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Dynamic Validation of Amal Phase Behaviour for EOR Application Using CO_2 as Solvent Injection

A. I. Abufarwa[1,*], A.E. Bezan[1],M. M. Elneca'a[1] ,M.M. Khazam[1]
[1]Department of Petroleum Engineering, Tripoli University, Tripoli, Libya
*Corresponding Author: farwa2008@gmail.com

Abstract

Injection of CO_2 into a reservoir for enhanced oil recovery (EOR) results in complex fluid phase behaviour that require accurate reservoir fluid characterizations by equations of state (EOS) to capture the phase interactions in miscible CO_2 floods. Amal is a giant Libyan field classified as low shrinkage type of oil and characterized by relatively law solution gas-oil ratio (GOR) of 400 scf/STB and oil gravity of 35 ^{o}API. The field has been producing since1960's under active bottom water drive that maintained the current reservoir pressure at levels higher than the bubble point pressure. The main objective of this paper is to establish an EOS model able to characterize Amal phase behaviour accurately in immiscible and miscible conditions. A model that statically validated against the conventional PVT data and dynamically validated to match the slim-tube experiments. Three parameters Peng–Robinson (PR) and Soave-Redlich-Kwong (SRK) equations of state are used to model the Amal phase behaviour. In addition, 1-D slim-tube model is built using commercial compositional simulator to simulate four slim tube experiments. The outcome revealed that conventional PVT data will not reflect the proper phase behaviour model when it was used to simulate the slim tube experiments. Therefore, further efforts are giving to EOS tuning. Also, the lumped compositional model was not so perfect to simulate the hump phenomenon in slim tube experiments like extended model did. Perfect match of all slim tube experiments from immiscible to miscible conditions at pressures of 2000, 3000, 3600 and 4000 psia were achieved indicating the validity and reliability of the realized phase behaviour model.

Keywords: Phase behaviour; equation of state modelling; EOR processes; CO_2 solvent injection

1. Introduction

An equation of state (EOS) is an analytical expression relating pressure to the volume and temperature. The expression is used to describe the volumetric behaviour, the vapour/liquid equilibria (VLE), and the thermal properties of pure substances and mixtures. EOS are very versatile tools for engineering applications. They can be used for all states of matter (mostly gas, vapour, and liquid), and they can describe transitions between states.

Tuning of EOS is necessary for characterizing the reservoir fluids and evaluating their volumetric performance at various pressure levels. Such a tuning exercise is performed against static measured data by adjusting the EOS parameters systematically. Typical laboratory data used in the tuning process include conventional PVT data such as flash and differential vaporisation, single contact, and multiple contact vapour- liquid phase equilibria measurements. Numerous studies[3] [4] for understanding and quantifying the mass transfer mechanisms occurring in CO_2 or a rich-gas injection and for designing the solvent composition and size requirements in gas injection processes have used tuned EOS to predict displacement efficiency.

In 1985, Kossack and Hagen [5] studied the capability of an EOS which was tuned against static experimental data, to simulate the phase behaviour in slim tube displacement. They managed to simulate binary system displacements but had limited success in simulating the displacements conducted on a ternary system. They concluded that the EOS with the phase match obtained from the static PVT experiments was not adequate for simulating the slim tube displacements and a different set of EOS parameters were required to match both PVT and displacement experiments.

In 1990, Mansoori et al. [6] investigated whether fluid descriptions based on PVT data alone could be used to predict the multiple contact behaviour and displacement efficiencies observed in dynamic rich gas displacement. They also concluded that the tuned fluid description based on PVT data alone was not enough for predicting oil recovery and displacement behaviour in the dynamic tests.

In 1994, Khazam at al. [7] have used a large amount of measured slim-tube data at different interracial tension values to develop relative permeability-saturation correlations as a function of the interracial tension. The reliability of the developed parameters was confirmed by comparing predicted and measured displacement data using multicomponent and real reservoir fluids at no mass transfer conditions. The simulated displacement results, for miscible and immiscible conditions, matched the experimental data favourably where the tuned model was capable of adequately predicting the static data covering the whole range of compositional variations. The study highlighted the value of displacement data for evaluating phase behaviour models particularity at conditions where significant mass exchange occurs between the phases.

Our study has dealt with a potential candidate field for future CO_2 EOR injection, where extensive conventional PVT analyses are available. Firstly, we assessed and analysed the PVT properties of Amal field in general and "B" region in particular. The fluid properties variation has been studied arealy and vertically, in order to select a representative PVT sample for our study. Fourteen (14) samples were collected and analysed, and as a result the PVT data have confirmed that the fluid is arealy homogenous with no conclusive trend in the vertical direction.

The phase behaviour modelling on the selected samples was carried out using three parameters PR and SRK EOS's. The first step in adjustment process was split of C_{7+} into three fractions using Whitson [8] gamma distribution then assigned the critical properties of each component. A non-linear regression program was applied to achieve perfect match with the conventional and special PVT data applying extended and lumped compositional models. An effort to identify the optimum grid numbers and time step was made to minimize and/or overcome numerical dispersion effect. Several sensitivity analyses scenarios have also done, such as comparison between horizontal and vertical numerical model to check and confirm gravity override/segregation effect was not exist. Also lumped versus extended compositional model to study the impact of phase behaviour models with two different schemes and its impact on slim tube experiments predictions.

The overall match of slim tube experiments was very good with some exception on the measured produced gas C_{5+} concentration, especially at the end of some experiments. The relative permeabilities at higher pressure experiments are sensitive to IFT values, particularly at low IFT value. These were simulated by compositional simulator applying the concept of IFT forces where the base relative permeability curves will approach to straight lines as the IFT approaches to zero.

2. Comparison and Assessment of Amal PVT Data

This study needs two types of PVT tests (conventional & special) and would be preferably if they are carried out on the same well sample (same fluid sample). In reality most of the early PVT data available for Amal B structure are conventional data while the only special PVT data was carried out on Well 27. The target PVT will be the one that have common reservoir composition analysis fairly close to that of well B27. Figure. 2.1. shows all the collected PVT data from different wells and as illustrated all these wells have almost similar composition trends and all are fairly close to Well B27 composition, though different labs are used to conduct different PVT samples.

