

Slim-tube simulation model for carbon dioxide enhanced oil recovery

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Abstract

A simulation model of the slim-tube test has been developed to validate the laboratory experiment and used EOS as well as to investigate the possibility of serving as a fast and reliable tool for MMP determination. Sensitivity analyses were performed by testing different grid block sizes (a different number of cells), changing Corey's coefficients for relative permeability curves, varying flow rates and PVT models. Minimum miscibility pressure from the simulation model is estimated as the intersection of the two different trend line curves of oil recoveries versus the injected volume of CO₂. The oil recoveries were underestimated by numerical simulation on a basic case model. This is related to the usage of single "X shaped" relative permeability curves in all simulation cases, i.e. for immiscible, near miscible and miscible conditions. In addition, by fine tuning binary interaction parameters in the equation of the state model and introducing different relative permeability curves for immiscible and near miscible cases, better matching of slim-tube simulation can be achieved.

Keywords

MMP, slim-tube, EOS, EOR, CO₂ injection

1. Introduction

CO₂-EOR is an attractive miscible process in which CO₂ is injected and mixed with reservoir oil, resulting in the oil swelling and a reduction in oil viscosity, thus affecting the capillary number, N_c . Microscopic displacement efficiency (E_D) largely depends on CO₂ injection conditions. Since it is a function of residual and critical oil saturation $E_D = f(S_{or}, S_c)$, properties of gaseous and liquid phases will change with the distance from the injector to the producer wells. When CO₂ starts to mix with the oil in different proportions at some distance from the injector, different oil compositions occur in the reservoir. As the composition of oil changes, oil volume increases, resulting in higher relative permeability to oil, reduced oil viscosity and changed S_{or} . If the minimum miscibility pressure (MMP) is not reached in the reservoir, the free CO₂ phase starts to flow several times faster than the oil phase, increasing the relative permeability to CO₂ phase in the flowing pathways. The effect of swelling can be observed in the laboratory by successive addition of CO₂ into the oil sample in a PVT cell, increasing the pressure until the new mixture of oil becomes a single phase (saturation pressure), and by re-

cording the volume of the new liquid composition at the observed pressure. The other beneficial effects are the oil viscosity reduction and favorable change of interfacial tensions (IFT) between the fluids in the reservoir. The change in the IFT is directly affecting the shape of relative permeability (k_r) curves - they become more linear (both phases become more mobile) when IFT between CO₂ and oil decreases until absolute miscibility is reached, characterized by an x-shaped relative permeability curve (see **Figure 1**).

To reduce laboratory work and time needed for determination of the optimal conditions for CO₂ Enhanced Oil Recovery (EOR), a sensitivity analysis of parameters in a slim tube simulation model has been performed. Slim-tube experiments compared with the simulation are rarely found in literature and are usually lacking systematic analysis of the parameters that affect the results of CO₂ EOR laboratory studies. The use of slim-tube simulation as a substitute for slim-tube experiments was not considered in literature so far.

The analysis described in this work is based on an extensive PVT laboratory study of an oil sample from the Ivanić oil field in Croatia. It is focused mainly on determining the minimum miscibility pressure (MMP) as threshold pressure above which maximum feasible recovery (i.e. displacement efficiency) is possible, which is prominent in a smaller amount of injected CO₂ to

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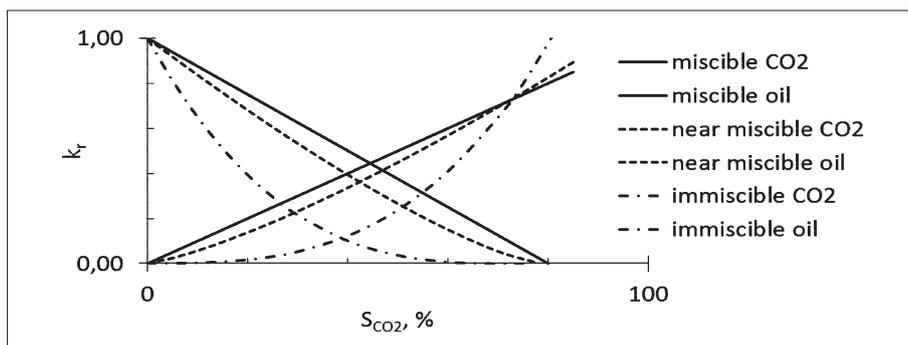


Figure 1: General shape of relative permeability curve at miscible, near miscible and immiscible conditions.

achieve target oil recovery (Alomair et al., 2015; Ayirala and Rao, 2011). The MMP was determined based on experimental slim-tube results and by analyzing the calibrated slim-tube simulation model. The slim-tube experiment is not a part of a routine PVT analysis – it requires special equipment, and is time consuming, which makes determining MMP based only on the equation of state (matched with experimental results) and the slim-tube simulation an attractive option.

2. Monographic literature review

The slim-tube experiments and its simulation as a part of EOR methods have been studied by various authors who are still considering it the best tool to study the miscibility and the interactions between the reservoir oil and the solvent. Different methods of predicting the MMP are presented where it is obvious that no uniform agreement of the MMP determination exist.

2.1. Laboratory and numerical studies of CO₂-EOR efficiency

Klinkenberg (1957) showed that the pore size distribution is related to immiscible and miscible displacement in a different way. Hall and Geffen (1957) proposed a mathematical model to predict volumes of bubble point liquid, gas flow in a two-phase zone and then for liquid saturation in different zones. They used pure methane, propane, butane and other simple compositions of fluids in their analysis, and divided the injection length to dry zone, two-phase region and region of complete liquid saturation. Their study is supplemented by the work of Lacey et al. (1958), who studied the length of the mixed zone in cores of different diameters, and found that the length of the mixed zone is proportional to the core diameter, but that these results cannot be extended to the reservoir scale.

After extensive laboratory studies, Blackwell et al. (1959) listed the key factors for miscible displacement: (1) the mixing between solvent and oil results principally from molecular diffusion, (2) channeling and bypassing of oil will occur in all (even homogeneous) reservoirs, (3) the volume of solvent required for complete recovery of the oil increases as the mobility ratio in-

creases at breakthrough, (4) higher permeability heterogeneity can be related with lower oil recovery, and (5) gravity segregation can prevent channeling in reservoirs with adequate permeability and dip. Their critical fingering rates were in good agreement with the theoretical model (about 0.00845 cm/s i.e. 1 ft/hour).

