Laboratory and Modelling Studies on the Effects of Injection Gas Composition on CO_2-Rich Flooding in Cooper Basin, South Australia

By

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For my wife Erika and our daughter Isabella

Abstract

This Ph.D. research project targets Cooper Basin oil reservoirs of very low permeability (approximately 1mD) where injectivities required for water flooding are not achievable. However, the use of injection gases such as CO_2 would not have injectivity problems. CO_2 is abundant in the region and available for EOR use. CO_2 was compared to other CO_2-rich injection gases with a hydrocarbon content including pentane plus components. While the effect of hydrocarbon components up to butane have been investigated in the past, the effect of n-pentane has on impure CO_2 gas streams has not.

One particular field of the Cooper Basin was investigated in detail (Field A). However, since similar reservoir and fluid characteristics of Field A are common to the region it is expected that the data measured and developed has applications to many other oil reservoirs of the region and similar reservoirs else where.

The aim of this Ph.D. project is to determine the applicability of CO_2 as an injection gas for Enhanced Oil Recovery (EOR) in the Cooper Basin oil reservoirs and to compare CO_2 with other possible CO_2-rich injection gases.

The summarised goals of this research are to:

- Determine the compatibility of Field A reservoir fluid with CO_2 as an injection gas.
- Compare CO_2 to other injection gas options for Field A.
- Development of a correlation to predict the effect of nC_5 on MMP for a CO_2-rich injection gas stream.

These goals were achieved through the following work:

- Extensive experimental studies of the reservoir properties and the effects of interaction between CO_2-rich injection gas streams and Field A reservoir fluid measuring properties related to:
  - Miscibility of the injection gas with Field A reservoir fluid

    - Solubility and swelling properties of the injection gas with Field A reservoir fluid
    - Change in viscosity-pressure relationship of Field A reservoir fluid due to addition of injection gas
- A reservoir condition core flood experiment
- Compositional simulation of the reservoir condition core flood to compare expected recoveries from different injection gases
- Development of a set of Minimum Miscibility Pressure (MMP) measurements targeted at correlating the effect of nC_5 on CO_2 MMP.

The key findings of this research are as follows:

- Miscibility is achievable at practical pressures for Field A and similar reservoir fluids with pure CO_2 or CO_2-rich injection gases.
- For Field A reservoir fluid, viscosity of the remaining flashed liquid will increase at pressures below ~2500psi due to mixing the reservoir fluid with a CO_2-rich injection gas stream.
- Comparison of injection gases showed that methane rich gases are miscible with Field A so long as a significant quantity of C_3+ components is also present in the gas stream.
- There is a defined trend for effect of nC_5 on MMP of impure CO_2. This trend was correlated with an error of less than 4%.
- Even though oil composition is taken into account with the base gas MMP, it still affects the trend for effect of nC_5 on MMP of a CO_2-rich gas stream.
- An oil characterisation factor was developed to account for this effect, significantly improving the results, reducing the error of the correlation to only 1.6%.

The significance of these findings is as follows:

- An injection pressure above ~3000psi should be targeted. At these pressures miscibility is achieved and the viscosity of the reservoir fluid-injection gas mix is reduced.

- CO_2 should be compared to gases such as Tim Gas should after considering the cost of compression, pipeline costs and distance from source to destination will need to be considered.
- The addition of nC_5 will reduce the MMP and increase the recovery factor, however the cost of the nC_5 used would be more than the value of increased oil recovered.
- The developed correlation for the effect of nC_5 on impure CO_2 MMP can be used broadly within the limits of the correlation.
- Further research using more oils is necessary to validate the developed oil characterisation factor and if successful, using the same or similar method used to improve other correlations.

STATEMENT OF ORIGINALITY

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 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.

I give consent to this copy of my thesis when deposited at the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

Johannes Bon
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DISCLAIMER

This Ph.D. thesis reflects the opinions of the author and does not necessarily reflect the opinions of the Cooper Basin Joint Venture parties.