The DL tests comparisons revelled that all the PVT measurements (i.e. RS, Bo, ρ_o, Pb, etc.) are fairly compatible and matching each other except for the well B3 which is substantially deviated from the other samples trend (Figures. 2.2 through 2D). The B3 measurements have shown substantially lower Rs and Bo measurements and higher density and viscosity measurements and therefore has been excluded from our selection. For the purpose of our study, well B1 (Table 2.1) was selected to represent the conventional data. In addition, another conclusion we can draw from the Figures is that the Amal B

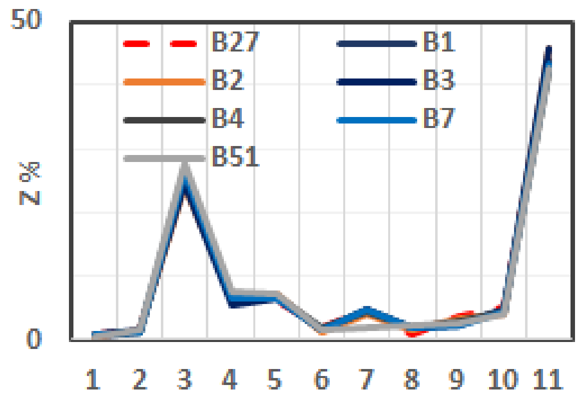

Figure 2.1: Composition of PVT Samples (B1, B2, B3, B4, B7, B51 and B27)

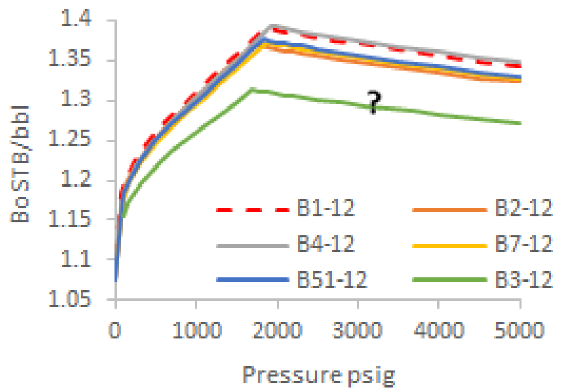

Figure 2.2: Formation Volume Factor of wells B1, B2, B3, B4, B7, B51) at 229° F

fluids are areally homogenous with almost similar properties.
Typically, in black oil reservoirs the bubble point pressure as well as the light and heavy component compositions are varied with depth. This is not the case of Amal B field where no clear trend of properties variation in the vertical directions. The change of Pb are varying within ±100 psi (within the experiment measurements accuracy) as indicated in Figure. 2.6.
In more depth characterization and comparison, Watson [9] factor was calculated for the completely Amal field. Figure 2.7. shows the plot of molecular weight versus specific gravity for C_{7+} fractions indicating an average Kw = 12.15 indicating that Amal field crude can be classified as Naphthenic.