The number of studies of miscibility mechanisms increased in the 1960's (Benham et al., 1960; Adamson and Flock, 1962; Rutherford, 1962). Benham et al. studied miscibility between rich gases and reservoir fluid. They used a pseudo ternary diagram with 3 components: methane, C₂-C₄ and C₅₊ and developed a correlation for the maximum methane concentration in miscible conditions as a function of temperature, pressure, C₅₊ molecular weight and C₂₊ molecular weight of injected gas. Different components in the ternary or pseudo ternary diagram are used for the analysis in literature (Wilson, 1960; Welge et al., 1961), but they are generally divided into light (and/or non-hydrocarbon) components, medium and high molecular weight components.

Deffrenne et al. (1961) warned that this approach is not suitable for describing the change of oil composition in different parts of a reservoir.

Koval (1963) proposed the K-factor method (which showed good predictions in miscible systems with viscous fingering and heterogeneity) using a modification applicable to Buckley-Leverett equations (1942). His results were followed up in a study performed by Dougherty (1963) who also observed mixing rate change with an extremely non-linear trend, and that displacement becomes more stable if flowing length is large enough. In this analysis, Koval's method showed very satisfactory results only for horizontal systems.

Peaceman and Rachford (1962) defined a numerical method for calculating the two-dimensional displacement of oil by solvent to mathematically describe the mechanics of viscous fingering and pore space heterogeneity. They used a random number generator that produced normally distributed random permeabilities and reached good agreement with the experimental results.

Perrine (1963) and Kyle and Perrine (1963) focused on establishing relationships on both unstable and stable displacements. Unstable displacements are found within viscous fingering and non-linear flow that is not in ac-

cordance with Darcy's law. They pointed to the need for experimental studies on the dependence of flowing velocity and heterogeneity.

Fitch and Griffith (1964) investigated the alternate injection of water and gas which resulted in greater areal sweep efficiency, and vertical sweep efficiency in stratified systems. Based on their experimentally determined solubility, swelling and viscosity data for CO₂ – oil systems.

Simon and Graue (1965) published correlations for predicting these properties as a function of viscosity and oil gravity. **Rathmell et al. (1971)** used long cores (up to 13 m, diameter about 5 cm, porosity, $\phi = 0.27$, permeability, $k=1000$ mD) to study CO₂ displacement at different pressures. They concluded that immiscible displacement by CO₂ can yield efficient recovery by oil vaporization and swelling of the heavy ends and that recovery increases with core length.

Awang and Ali (1980) examined thermal effects of injected solvent. They did not find a good match between the observed and calculated temperature and concentration profiles which is attributed to the complex relationship between heat convection and the dispersion of phases.

Numerical simulation algorithms applicable to CO₂ flood predictions were developed by Lantz (1971), **Pope and Nelson (1978)**, **Orr (1980)** and **Graue and Zana (1981)**.

Teja and Sandler (1980) estimated the densities of CO₂-oil mixtures, swelling factors and solubility of CO₂ in oil at a given temperature, by using equation of state (EOS) parameters, primarily adequate mixing rules and adjusted binary interaction parameters (BIP). Almost the same results are summarized in **Mulliken and Sandler (1980)** and an appropriate EOS is proposed. **Gardner et al. (1981)** studied phase behavior of CO₂-oil system and recommended data from multiple-contact before single-contact experiments be used in determining phase-behavior models for CO₂ flooding simulations.

Wang (1982) showed by visual observations at specially designed equipment, that miscible, semi-miscible and immiscible displacement exist simultaneously during CO₂ flood. He concluded that oil recovery cannot be the only criterion for determining the MMP and proposed guidelines for choosing optimal CO₂ slug in the WAG process.

The work of **Orr et al. (1983)** is one of the few where experimental slim-tube results are compared with simulated slim-tube results for CO₂ injection. They observed phase composition and density change during CO₂ injection and concluded that the continuous multiple-contact (CMC) test offers significant advantages over the slim-tube test.

However, for the simulation model they used the relative permeability correlation given by **Naar et al. (1962)** which might be inadequate for near-miscible and misci-

ble conditions, and their conclusion is based on one sample, four pressures and a very low (reservoir) temperature of 32°C.

Glase (1985) clearly defined MMP as the lowest pressure at which the distinct point of maximum curvature is apparent when recovery of oil is plotted against the pressure at 1.2 PV gas injected. When a distinct point of maximum curvature is not apparent, the 95 % recovery of oil at 1.2 PV injected gas is used to define the MMP. His study showed that paraffinicity has a strong effect on MMP and corrected the K factor for C7+ to adjust his results with MMP's from North Sea oil systems.

Considering the MMP predicting correlations, they can be helpful for a quick assessment, but they are more or less accurate considering different oil compositions, i.e. the accuracy strongly depends on carbon-number distributions.

2.2. Relative permeability at immiscible and near miscible conditions

Sigmund et al. (1984) proposed a method for slim tube simulation in conjunction with a simple correlation for relative permeability in the model (see **Equation 1** and **Equation 2**):

$$k_{ro} = \left(\frac{S_o - 0.15}{1 - 0.15} \right)^2 \quad (1)$$

and

$$k_{rg} = \left(\frac{S_g - 0.04}{1 - 0.19} \right)^2 \quad (2)$$

Where:

S_o, S_g – oil and gas saturations

k_{ro}, k_{rg} – oil and gas relative permeabilities

The model showed applicability for complex oil models, characterized by **Peng-Robinson's (1976)** equation of state (EOS) and more than 10 components. **Jankovic (1986)** who obtained excellent matches with experimental solvent and oil relative permeabilities published more extensive analysis results. For a homogeneous pore system, with a mobility ratio of $M=1$ and very small interfacial tension $IFT \approx 1$, the relative permeability of solvent and oil showed straight lines through the origin.

Civan and Donaldson (1989) developed a semi-analytical method that should allow high displacement flow rates for unsteady-state measurements by the inclusion of capillary pressure to better describe the end effects.

Parvazdavani et al. (2013) measured relative permeability for light oils and CO₂, and for dolomite and sandstone rock samples. Since the Civan and Donaldson method underestimates relative permeability for oil, they validated Civan and Donaldson's method by estimating relative permeabilities as a starting point for further slim-tube history matching. They showed their