PUBLISHED PAPERS FROM THIS WORK

1. Bon, J. and Sarma, H.K.: "**Investigation of the Effect of Injection Gas Composition on CO_2-rich MMP and its Implications in Flooding in an Onshore Australia Oil Field**", paper to be presented at the Canadian International Petroleum Conference 60th Annual Technical Meeting of the Petroleum Society, Calgary, Alberta, Canada, June 16-18 2009
2. Bon, J., Sarma, H.K., Rodrigues, T. and Bon, J.G.: "**Reservoir Fluid Sampling Revisited - A Practical Perspective**", *SPE Reservoir Evaluation & Engineering*, Vol. 10, No. 6 (December 2007) 589-596
3. Bon, J., Emera, M.K and Sarma, H.K.: "**An Experimental Study and Genetic Algorithm (GA) Correlation to Explore the Effect of nC_5 on Impure CO_2 Minimum Miscibility Pressure (MMP)**", paper SPE 101036 presented at the SPE Asia Pacific Oil & Gas Conference and Exhibition (APOGCE), Adelaide, Australia, 11–13 September 2006
4. Bon, J., Sarma, H.K., Rodrigues, T. and Bon, J.G.: "**Reservoir Fluid Sampling Revisited - A Practical Perspective**", paper SPE 101037 presented at the SPE Asia Pacific Oil & Gas Conference and Exhibition (APOGCE), Adelaide, Australia, 11–13 September 2006
5. Bon, J., Sarma, H.K. and Theophilos, A. M.: "**An Investigation of Minimum Miscibility Pressure for CO_2-Rich Injection Gases with Pentanes-Plus Fraction**", paper SPE 97536 presented at the International Improved Oil Recovery Conference (IIORC) in Asia Pacific, Kuala Lumpur, Malaysia, December 5-6 2005
6. Bon, J. and Sarma, H.K.: "**A Technical Evaluation of a CO_2 Flood for EOR Benefits in the Cooper Basin, South Australia**", paper SPE 88451 presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition (APOGCE), Perth, Australia, October 18-20 2004

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NOMENCLATURE

Nomenclature and units used throughout this thesis are as follows:

ENGLISH

Symbol	Description	Unit
A	Cross sectional area of core plug	cm^2
BHP	Bottom hole pressure	psi
B_g	Gas formation volume factor	rcf/scf
B_o	Oil formation volume factor	rb/stb
B_{od}	Depletion oil formation volume factor	rb/stb
B_{odb}	Depletion oil formation volume factor at bubble point pressure	rb/stb
B_{of}	Flash oil formation volume factor	rb/stb
B_{ofb}	Flash oil formation volume factor at bubble point pressure	rb/stb
B_{oi}	Initial oil formation volume factor	rb/stb
B_t	Total formation volume factor	rb/stb
B_{td}	Depletion total formation volume factor	rb/stb
C_1	Constant for oil viscosity	
C_2	Constant for oil viscosity	
C_g	Constant for GA fitness factor determination	
c_o	Oil compressibility	psi^{-1}
D	Plug diameter	cm
E	Gas expansion factor	scf/rcf
E_A	Areal sweep efficiency	
E_D	Displacement efficiency	
E_M	Mobilization efficiency	
E_R	Overall recovery efficiency	
E_V	Vertical sweep efficiency	
F_R	Mole fraction of intermediates	
$Fit(i)$	Average fitness of chromosome i	
GHV	Gross heating value	BTU/ft^3
GHV_i	Gross heating value for component i	BTU/ft^3
I	Oil characterization index	
k	Permeability	mD
L	Core plug length	cm
$Liq\%$	Liquid Percent	
m	Mass	
M	Mole fraction	mol%
M_i	Mole fraction of component i	mol%
M_{C1}	Mole fraction of methane and nitrogen in the reservoir fluid	mol%

M_{nC5}	The mole fraction nC_5 in the injection gas stream	mol%
M_{C5+}	Mole fraction of C_5+ in the oil	mol%
MW	Molecular weight	g.mol
MW_i	Molecular weight of component i	g.mol
MW_{inj}	Molecular weight of injection gas	g.mol
MW_{air}	Mole weight of air	g.mol
MW_{C5+}	Molecular weight of C_5+ of the reservoir fluid	g.mol
MW_{C7+}	Molecular weight of C_7+ component in stock tank oil	g.mol
MF_i	Modification Factor of component i	
MMP	Minimum miscibility Pressure	psia
MMP_{base}	MMP for base injection gas (no nC_5), psia	psia
MMP_{cal}	Calculated MMP	psia
MMP_{exp}	Experimental MMP	psia
$MMP_{GA\text{-}nC5.enriched}$	GA-based MMP for nC_5 enriched gas, psia	psia
$MMP_{LRM1\text{-}nC5\ enriched}$	The MMP for the nC_5 enriched gas correlated with LRM1	psia
$MMP_{LRM2\text{-}nC5\ enriched}$	The MMP for the nC_5 enriched gas correlated with LRM1	psia
$MMP_{impure(MPa)}$	Impure CO_2 MMP	MPa
$MMP_{pure(MPa)}$	Pure CO_2 MMP	MPa
n	Number of moles	
NHV	Net heating value	BTU/ft^3
NHV_i	Net heating value of component i	BTU/ft^3
P	Pressure	psia
P_c	Critical pressure	psia
$P_{C,CO2}$	Critical Pressure of CO_2	psia
$P_{C,inj}$	Critical pressure of injection gas	psia
P_{cw}	Weight fraction based critical pressure	psia
$P_{cw\text{-}base}$	Weight averaged pseudo-critical pressure of the base gas (no nC_5)	psia
$P_{cw\text{-}nC5}$	Weight averaged pseudo-critical pressure of the injected nC_5 enriched gas	psia
P_{pc}	psuedo-critical pressure	psia
P_{pr}	psuedo-reduced pressure	
P_R	Reservoir pressure	psi
P_{sat}	Saturation pressure	psia
$PFit(i,j)$	Fitness function of GA correlation for data number j of chromosome i	
pen	Penalty function, used for GA fitness factor determination	
q	flow rate	cc/sec
r	radius	ft, in
r_e	effective reservoir radius	ft