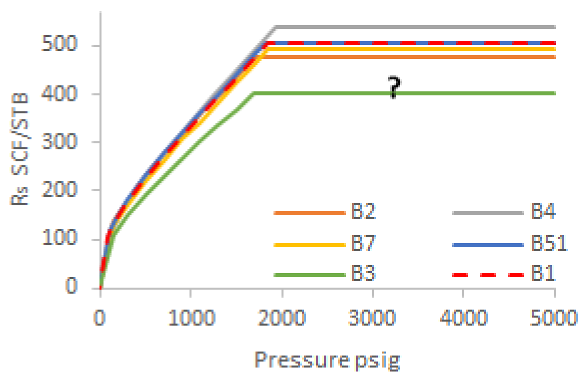

Figure 2.3: Solution Gas Oil Ratio of wells (B1, B2, B3, B4, B7, B51) at 229° F

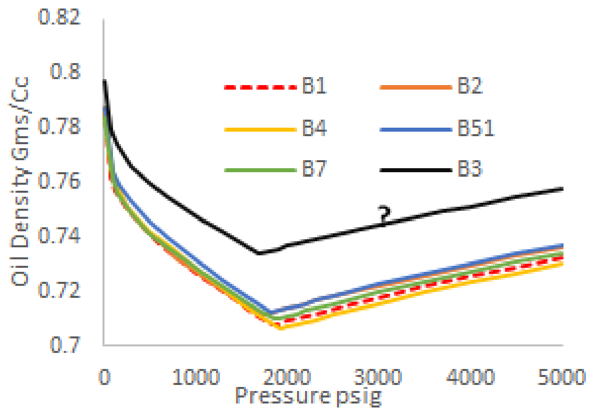

Figure 2.4: Oil Density of wells (B1, B2, B3, B4, B7, B51) at 229° F

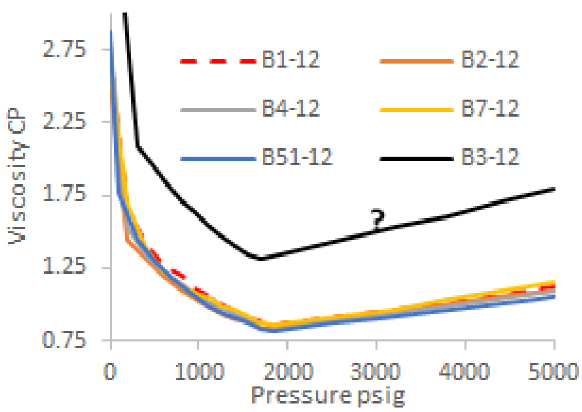

Figure 2.5: Oil Viscosity of wells (B1, B2, B3, B4, B7, B51) at 229° F

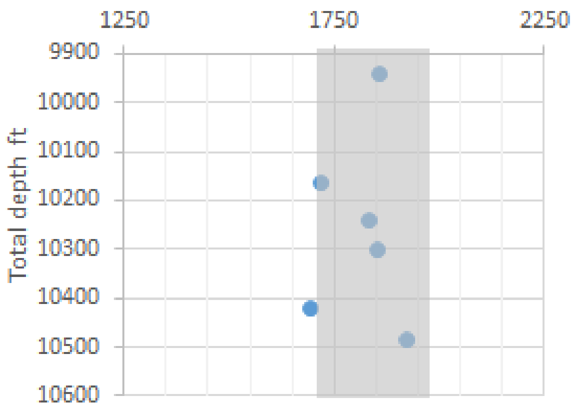

Figure 2.6: Saturation Pressure Variation with Depth

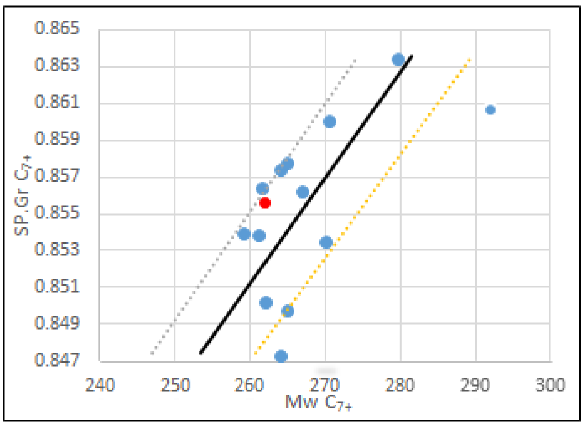

Figure 2.7: Specific gravity vs. molecular weight for C_{7+} fractions

Table 2.1: Amal Fluid (B1) Components

Component	MOL %
CO_2	0.5
N_2	1.35
C_1	25.62
C_2	6.67
C_3	6.8
IC_4	1.44
nC_4	4.65
IC_5	1.81
nC_5	2.61
C_6	4.62
C_{7+}	43.93

3. Phase Behaviour Modelling of Amal Fluid

Most EOS characterizations are not truly predictive and compositions may be off by several mole percent for key components. In addition, the EOS may predict a bubble point incorrectly. This lack of predictive capability by the EOS probably because of insufficient compositional data for the C_{7+} fractions, inaccurate properties for the C_{7+} fractions, inadequate BIP's, or incorrect overall composition. The EOS characterization can be improved in a number of ways, and the strategy followed in this study as those proposed by literatures [9, 10].

This study has used three parameter gamma probability distribution function (for both PR & SRK EOS's) for the sake of splitting C_{7+} into three pseudo-components. Table 3.1 shows C_{7+} fractions after splitting. The M and γ of pseudo components are in good match and agreement, with the molecular weights and specific gravity proposed by Katz-Firoozabadi [11] as shown in Figure 3.1.

The critical properties of each pseudo-component should be estimated using the proper correlations. Therefore, Kesler-Lee correlation [12, 13] and Edmister correlation [14] were used to calculate Tc, Pc and ω respectively for PR EOS. While only Kesler-Lee correlation was used to calculate the critical properties for SRK EOS.

Molar averaging groping technique [15] is used to reduce number of components from 13 to 8 components. Table 3.2 shows the composition after grouping.

The goal of PVT analysis is to provide a tuned EOS that can model the reservoir fluid in simulation studies. The selection of regression parameters is cru-

Table 3.1: Compl extended Model

Comp.	Mol%	M
CO_2	0.5	-
N_2	1.35	-
C_1	25.62	-
C_2	6.67	-
C_3	6.8	-
IC_4	1.44	-
NC_4	4.65	-
IC_5	4.62	-
NC_5	2.61	-
C6	1.81	-
FRC1	16.927	119.59
FRC2	19.721	266.82
FRC3	7.2816	580

Table 3.2: Comp. of Lumped Model

Comp.	Mol%	M
CO_2	0.5	0.1629
N_2 C_1	1.35	16.642
C_2	6.67	1.4847
C_3C_4	6.8	50.724
C_5C_6	4.62	74.532
FRC1	16.927	119.59
FRC2	19.721	266.82
FRC3	7.2816	580

cial in determining the quality of the tuned fluid model. Table 3.3 illustrates the EOS's parameters that have been adjusted to simulate conventional & special PVT data using the extended composition model (13 components) and lumped (8 components) model for both PR and SRK. Excellent match has been achieved between simulated and measured PVT data (for both conventional and special experimental). Figures 3.2 through 3.8 show the match results using PR EOS for the extended model. Also, perfect matches were obtained for the lumped models and by SRK EOS.

The critical volume of pseudo-components was selected as regression parameter for all models to match the measured viscosity using Lohrenz-Bray-Clark (LBC correlation [16]. An acceptable match was achieved for viscosity measurements as shown in Figure 3.9.

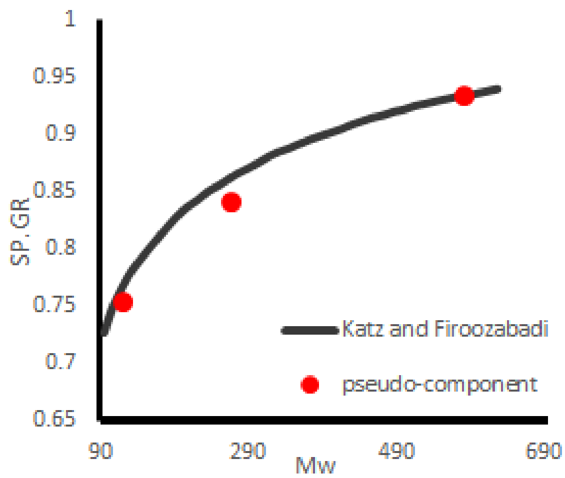

Figure 3.1: Molecular weights and specific gravity proposed by Katz-Firoozabadi and results of splitting

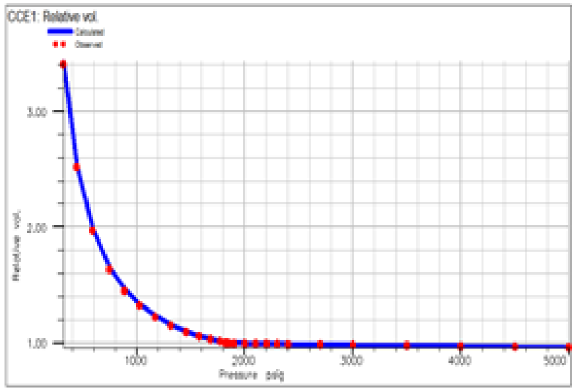

Figure 3.2: CCE Relative volume. Comparing measured and PR EOS extended predictive model