Table 1: Reservoir fluid composition and properties

Comp	Comp (mol %)	MW	SG	Tc (°C)	Pc (bar)	AF	A	B	Vcrit (m ³ /kg mol)	Vol. Shift	P-chor	Tb (°C)
N2	0.094	28.01	1.026	-147.3	33.92	0.039	0.42748	0.08664	0.0898	-0.1540	60.4	-195.75
CO2	0.462	44.01	1.101	30.9	73.98	0.239	0.42748	0.08664	0.0939		78.0	-78.45
C1	33.246	16.04	0.415	-82.5	46.41	0.011	0.42748	0.08664	0.0992	-0.1540	70.0	-161.55
C2	3.921	30.10	0.546	32.1	48.84	0.099	0.42748	0.08664	0.1483	-0.1002	115.0	-88.55
C3	3.110	44.10	0.585	96.7	42.57	0.153	0.42748	0.08664	0.2030	-0.0850	155.0	-42.05
C4	2.833	58.10	0.600	151.8	37.97	0.199	0.42748	0.08664	0.2550	-0.0641	200.0	-0.45
C5	2.808	72.20	0.630	196.4	33.75	0.251	0.42748	0.08664	0.3040	-0.0418	245.0	36.05
C6	2.783	86.20	0.664	234.5	30.32	0.299	0.42748	0.08664	0.3700	-0.0147	282.5	68.75
C7::C13	7.242	98.55	0.717	251.6	30.17	0.315	0.42748	0.08664	0.7492	0.1700	462.8	102.30
C14::C19	13.601	135.84	0.762	317.3	24.83	0.416	0.42748	0.08664	0.8740	0.1800	659.3	166.53
C20::C25	14.290	206.65	0.807	407.7	17.84	0.612	0.42748	0.08664	0.9365	0.2200	802.2	266.06
C26::C32	10.414	319.83	0.849	502.5	12.19	0.917	0.42748	0.08664	0.9989	0.2400	950.9	381.43
C33::C46	5.195	500.00	0.889	597.4	8.43	1.201	0.42748	0.08664	1.2486	0.3800	1158.0	502.70

Table 2: List of Binary Interaction Parameter used in the EOS

	N ₂	CO ₂	C1	C2	C3	C4	C5	C6	PS-1	PS-2	PS-3	PS-4	PS-5
N2													
CO2	0.02		0.12	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
C1	0.06	0.12		0.00	0.00	0.00	0.00	0.00	0.06	0.08	0.09	0.11	0.14
C2	0.08	0.15	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.08	0.15	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C4	0.08	0.15	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00
C5	0.08	0.15	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00
C6	0.08	0.15	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
PS-1	0.08	0.15	0.06	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00
PS-2	0.08	0.15	0.08	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00
PS-3	0.08	0.15	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
PS-4	0.08	0.15	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
PS-5	0.08	0.15	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

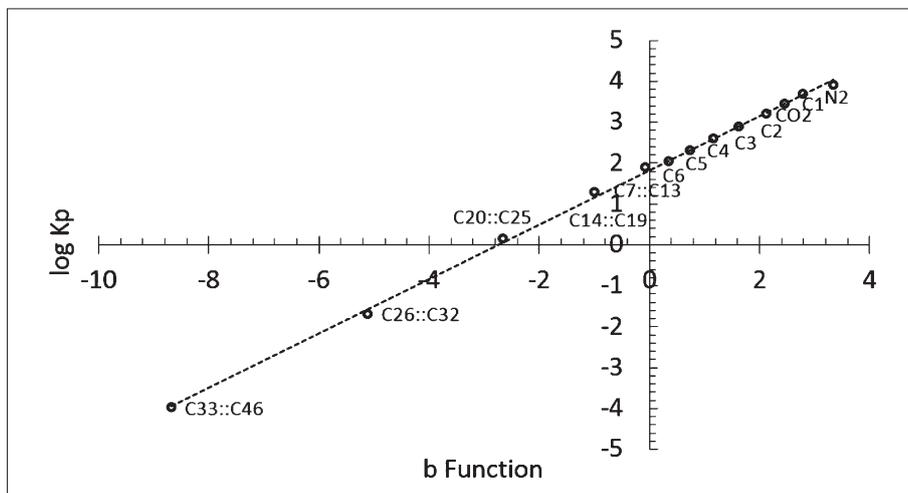


Figure 2: Hoffman plot for K-values quality check using the DL test EOS results for 81 bar pressure step