r_w	well bore radius	ft
R_s	Solution GOR	scf/stb
R_{sd}	Depletion solution GOR	scf/stb
R_{sdb}	Depletion solution GOR at bubble point	scf/stb
R_{sfb}	Flash solution GOR at bubble point	scf/stb
$\overline{S_o}$	Average oil saturation in swept zone	
S_{oi}	Initial oil saturation	
S_{orp}	Ultimate residual oil saturation	
T	Temperature	
T_c	Critical temperature	
$T_{c,inj}$	Critical temperature of injection gas	K
T_{ci}	Critical temperature of the gas component i, °F.	°F
T_{Ci}	Critical temperature of component i	K
T_{CM}	Critical temperature of the mix	K
T_{cm}	Pseudo-critical temperature of the mixture	°F
T_{cw}	Weight fraction based critical temperature	°F
$T_{cw\text{-}base}$	Weight averaged pseudo-critical temperature of the base gas (no nC_5)	°F
$T_{cw\text{-}nC5}$	weight average pseudo-critical of the injected nC_5 enriched gas	°F
T_{pc}	psuedo-critical temperature	
T_{pr}	psuedo-reduced temperature	
T_{res}	Reservoir temperature	°F
T_{RES}	Reservoir temperature	K
TE_o	Oil thermal expansion	$°F^{-1}$
t_{roll}	Roll time	sec
V	Volume	cc
V_B	Bulk volume	cc
V_P	Pore volume	cc
V_g	Gas volume	cf
$V_{g,res}$	Gas volume at reservoir conditions	rcf
$V_{g,surf}$	Gas volume at surface conditions	scf
$V_{g,cell}$	Gas cell volume	cc
V_o	Oil volume	bbl
$V_{o,res}$	Oil volume at reservoir conditions	rbbl
$V_{o,surf}$	Oil volume at surface conditions	stb
$V_{o,cell}$	Oil cell volume	cc
$V_{t,res}$	Total volume at reservoir conditions	rbbl
$V_{t,surf}$	Total volume at surface conditions	stb
V_{pump}	Pump volume	cc
$V_{pump,sat}$	Pump volume at saturation pressure	cc

V_{rel}	Relative total volume, swollen volume or swelling factor	
V_{sat}	Volume at the saturation pressure	cc
$V_{sat(new)}$	New saturation volume	cc
$V_{sat(orig.)}$	Original saturation volume	cc
Vol/Int	The ratio of volatile components (methane and nitrogen) to intermediate components (ethane to butane)	
W_{dry}	Dry weight of core plug	gm
w_i	Weight fraction of component i	wt%
W_{sat}	Saturated weight of core plug	gm
Y	The Y-function	
y_2	Mole fraction of non-CO_2 component in injection gas	
y_i	Mole fraction of component i	
Z	Compressibility factor (Z)	
Z_{sc}	Compressibility factor (Z) at standard conditions	

GREEK

<u>**Symbol**</u>	<u>**Description**</u>	<u>**Unit**</u>
α	Slope of the relationship between $MMP_{nC5\ enriched}$ / MMP_{base} vs $M_{C5+,oil}$ / MW_{C5+}	
α_{inj}	Johnson and Pollin (1981) Injection gas constant	psia/K
β_{GA}	GA multiplication factor	
β	Intercept of the relationship between $MMP_{nC5\ enriched}$ / MMP_{base} vs $M_{C5+,oil}$ / MW_{C5+}	
Δ	Difference	
ϕ_e	Effective porosity	
γ_G	Gas Gravity	
λ_{GA}	GA multiplication factor	
μ	Viscosity	cP
μ_g	Gas viscosity	cP
μ_o	Oil viscosity	cP
μ_w	Water viscosity	cP
ρ_{oil}	Oil density	gm/cc, lb/ft^3
ρ_r	reduced density	
ρ_{water}	Density of water	gm/cc, lb/ft^3
ρ_{steel}	Density of steel	gm/cc, lb/ft^3
ρ_{steel}	Density of steel	gm/cc, lb/ft^3

ACRONYMS

Acronym	**Description**
CCE	Constant Composition Expansion
CGR	Condensate Gas Ration
CME	Constant Mass Expansion
CMS	Constant Mass Study
CVD	Constant Volume Depletion
EOR	Enhanced Oil Recovery
FID	Flame Ionisation Detector
FVF	Formation Volume Factor
GC	Gas Chromatograph
GOR	Gas Oil Ratio
MMP	Minimum Miscibility Pressure
PV	Pore Volume
PVT	Pressure, Volume, Temperature
RBA	Rising Bubble Apparatus
SARA	Saturates, Aromatics, Resins, Asphaltenes
TCD	Thermal Conductivity Detector
WFT	Wireline Formation Tester