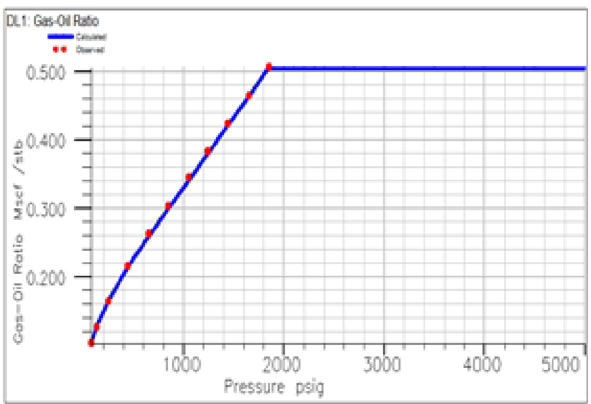

Figure 3.3: DLE Gas-Oil Ratio Mscf/stb, comparing measured and PR EOS extended predictive model

Table 3.3: EOS Adjusted

EOS \ Parameters	Ω_A	Ω_B	Tc	Pc	ω	S shift	BIC
Extended / Lumped PR			✓	✓		✓	✓
Extended / Lumped SRK	✓	✓				✓	✓

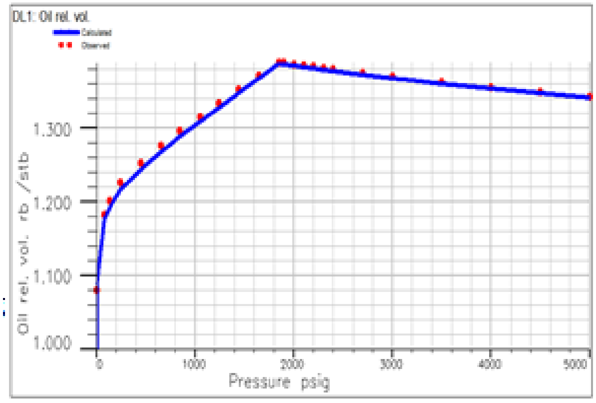

Figure 3.4: DLE formation volume factor rb/stb, comparing measured and PR EOS extended predictive model

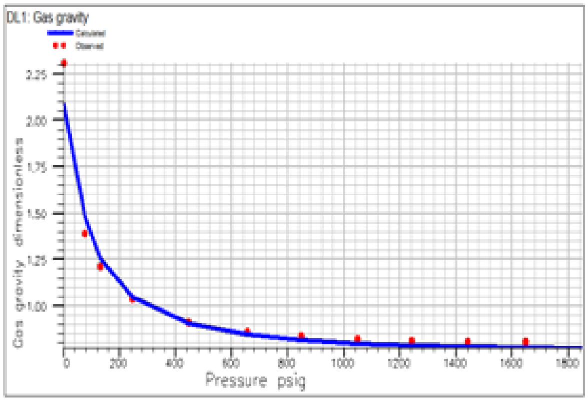

Figure 3.6: DLE Gas gravity, comparing measured and PR EOS extended predictive model

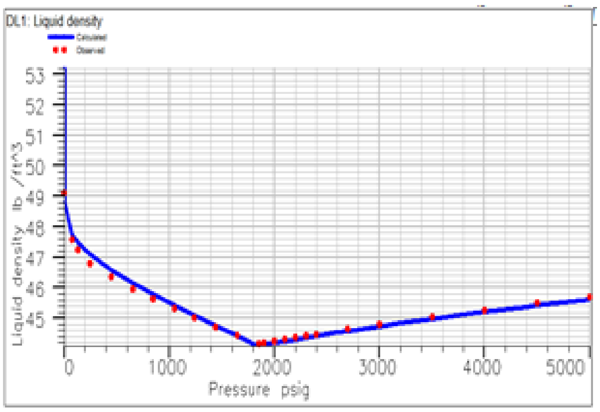

Figure 3.5: DLE Liquid density lb/ft^3, comparing measured and PR EOS extended predictive model

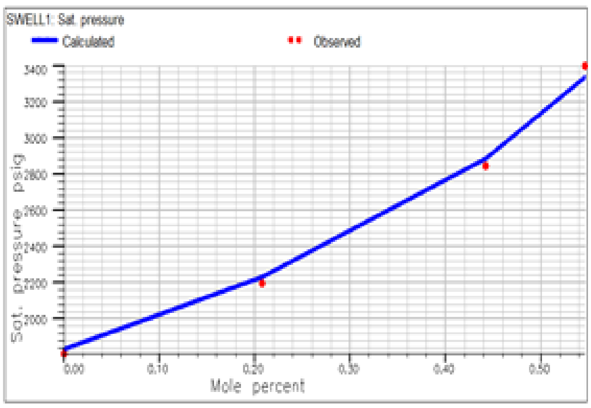

Figure 3.7: Swell sat. Pressure psig, comparing measured and PR EOS extended predictive model

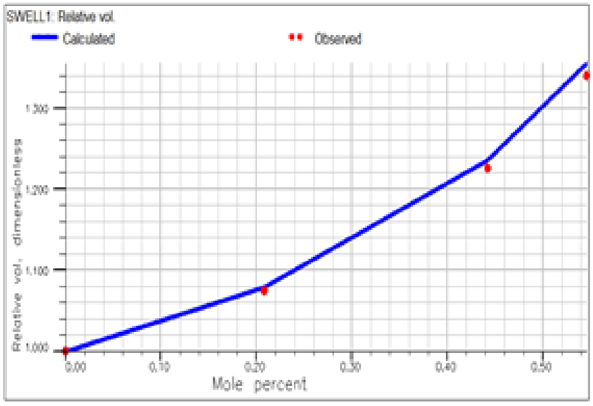

Figure 3.8: Swell Relative vol., comparing measured and PR EOS extended predictive model