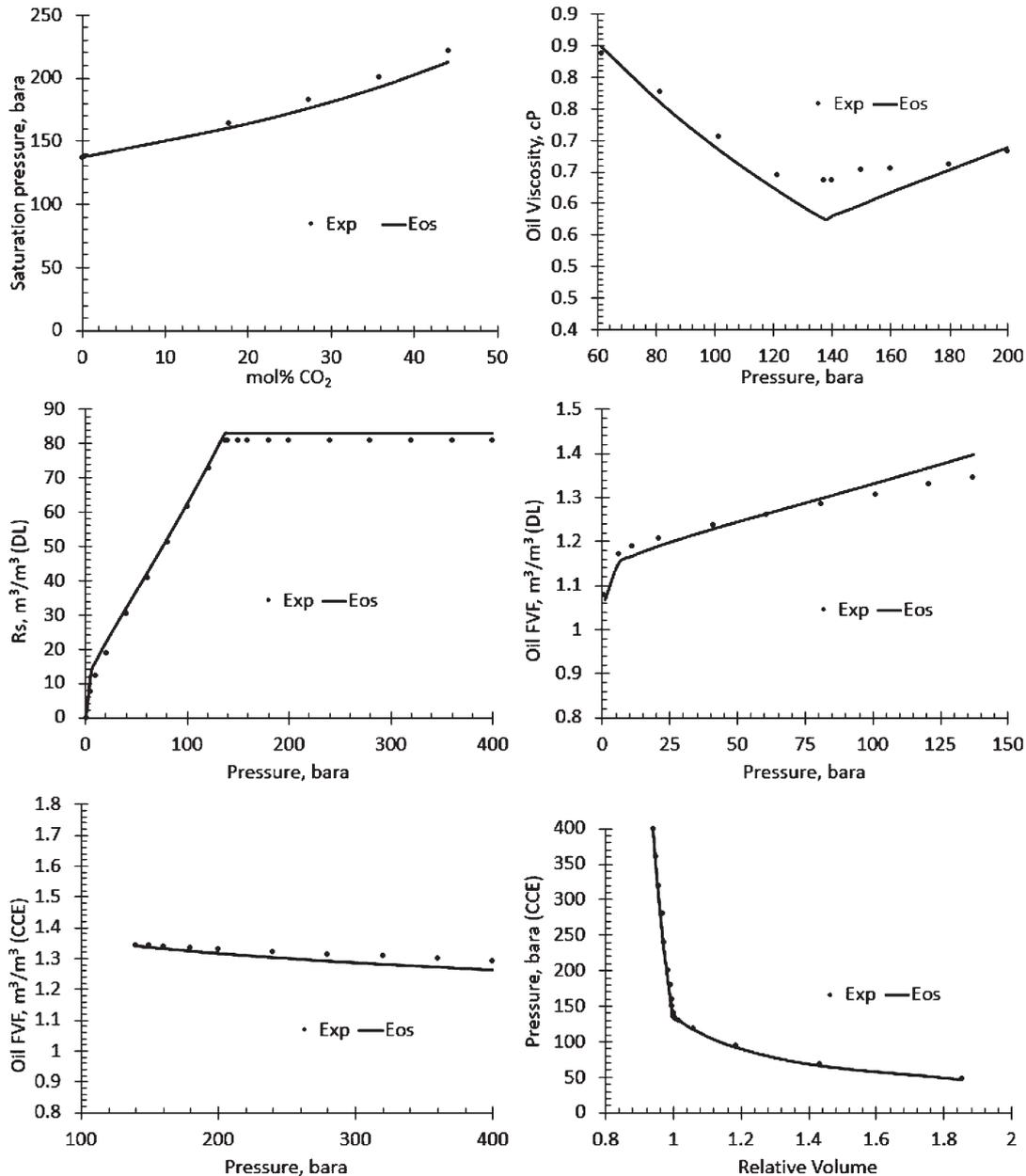


Figure 3: Comparison of experimental and simulated PVT data

analysis at several pressures and found that the effect of near miscibility is more pronounced for the CO₂ relative permeability (Corey's exponent approaches one) than for the oil relative permeability (which had almost no change with pressure).

Li et al. (2015) used both core samples and the slim-tube to find reliable relative permeability curves for simulation purposes. They correlated the shape factor in Corey's model with displacement pressure but emphasized that the relative permeability curves should be adjusted with the history-matching method. CO₂-oil relative permeability curves obtained in the composite core were more reliable than those of the short core segment but still not accurate enough to simulate miscible conditions.

2.3. Feasibility of CO₂-EOR

There are alternatives to the slim-tube test to evaluate CO₂-EOR. However, the slim-tube experiment connects a volume of injected CO₂ with oil recovery. Wolsky and Jankowski (1986) developed a techno-economic framework to estimate the feasibility of CO₂ EOR projects. They combined all techno-economic parameters into a single equation and concluded that the key economic parameters for determining the permissible cost of CO₂ supply and target additional recovery are oil price and internal rate of return. Martin and Taber published (1992) a figure that relates the maximum CO₂ cost for CO₂ flooding with oil price and rate of return. Even though the operating costs are significantly different

Table 3: Slim-tube properties from the laboratory experiment

Length, (cm)	2070
Inside diameter, (cm)	0.395
Grain type	Quartz sand
Grain size, (mm)	0.125-0.075
Porosity, (%)	44.2
Permeability, (mD)	5056

Table 4: Reported Oil Recoveries for each CO₂ injection step

Injection Pressure, bar	Oil Recovery, %
150	68.54
175	87.68
190	91.60
210	95.81
220	95.06
240	95.89

nowadays, the diagram shows a linear correlation between costs, amount of injected CO₂ and produced oil.

3. Experiments and numerical model

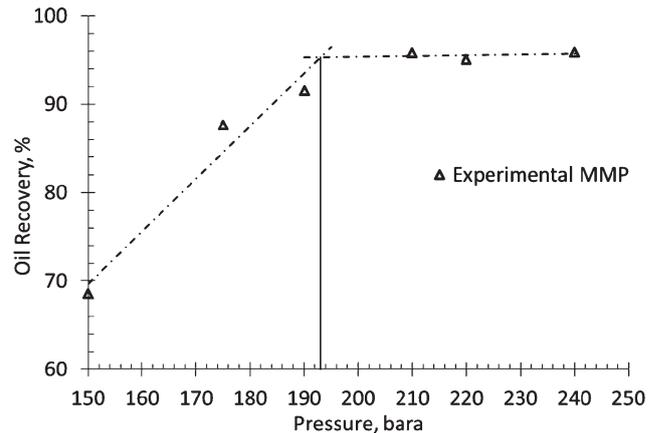
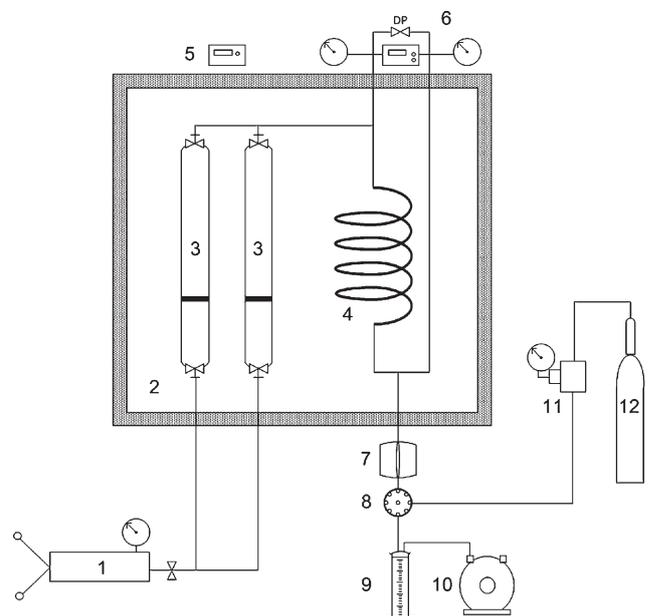
All of the laboratory experiments were conducted at INA upstream laboratory at the beginning of the 1990s. That includes the standard PVT analyses with the addition of the swelling test using recombined oil and CO₂, and the slim-tube experiment. Numerical modeling was performed in Schlumberger Eclipse 300 software.

3.1. PVT analysis

Laboratory PVT Experiments – wellstream analysis, constant composition expansion (CCE), differential liberation (DL), separator test and viscosity measurements were conducted in order to obtain the volumetric behavior and the original reservoir fluid composition. Separator oil and gas were physically recombined according to the average field gas to oil ratio (GOR) value of 67.5 m³/m³. Oil swelling test with CO₂ as a solvent fluid was also performed, starting from the initial bubble point pressure of 137.2 bar up to 220 bar where saturation pressures were recorded. In that range, no critical phase transition was observed (see **Figure 3**).

3.2. EOS modeling

Fluid modeling was done within the IPM PVTp software using the **Soave-Redlich-Kwong (1972)** EOS. The tuning was done by splitting the C₇₊ fractions into 5 pseudo fractions (PS), giving a total of 13 components. Binary interaction parameters (BIP) between the C₁ and PS were used to develop the phase envelope curve. The BIPs regarding the hydrocarbon interaction between nitrogen

**Figure 4:** MMP determination from the laboratory slim-tube experiment**Figure 5:** an experimental setup for slim-tube test is shown. Numbers indicate the main components: 1–volumetric displacement pump, 2 – oven, 3 – CO₂ and oil filled cylinders, 4 – slim-tube, 5 – temperature regulation unit, 6 – diff. pressure transducer, 7 – sight glass, 8–BPR valve, 9 – graduated cylinder, 10 – gasometer, 11 – pressure multiplier and 12 – nitrogen bottle.**Figure 5:** Standard Slim-tube experimental setup.

and CO₂ were selected according to the recommendations from **Whitson and Brule (2000)**. Volumetric data was matched by modifying the pseudo fractions' critical properties and volume shift data. The viscosity measurement tuning for the LBC correlations (**Lohrenz et al., 1964**) was done by changing the critical volume parameter for all the PS. After the tuning process, the quality of the match was validated with the Hoffman plot (**Hoffman et al., 1953**), showing a good linear trend (see **Figure 2**). A summary of the tuned properties is given in **Table 1** and **Table 2**. A comparison of the experimental and simulated PVT data is shown in **Figure 3**.

