



Laboratory and Modelling Studies on the Effects of Injection Gas Composition on CO₂-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 CO₂ would not have injectivity problems. CO₂ is abundant in the region and available for EOR use. CO₂ was compared to other CO₂-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 CO₂ 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 CO₂ as an injection gas for Enhanced Oil Recovery (EOR) in the Cooper Basin oil reservoirs and to compare CO₂ with other possible CO₂-rich injection gases.

The summarised goals of this research are to:

- Determine the compatibility of Field A reservoir fluid with CO₂ as an injection gas.
- Compare CO₂ to other injection gas options for Field A.
- Development of a correlation to predict the effect of nC₅ on MMP for a CO₂-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 CO₂-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.

- CO₂ 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 nC₅ will reduce the MMP and increase the recovery factor, however the cost of the nC₅ used would be more than the value of increased oil recovered.
- The developed correlation for the effect of nC₅ on impure CO₂ 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.

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Johannes Bon
February 2009

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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 CO₂-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 nC₅ on Impure CO₂ 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 CO₂-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
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NOMENCLATURE

Nomenclature and units used throughout this thesis are as follows:

ENGLISH

| <u>Symbol</u> | <u>Description</u> | <u>Unit</u> |
|---------------|--|--------------------------|
| 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_{nC_5} | The mole fraction nC_5 in the injection gas stream | mol% |
| M_{C_5+} | 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_{C_5+} | Molecular weight of C_5+ of the reservoir fluid | g.mol |
| MW_{C_7+} | 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 |
| $MMP_{GA-nC_5.enriched}$ | GA-based MMP for nC_5 enriched gas, psia | psia |
| $MMP_{LRM1-nC_5.enriched}$ | The MMP for the nC_5 enriched gas correlated with LRM1 | psia |
| $MMP_{LRM2-nC_5.enriched}$ | 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,CO_2} | Critical Pressure of CO_2 | psia |
| $P_{C,inj}$ | Critical pressure of injection gas | psia |
| P_{cw} | Weight fraction based critical pressure | psia |
| $P_{cw-base}$ | Weight averaged pseudo-critical pressure of the base gas (no nC_5) | psia |
| P_{cw-nC_5} | 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 |

Nomenclature

| | | |
|------------------|--|------------------|
| 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 |
| $T_{cw-base}$ | Weight averaged pseudo-critical temperature of the base gas (no nC ₅) | °F |
| T_{cw-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 |

Nomenclature

| | | |
|------------------|---|-----|
| 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

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