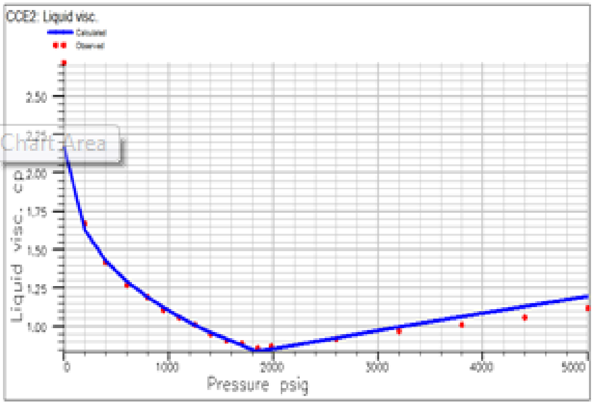

Figure 3.9: Liquid visc. Comparing measured and PR EOS extended predictive model

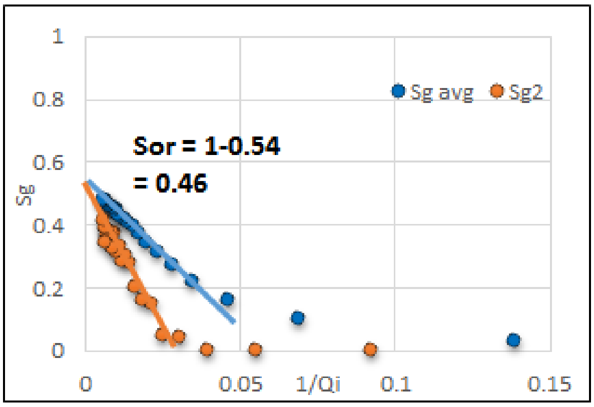

Figure 4.1: Extrapolation to residual saturation (Bardon and Longeron Method)

4. Base Relative Permeability Determination

In order to have proper simulation of slim-tube experiments, it is necessary to have the proper flow model to simulate the two phase flow inside the slim-tube experiment. The base relative permeability curves were back calculated from the immiscible slim tube experiment at 2000 psia (IFT 5 dyne/cm^2) using two analytical graphical techniques (Bardon-Longeron and Jones-Roszelle).

Figure 4.1. shows both the average gas saturation and the outflow-face gas saturation curves, using the tangent intercepts, and the extrapolation to infinite throughput where the average and point saturations approaches to unique value. Figure 4.2. shows the final back calculated relative permeability curve obtained using Bardon and Longeron method. Same results were also obtained by using Jones and Roszelle technique and both methods predict identical results of relative permeability values as shown in Figure 4.3.

5. Slim Tube One-Dimension (1-d) Model

Slim-tube displacement experiments were simulated using 1-D compositional simulator software (Eclipse 300). The 1-D simulation model was designed to be equivalent to the typical slim tube laboratory experiment in dimensions, conditions and rock properties. The 1-D dimension model was constructed as shown in Figure 5.1. With 200 grids in horizontal direction and an injector placed at one end (1st grid) and a producer at the other end (200th grid). The length of each grid block in the grid system was fixed at

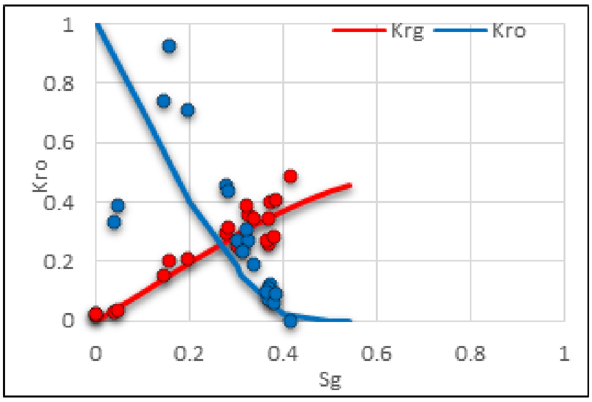

Figure 4.2: Relative permeability curve (Bardon and Longeron method)

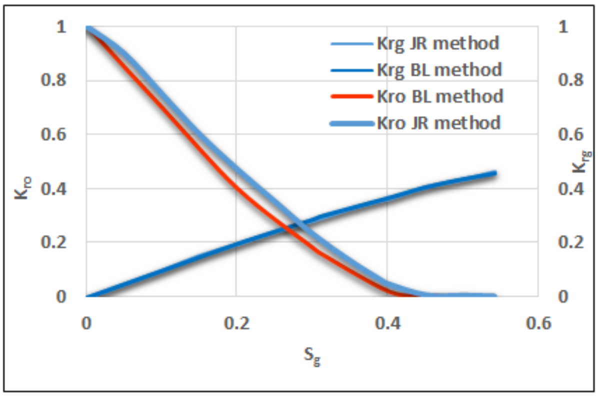

Figure 4.3: BL & JR relative permeability

6.075 cm, while the thickness and the width of each grid block was fixed at 0.4136 cm. The model has a uniform porosity of 0.353, a constant absolute permeability of 4.6 D, and the total pore volume of 73.37 cm^3. In each experiment, solvent fluid (CO_2) was injected at rate of 7.1 cm^3/hr to simulate slim tube experiments.

Series of simulation runs were conducted over a range of tested pressures (2000 to 4000 psia) at reservoir temperature of 225o F. Figures 5.2 through 5.6 show the comparison results of the immiscible slim tube experiment at 2000 psia, that covers the prediction of produced oil RF, pressure drop across slim-tube experiment, CO_2 concentration versus pore-volume injected (PVi), C_1/N_2 concentration and C_{5+} concentration. The predictions were made by both lumped and extended compositional models and both almost have identical results. Overall match is good with some exceptions at the late C_{5+} concentration after the B.T. Perfect simulation of CO_2 concentration was achieved. The predicted RF at the end of experiment is 42.8% compared to the measured one of 41.5%. At the levels of immiscible conditions (2000 psia) experiments, both the extended and lumped models have almost shown identical predictions.

It should be pointed out that match of only the conventional PVT data is not suffient to model the slim-tube experiment and will not reflect the prospected phase behaviour model. We have made number of back and forth trials with special attentions and more efforts paid to the strategy adopted for EOS tunings, especially the splitting proportional and weight factor applied for the tuned parameters. Also, we have noticed that CO_2 related parameters are very sensitive to the tuning exercise.

Several sensitivity runs were carried out to assess the impact of certain physical and/or numerical phenomenon. In addition, to validate the numerical model and to eliminate any adverse flow effects that can impact the model predictions.