3.3. Slim-tube experiment

The slim-tube test was conducted by injecting CO₂ through the 20.7 m long coil tube with the inside diameter (ID) of 0.395 cm, initially saturated with the recombined oil. The properties of the slim-tube are given in **Table 3**. The tube was prepacked with quartz sand (120 – 230 mesh, 0.125 – 0.075 mm). A total of 6 injection pressures were reported where 1.2 slim-tube's pore volumes (PV) of CO₂ were injected. Two injection rates were used during the test. The first rate of 3 cm³/h was used until the injected amount of CO₂ reached the value of 0.7 PV and then the rate was doubled to a value of 6 cm³/h and kept until the final value of 1.2 PV injected CO₂ was reached. The produced volumes of oil and gas were measured and collected prior the chromatographic analysis.

The outflow and CO₂ breakthrough was observed both on the sight glass, exhibiting the potential flow of bubbles, as well as on the gasometer.

MMP estimation from the laboratory slim-tube experiment is determined at the intersection of the two trend lines on oil recovery versus injection pressure chart, yielding the MMP value of 193.0 bar at 95.34% oil recovery (see **Figure 4**). The overall recoveries for each injection step are given in **Table 4**.

3.4. Slim-tube numerical model

A Numerical 1D compositional model was created. For a base case model, a grid block of 500×1×1 cells was used. This case included the same CO₂ injection rates at reservoir conditions (RC) were used as in the experiment (3+6 cm³/h). Relative permeabilities for all of the injection pressure steps were set to an "X shape" type curve, starting from the origin and ending at one. Binary interaction parameters for the PS-CO₂ pairs were not fine-tuned meaning they were kept at a value of 0.15. The base case model properties are given in the **Table 5**.

In order to inspect the impact of varying the number of cells, CO₂ injection rates, heterogeneity regarding the porosity and permeability, relative permeability and different BIPs, various models with different properties were created and simulated.

The dimensions of the grid were fixed but the number of cells was altered in order to quantify the effect on MMP prediction and oil recovery. Slim-tube properties regard-

ing the dimensions, porosity and permeability values from **Table 3** were also used in the simulation model.

4. Results and discussion

In order to inspect and quantify the impact of different parameters (number of cells, injection rates, BIPs and relative permeability), various scenarios were tested. The results for the MMP determination with respect to the experimental data from a base case model can be seen in **Figure 6**. Overall MMP prediction is good, giving the MMP value of 198.4 bar which is 5.4 bar higher than the experimental MMP. The Oil recovery for the simulated MMP is lower, resulting in a total value of 88.3% oil produced.

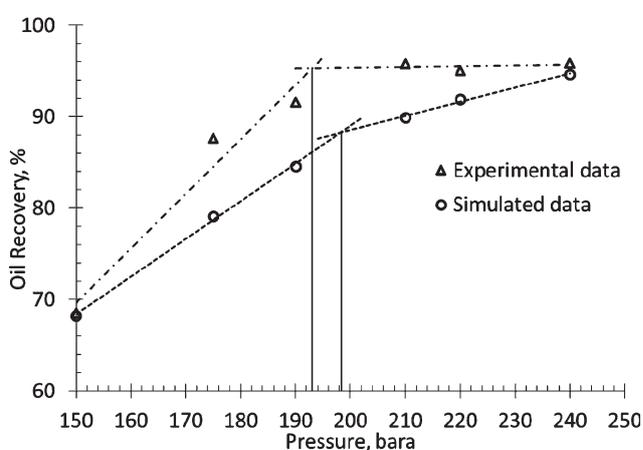


Figure 6: MMP determination from the base case model compared to the experimental data

Base case models with a different number of cells (50 and 2000) were tested. From the given results (see **Figure 7**), it is obvious that for each pressure step no significant difference in the oil recovery is observed for the 500 and 2000 number of cells. The model with 50 cells yielded lower overall oil recovery for each step.

Similarly, sensitivity to injection rates was tested. Flow rates used and compared were 3+6, 2, 7 and 28 cm³/h (see **Figure 8**). The only flow rate with a more notable difference in the cumulative oil recovery was with 28 cm³/h. Overall, there is a minor change in the oil recovery between all of the flow rates used.

A BIP value of 0.15 was used in the Base case model EOS for all PS-CO₂ pairs. The EOS made a good predic-

Table 5: Properties of the base case model

Number of Cells	500
CO ₂ injection Rate at RC:	3 cm ³ /h until 0.7 PV, 6 cm ³ /h until 1.2 PV CO ₂ injected
BIP PS-CO ₂	0.15
Relative Permeability	X shape
Porosity, (%)	44.2, single value
Permeability, (mD)	5056, single value

Table 6: BIP Fine tuning results

BIP	MMP, (bar)	Oil Recovery, (%)
0.15	198.37	88.30
0.14	197.92	91.23
0.13	197.02	93.81
0.12	195.74	95.99
0.11	194.06	97.63

