interfacial tension, dyne/cm, $[M/T^2]$

Subscripts

x	x-direction
y	y-direction
z	z-direction
V	Vertical
H	Horizontal
s	Solution
g	Gas
o	Oil
s	Solvent

ACRONYMS

Acronym	**Description**
B-L	Buckley-Leverett
CCE	Constant Composition Expansion
CVD	Constant Volume Depletion
DL	Differential Liberation
EOR	Enhanced Oil Recovery
FVF	Formation Volume Factor
GOC	Gas-Oil Contact
GOR	Gas-Oil Ratio
GRR	Gravity Drainage Reference Rate
HC	Hydrocarbon gas
HZGI	Horizontal Gas Injection
Imm	Immiscible
IWP	Irregular Well Pattern
Misc	Miscible
MMP	Minimum Miscibility Pressure
PVT	Pressure, Volume, Temperature
RWP	Regular Well Pattern
Sec	Secondary CO_2 injection
Tert	Tertiary CO_2 injection
VGI	Vertical Gas Injection
VRR	Voidage Replacement Ration
WOC	Water-Oil Contact