To select the optimum grid-cell size and the time step that minimize and/or overcome numerical dispersion effect, several 1-D models were constructed with different number of grid-blocks (50,100,200,400). More efforts were done to identify the optimum time step for each number of grid-blocks that will produce the lowest numerical dispersion. We have noticed that with careful selection of time-step the numerical dispersion can be eliminated even with the 50 grid-blocks and the immiscible slim tube experiment at 2000 psia is perfectly matched. For the purpose of this study we decided to use 200 grid-blocks for

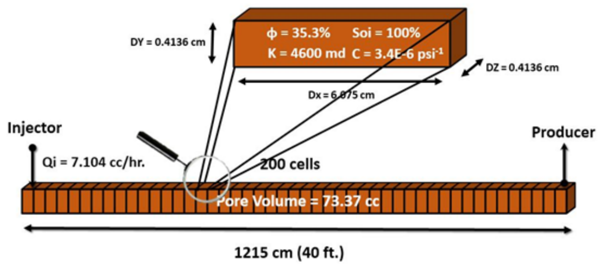

Figure 5.1: Slim Tube one-dimension (1-D) Model specification

all our simulation runs.
We have also investigated the impact of using horizontal model versus vertical model to ensure no gas override during the simulation of displacement process. Both models predictions are identical and have confirmed no segregation or gravity override effects are exist in the model.
Once the good match on the immiscible experiment at 2000 psia was achieved and all the adverse flow factors have been eliminated, then the miscibility mechanism of other slim tube experiments at higher pressures were simulated with the IFT change with the relative permeability curves using Khazam et al correlation [7].
The overall match of these high pressure experiments (3000, 3600 and 4000 psia) are very acceptable with some exceptions at the last few C_{5+} concentration measurements (likely measurement errors).
The impact of extended composition model versus lumped model was clearly seen in the near critical miscibility pressure experiment at 3000 psia. The extended compositional model has better prediction of the hump phenomenon, realized during the C_1/N_2 concentration measurement at breakthrough, compared to lumped model (Figure 5.7.)
Also, better physical dispersion prediction by the extended model for both CO_2 and C_1/N_2 concentrations are noticed when they compared with the lumped model (Figure 5.9.). However, with these sensitive variation between the extended and limped model, still the lumped model is fair enough to be used for future EOR compositional studies.
The Measured RF and CO_2 concentration for all the above experiments are shown in Figure 5.8 through 5.13. The predicted RF at the end of each experiment is very close to the measured values, confirming near critical miscibility status at 3000 psia experiment and complete miscible drive mechanisms at 3600 and 4000 psia with RF more than 94%.