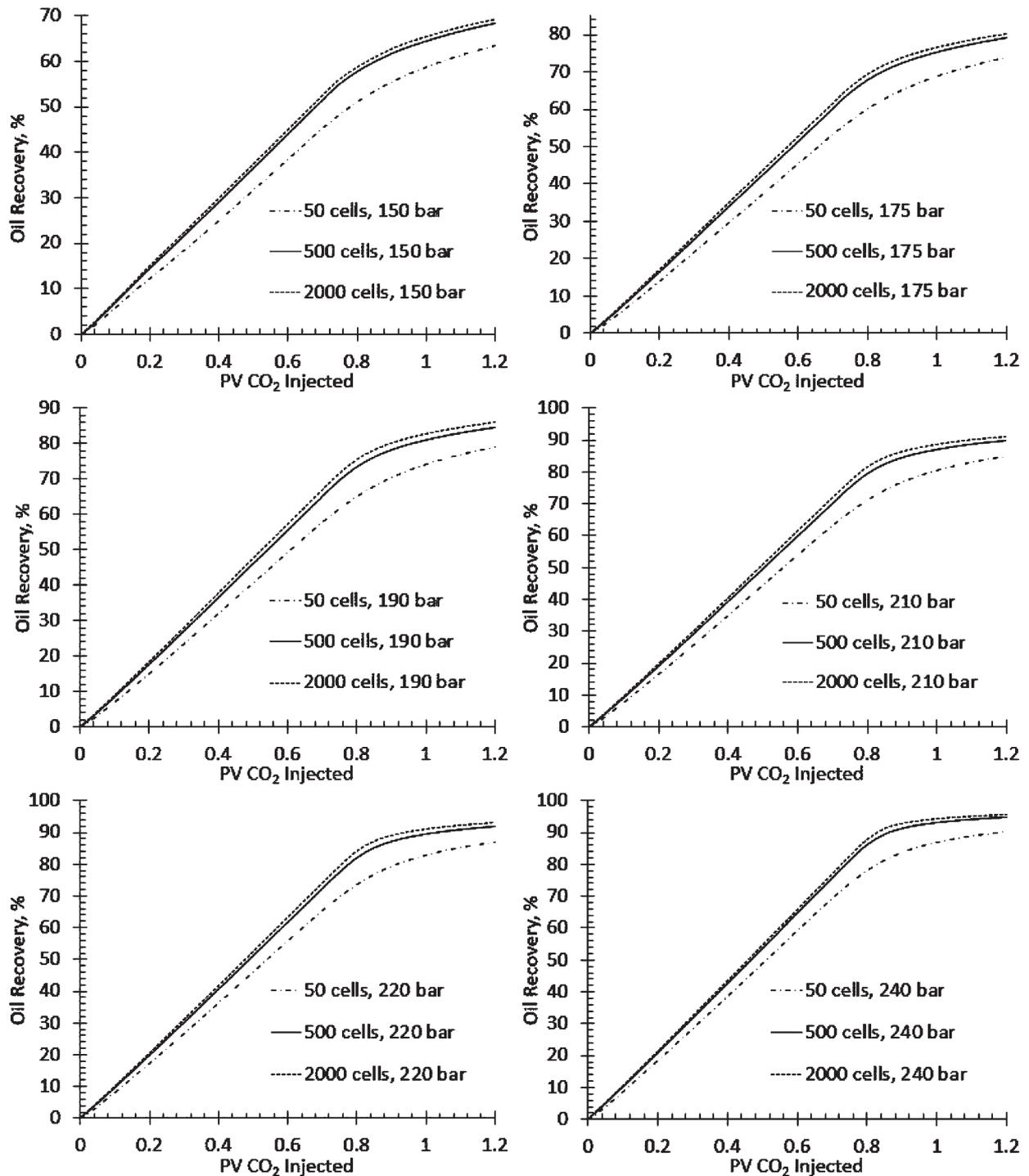


Figure 7: The results from a cell number sensitivity analysis.

tion of the interactions between the hydrocarbon components and the CO₂ in the swelling test but the oil recovery in the simulated slim-tube test was slightly underestimated. In order to try to improve the prediction of the cumulative oil recovery, the BIP's were slightly altered. As can be seen from Figure 9 and Table 6, the closest MMP prediction with respect to the oil recovery compared to the experimental MMP data is using the BIP value of 0.12.

After the BIP fine-tuning, considering the case where the BIP used was 0.12, it was evident from Figure 9 that the simulation results for the oil recovery at 150 bar injection pressure were too high in comparison with the experimental data. Standard Corey equations for the oil relative permeability (Brooks and Corey 1964) were used to generate a slightly different curve. The Corey exponent used for the oil phase was 2 while the exponent for the gas phase (CO₂) was unchanged, meaning it was

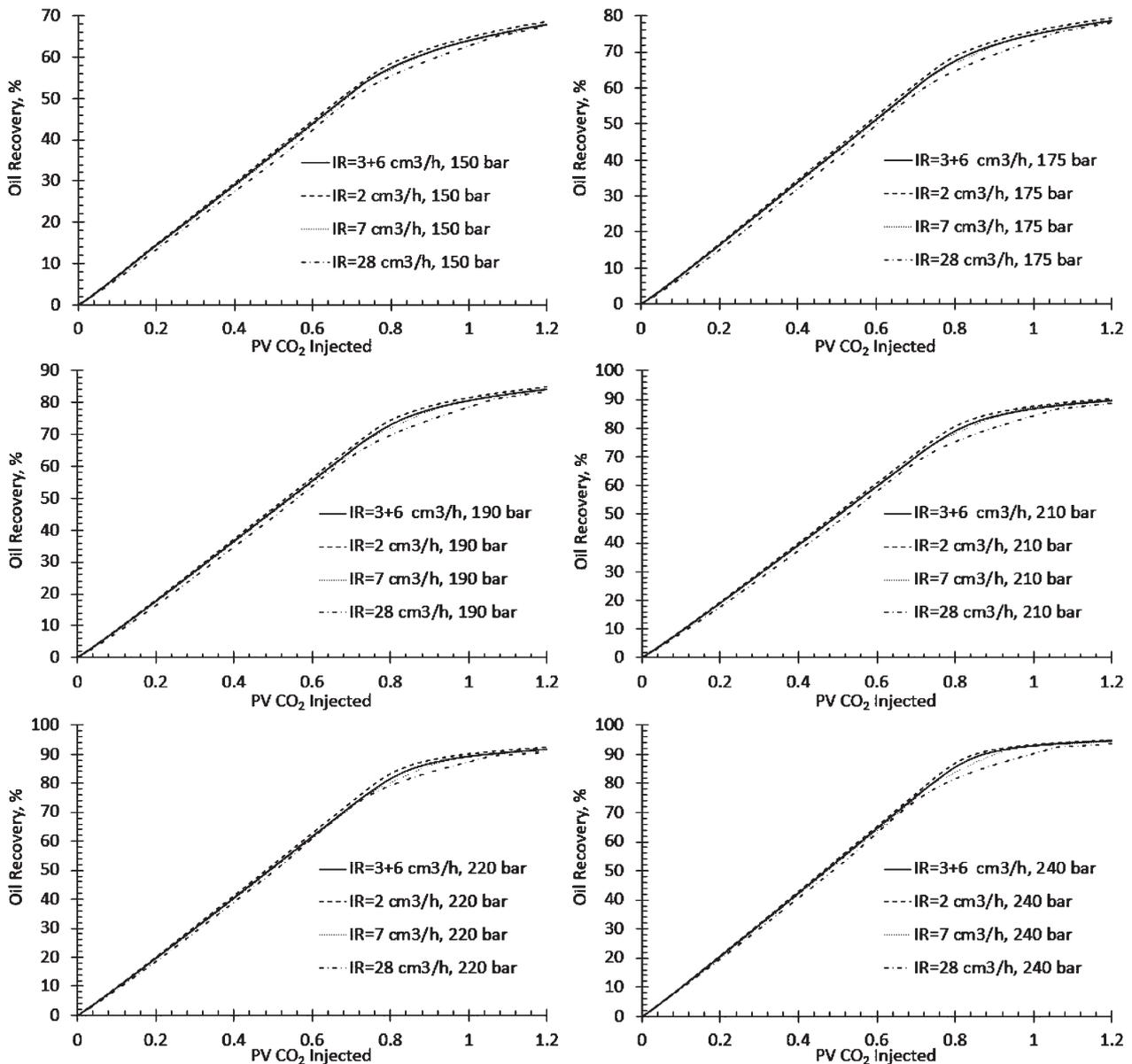


Figure 8: The results from an injection rate (IR) sensitivity analysis.

