A Numerical Investigation into the Potential to Enhance Natural Gas Recovery in Water-drive Gas Reservoirs through the Injection of CO_2

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Abstract

The injection of carbon dioxide (CO_2) into oil reservoirs for the purpose of enhancing recovery has been performed for decades. Conversely, the injection of CO_2 into natural gas reservoirs has received very little attention, primarily due to the typically high recovery achievable under primary depletion. This high recovery is however associated with volumetric gas reservoirs only. If the reservoir is in the presence of an active water-drive, recovery can be considerably lowered. This is caused by pressure maintenance and the trapping of gas, rendering a volume of gas immobile. Consequently, any technique that reduces reservoir pressure and/or retards the influx of the aquifer will enable natural gas recovery to be enhanced.

In this thesis, the injection of CO_2 has been proposed as a method of retarding the influx of the aquifer. Favourable fluid properties between the injected CO_2 and natural gas also allow the displacement of natural gas towards the production wells with minimal mixing. This thesis investigates the nature of the effects of a number of parameters deemed potentially influential on the displacement of natural gas by CO_2 and the ability to produce and enhance recovery with as low a producing CO_2 concentration as possible. Parameters chosen include uncontrollable reservoir and fluid properties such as permeability, thickness, diffusion coefficients and salinity. Controllable factors are also investigated, such as the timing of injection, production and injection rates and the type of wells employed. This investigation was conducted through the use of numerical simulation. Simulations were first performed on a simple, conceptual model in order to understand the key processes involved in the CO_2 enhanced gas recovery process. The results of these studies were then applied to a more complex numerical investigation involving a model of the Naylor gas field.

The results of the initial studies found that the parameters which determined the extent of viscous and gravity forces, such as permeability, thickness and formation dip, were the most influential in determining the stability of the displacement, and consequently the recovery achievable at the breakthrough of CO_2 at the production well. The fluid properties, such as water salinity and the diffusion coefficient, were found to have less of an impact than the reservoir properties. Efficient displacement in a non-dipping reservoir was possible with either viscous or gravity dominated displacement, while only gravity stable displacement was preferred in a dipping reservoir. The primary recovery efficiency did however dictate where the injection of CO_2 should be targeted in order to achieve incremental recovery with the lowest producing CO_2 concentration. Due to the low primary recovery efficiency, the injection of CO_2 should be targeted in high permeability, non-dipping reservoirs.

The presence of heterogeneity accelerated the breakthrough of CO_2, and so it was shown that delaying the injection of CO_2 was beneficial in maximising the recovery at the initial breakthrough of CO_2. However, once CO_2 had reached the production well, the rate of increase in CO_2 production was considerably more rapid if injection was delayed. The choice of the timing of injection and the ability to maximise incremental recovery is therefore heavily influenced by the maximum allowable producing CO_2 concentration, which will be determined by the economics of the project. The investigation into the other controllable parameters showed that the operational strategies which either lowered the susceptibility for CO_2 to cone into the production well, or which mitigated against the uneven advancement of CO_2 due to heterogeneity were preferred.

Ultimately this study showed that the injection of CO_2 can effectively retard the influx of the aquifer and efficiently displace natural gas towards the production well. By understanding the mechanisms involved in this displacement process, operational parameters can be optimised accordingly to maximise natural gas recovery with the lowest producing CO_2 concentration. The extent of incremental recovery is subsequently determined by the maximum producing CO_2 concentration allowable, as determined by the economics of the project.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution.

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Table of Contents

List of Figures

List of Tables

Nomenclature

Symbol	Description
ϕ	porosity
λ	mobility of the fluid
λ	exponent (relative permeability correlation)
μ	viscosity
ρ	density
A	area
B_g	formation volume factor
B_{gi}	initial formation volume factor
B_{ga}	formation volume factor at abandonment conditions
C	concentration
C	Land's trapping constant
c_t	total aquifer compressibility
D	diffusion coefficient
E	expansion factor
g	gravity constant
G	gas volume initially in place
G_p	gas volume produced
h	thickness
k	permeability
k_r	relative permeability
k_{rg}	gas relative permeability
k_{rl}	liquid relative permeability
l	length
M	mobility ratio
n	number of moles
p	pressure
P_c	capillary pressure
P_0	strength coefficient
q	flow rate
R	universal gas constant
R^2	correlation coefficient
$R^2_{adjusted}$	adjusted correlation coefficient

$R_{v/g}$	viscous to gravity ratio
sc	standard conditions
S_g	gas saturation
S_{gr}	residual gas saturation
S_{gt}	trapped gas saturation
S_{lr}	residual liquid saturation
S_w	water saturation
S_{wi}	initial water saturation
S_{wir}	irreducible water saturation
t	time
T	temperature
u	Darcy velocity
V	volume
W	total water volume
W_e	cumulative volume of water influx
x	distance
x_g	gas phase concentration
x_l	aqueous phase concentration
Z	compressibility factor

Acronyms	Description
ANOVA	ANalysis Of VAriance
CCD	Central Composite Design
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon dioxide
CO2CRC	Co-operative Research Centre for Greenhouse Gas Technologies
CSEGR	Carbon Sequestration with Enhanced Gas Recovery
ED	Experimental Design
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
GWC	Gas Water Contact
HCPV	Hydrocarbon Pore Volume
MM	Million

NPV	Net Present Value
OBPP	Otway Basin Pilot Project
OGIP	Original Gas in Place
PDE	Partial Differential Equations
PVT	Pressure Volume Temperature
RF	Recovery Factor
RMSE	Root Mean Square Error
Scf	Standard Cubic Feet
SGS	Sequential Gaussian Simulation
STB	Stock Tank Barrel