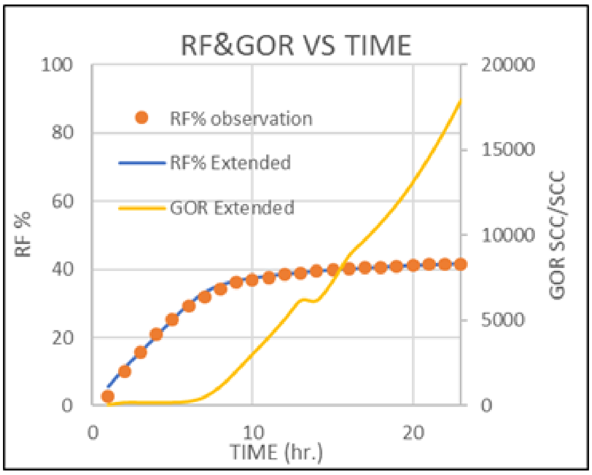

Figure 5.2: Recovery Factor and GOR VS Time at 2000 psia

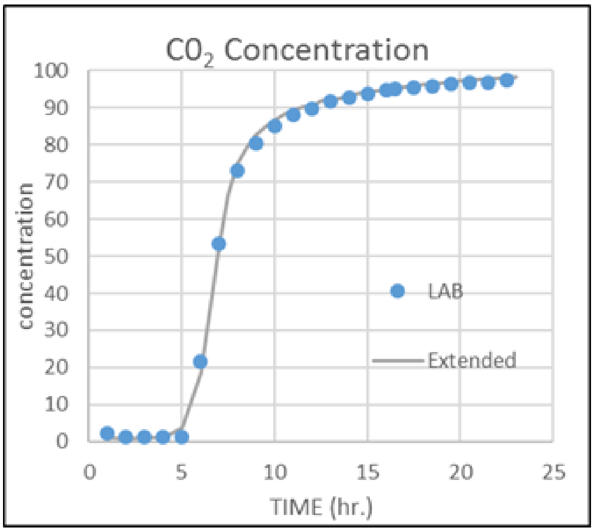

Figure 5.3: CO_2 Concentration Vs Time At 2000 psia

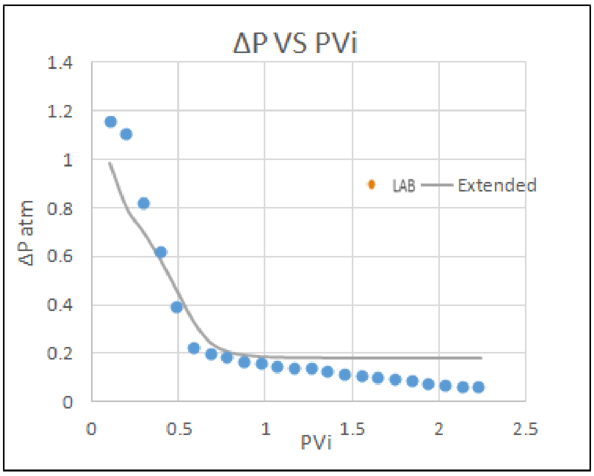

Figure 5.4: Differential Pressure Vs Pore Volume Injector at 2000 pisa

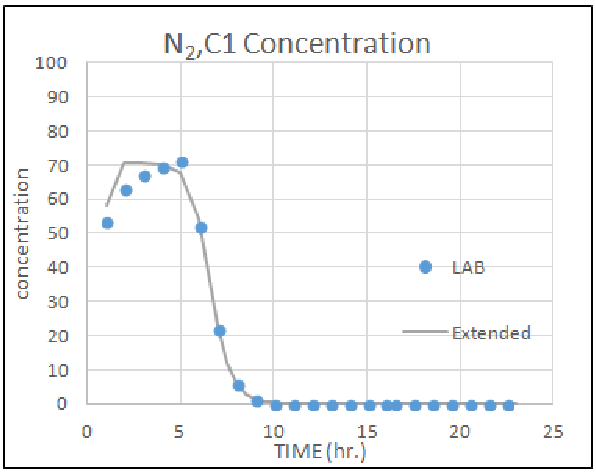

Figure 5.5: N_2, C_1 Concentration Vs Time at 2000 psia

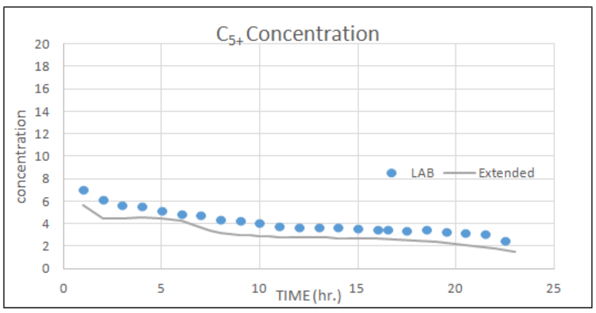

Figure 5.6: C_{5+} Concentration Vs Time at 2000 psia

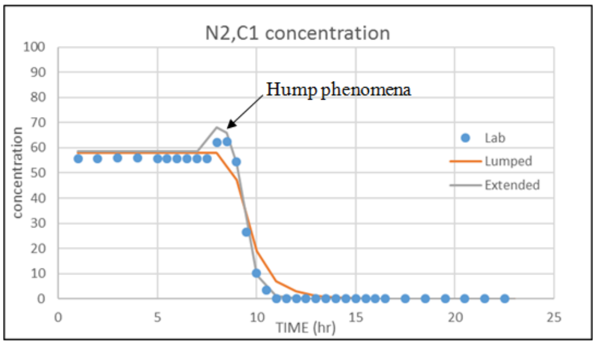

Figure 5.7: N_2, C_1 Concentration Vs Time at 3000 psia

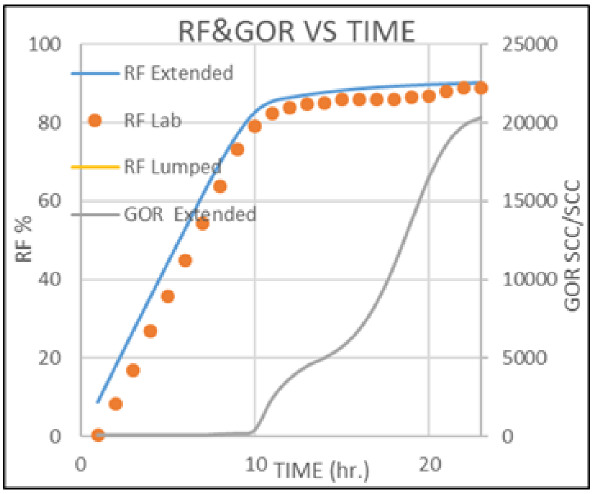

Figure 5.8: Recovary Factor and GOR VS Time

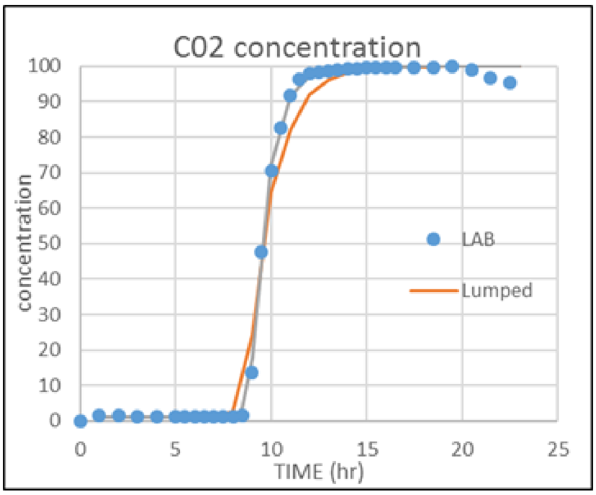

Figure 5.9: CO_2 Concentration Vs Time At 3000

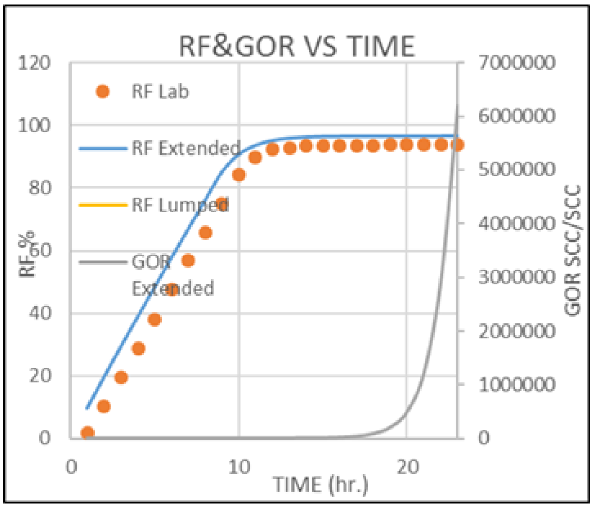

Figure 5.10: Recovary Factor and GOR VS Time

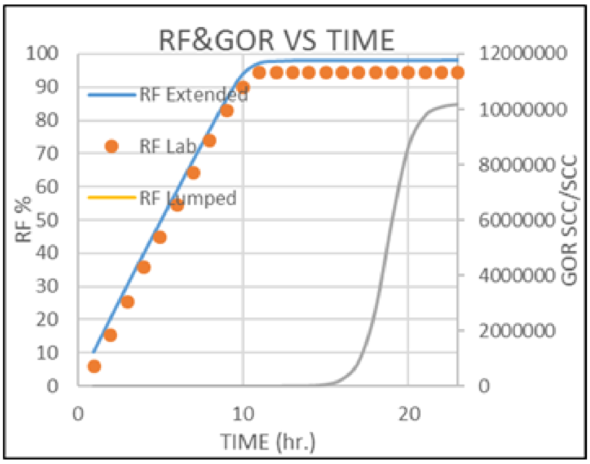

Figure 5.12: Recovary Factor and GOR VS Time at 4000 psia

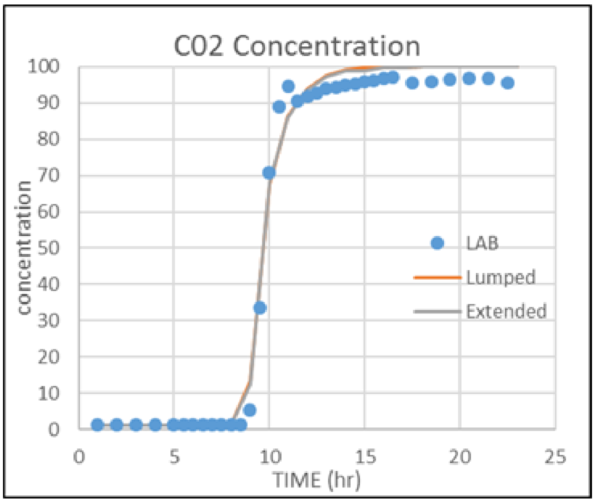

Figure 5.11: CO_2 Concentration Vs Time

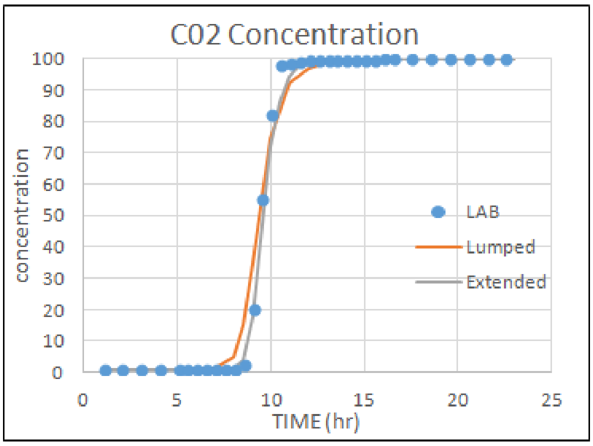

Figure 5.13: CO_2 Concentration Vs Time At 4000 psia

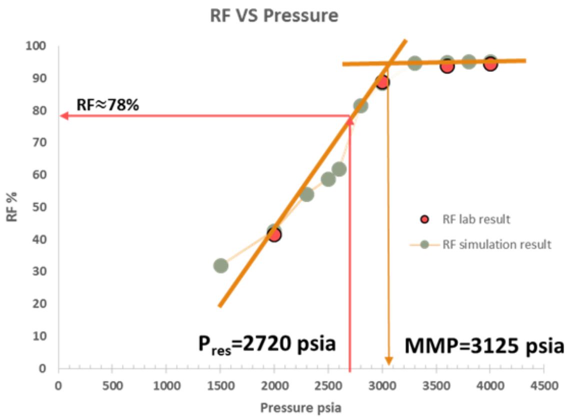

Figure 6.1: Recovary Factor Vs Pressure

6. Minimum Miscibility Pressure (MMP) Determination Using 1-D Model

After several simulation runs with different pressure ranges from 2000 to 4000 psig, the obtained recovery factor at the end of each simulation run was plotted against the measured slim tube recovery factors. An S shape trend based on simulation results was pictured which is aligned with many literature findings [7]. The predicted minimum miscibility pressure (MMP) using 1-D-model is aligned with the measured data (3125 psia). Figure 6.1. Shows the RF versus pressure and the MMP estimation. These data indicate that substantial amounts of hydrocarbon constituents were extracted by the CO_2 as it was displaced through the slim-tube.

7. Conclusions

- Amal fluid is classified as Naphthenic type fluid (Watson Factor = 12.15). Also, the PVT data confirms that the fluid is arealy homogenous with no clear trend in the vertical direction.
- Reasonable match was achieved for Amal conventional and special PVT experiments using both PR and SRK with the proper selection of the tuning parameters. Also, acceptable match was achieved with the extended compositional model (13 components) and Lumped model (8 components).