1. Good matching with the experimental value is shown in **Figure 10**.

The porosity and permeability heterogeneity impact on the simulation results was compared with a homogeneous base case model (see **Figure 11**). A log-normal distribution was used, with several mean and variance values. The heterogeneous model showed no evidence of any difference compared to the base case model. This can be addressed to the nature of the 1D model, i.e. the nature of the slim-tube experiment, where viscous fingering due to heterogeneity is intentionally avoided.

5. Conclusions

Throughout this work, different parameters were quantified to account for the effect on the overall MMP

estimation by numerical simulation of the slim-tube experiment in order to potentially produce a reliable simulation model, capable of replacing the expensive and complex experimental procedures. Besides, this approach becomes a good routine to quality check the EOS and to perform the fine-tuning before using the EOS on a full field reservoir model.

The results of the experimental PVT study were matched to obtain the equation of state for CO₂-EOR compositional simulation. A Modified SRK equation of state showed the best match with the relevant PVT laboratory data and MMP prediction from the slim-tube numerical model. For the fluid composition studied, by applying the trend line intersection method, it is possible to obtain a good estimation of the MMP value with slightly underestimated oil recovery. However, considering the

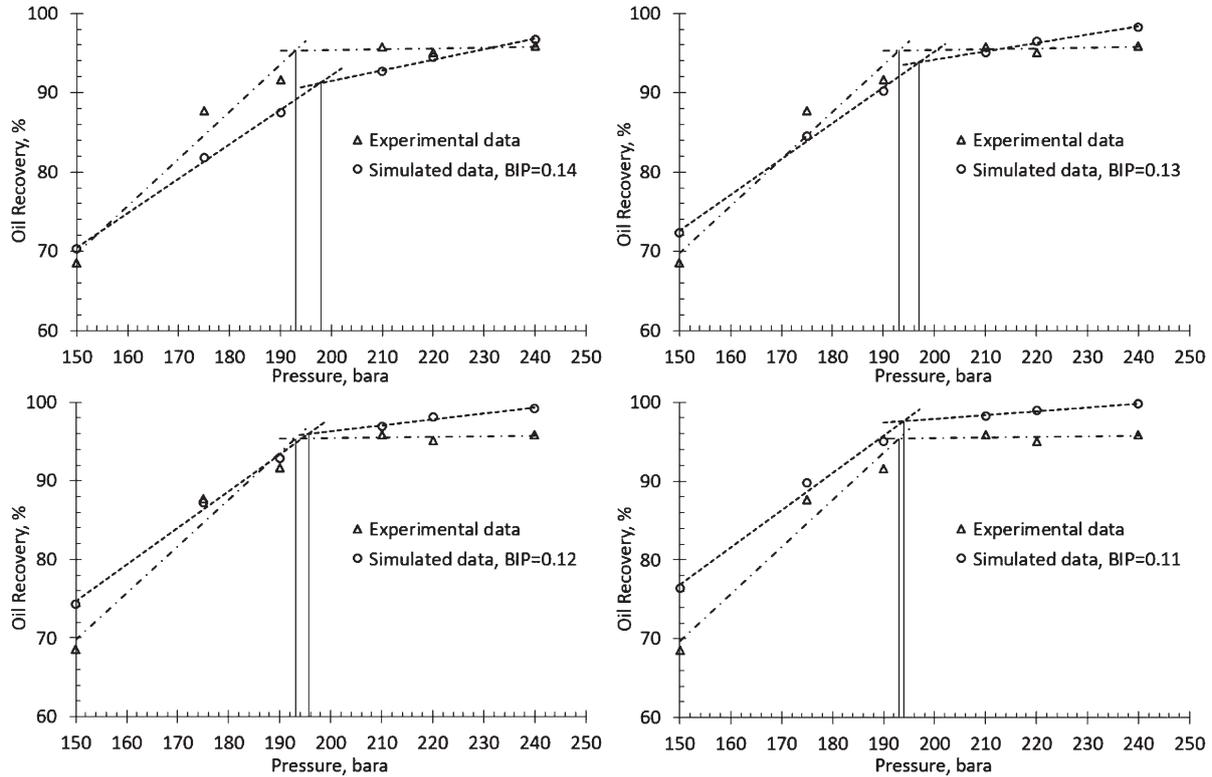


Figure 9: The impact of BIP fine-tuning on MMP and oil recovery

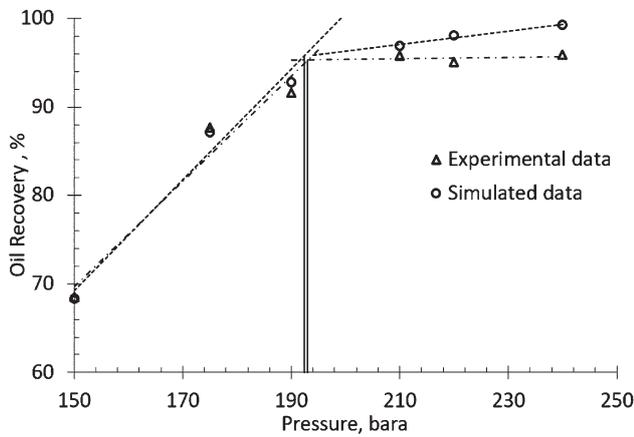


Figure 10: The impact of altered relative permeability at 150 bar pressure step

cases where the intersection cannot be unambiguously determined, the oil recovery criterion (usually 94% or 95%) has not been validated. The underestimation of oil recovery in a slim-tube simulation has been observed by various authors in literature, indicating that more data should be examined. In addition, it is clear that the key miscibility controlling parameters are found in the PVT experiments and its implementation in the EOS.