- Match of only the conventional PVT data will not reflect the proper phase behaviour model when will be used to simulate the slim tube experiments. Therefore, special attention and more efforts should be giving to EOS tuning to match both the conventional and special tests for EOR simulation studies.
- For proper dynamic validation of Amal phase behaviour other adverse flow effects, such as numerical dispersion, should be eliminated or minimized. This was done by the proper selection of the size and number of E300 1-D cells (200 grid blocks) and the time step.
- The base relative permeability curves are another important flow tool to simulate slim tube experiments and to validate Amal phase behaviour model. The base relative permeability curves were back calculated from the immiscible slim tube experiment at 2000 psia (IFT 5 Dyne/cm) using Bardon-Longeron and Jones-Roszelle analytical techniques.
- The relative permeabilities at higher pressure experiments are sensitive to IFT values, especially at low IFT value. These were simulated by applying the concept of IFT forces where the base relative perm curves will approach to straight lines as the IFT approaches to zero.
- The hump phenomena before B.T. time was better simulated with the extended compositional model compared to the lumped model. This highlights the favourability of extended compositional model in future EOR simulation studies.
- Perfect match of all slim tube experiments from immiscible to miscible conditions (2000, 3000, 3600 and 4000 psia) were achieved indicating the validity and reliability of Amal phase behaviour model.
- The multiple contact MMP pressure of Amal field, using CO_2 as injection solvent, is around 3125 psia based on measured and predicted results.

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Nomenclature

RS = Dissolved Gas Oil Ratio
Bo = Formation Volume Factor
ρo= Oil Density
μo= Oil viscosity
Kw = Watson Factor
M = molecular weight
γ= specific gravity
Tc = Critical Temperature
Pc = Critical Pressure
ω= Acentric factor
VC = Critical Volume
γ_2^{-1}= effective viscosity
Sor = Residual oil saturation
μ= Viscosity
Kr = Relative Permeability
Pb = Bubble Point
PVi = Pore volume Injector
B.T. = Time Breakthrough
MMP = Minimum Miscibility Pressure
DL = Differential Liberation
CCE = Constant Composition Expansion
BIP = Binary Interactive coefficient
GOR = Gas Oil Ratio
LBC = Lohrenz-Bray-Clark
RF = Recovery Factor

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