In terms of the recommendations and restrictions regarding the simulation model parameters (number of cells, flow rates, heterogeneity), a model comprising of 500 cells should provide reliable results with a fast run-time. Flow rates used in the simulation should be around 5 cm³/h in order to have an optimal time-step. The heterogeneity of porosity and permeability does not have any effect on the simulation outcome. Relative permea-

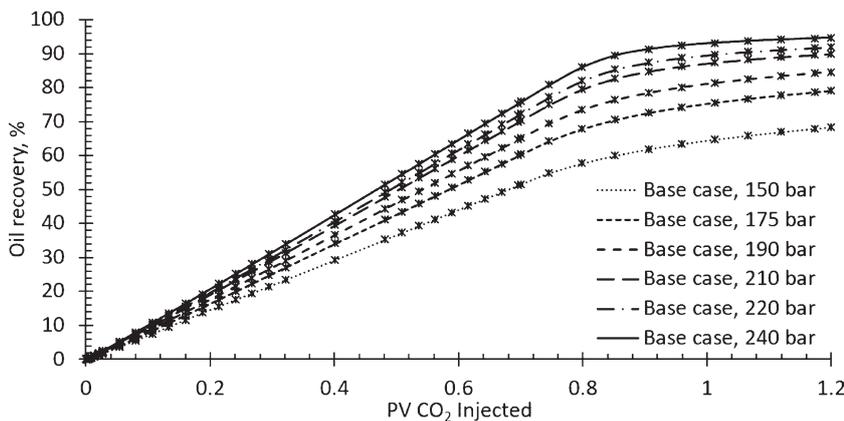


Figure 11: Comparison of homogeneous and heterogeneous models. The data obtained through the heterogeneous model is represented with cross type marks while the lines represent the values from a homogeneous base case model.

bility can possibly slightly affect the final MMP estimation. Non-miscible relative permeability should be considered for the lower injection pressures, further away from the MMP zone, where miscible conditions are not yet established.

It is evident that the simulation model of the slim-tube experiment should be tested and compared to other slim tube experiments utilizing different fluid models (EOS).

6. References

- Adamson, J. A., & Flock, D. L. (1962). Prediction of Miscibility. *Journal of Canadian Petroleum Technology*, 1(02), 72-77.
- Alomair, O., Malallah, A., Elsharkawy, A., & Iqbal, M. (2015). Predicting CO₂ minimum miscibility pressure (MMP) using alternating conditional expectation (ACE) algorithm. *Oil & Gas Science and Technology—Revue d'IFP Energies nouvelles*, 70(6), 967-982.
- Alston, R. B., Kokolis, G. P., & James, C. F. (1985). CO₂ minimum miscibility pressure: a correlation for impure CO₂ streams and live oil systems. *Society of Petroleum Engineers Journal*, 25(02), 268-274.
- Ayrala, S.C. and Rao, D.N. (2011). Comparative evaluation of a new gas/oil miscibility-determination technique. *Journal of Canadian Petroleum Technology*, 50(9/10), pp. 71-81.
- Benham, A. L., Dowden, W. E., & Kunzman, W. J. (1960). Miscible Fluid Displacement - Prediction of Miscibility. *Trans. Aime*, 219. Society of Petroleum Engineers
- Blackwell, R. J., Rayne, J. R., & Terry, W. (1959). Factors influencing the efficiency of miscible displacement, *Petroleum Transactions, AIME*, 217, pp.1-8
- Buckley, S. E. and Leverett, M. C., (1942). Mechanism of Fluid Displacement in Sands, *Trans., AIME Vol. 146*(01), 107-116.
- Chung, F. T., Jones, R. A., & Nguyen, H. T. (1988). Measurements and correlations of the physical properties of CO₂-heavy crude oil mixtures. *SPE reservoir engineering*, 3(03), 822-828.
- Civan, F., & Donaldson, E. C. (1989). Relative permeability from unsteady-state displacements with capillary pressure included. *SPE Formation Evaluation*, 4(02), 189-193.
- Dougherty, E. L. (1963). Mathematical model of an unstable miscible displacement. *Society of Petroleum Engineers Journal*, 3(02), 155-163.
- Enick, R. M., Holder, G. D., & Morsi, B. I. (1988). A thermodynamic correlation for the minimum miscibility pressure in CO₂ flooding of petroleum reservoirs. *SPE Reservoir Engineering*, 3(01), 81-92
- Fitch, R. A. and Griffith, J. D. (1964). Experimental and calculated performance of miscible floods in stratified reservoirs. *Journal of Petroleum Technology*, 16(11), 1289-1298.
- Gardner, J. W., Orr, F. M., & Patel, P. D. (1981). The effect of phase behavior on CO₂-flood displacement efficiency. *Journal of Petroleum Technology*, 33(11), 2068-2081.
- Glasø, O. (1985). Generalized minimum miscibility pressure correlation (includes associated papers 15845 and 16287). *Society of Petroleum Engineers Journal*, 25(06), 927-934.
- Graue, D. J., & Zana, E. T. (1981). Study of a possible CO₂ flood in Rangely Field. *Journal of Petroleum Technology*, 33(07), 1-312.
- Hall, H. N. & Geffen, T. M., (1957). A laboratory study of solvent flooding. *Petroleum Transactions, AIME*, 210, p.p. 48-57
- Holm, L. W., & Josendal, V. A. (1974). Mechanisms of oil displacement by carbon dioxide. *Journal of petroleum Technology*, 26(12), 1-427.
- Holm, L. W., & Josendal, V. A. (1982). Effect of oil composition on miscible-type displacement by carbon dioxide. *Society of Petroleum Engineers Journal*, 22(01), 87-98.
- Holm, L.W. and Josendal, V.A., (1980). Discussion of Determination and Prediction of CO₂ Minimum Miscibility Pressures. *Journal of Petroleum Technology*, 32(01), 160-168.
- Jankovic, M. S. (1986). Analytical miscible relative permeability curves and their usage with compositional and pseudo-miscible simulators. *Journal of Canadian Petroleum Technology*, 25(04).
- Klinkenberg, L. J. (1957). Pore size distribution of porous media and displacement experiments with miscible liquids. *Journal of Petroleum Technology*, 9(04), 63-66.
- Koval, E. J. (1963). A method for predicting the performance of unstable miscible displacement in heterogeneous media. *Society of Petroleum Engineers Journal*, 3(02), 145-154.
- Kyle, C. R., & Perrine, R. P. (1965). Experimental studies of miscible displacement instability. *Society of Petroleum Engineers Journal*, 5(03), 188-195.
- Lacey, J. W., Draper, A. L., & Binder Jr, G. G. (1958). Miscible fluid displacement in porous media. *Trans AIME*, 213, pp.76-79
- Lantz, R. B. (1971). Quantitative evaluation of numerical diffusion (truncation error). *Society of Petroleum Engineers Journal*, 11(03), 315-320.
- Lee, J. I. (1979). Effectiveness of carbon dioxide displacement under miscible and immiscible conditions. Report RR-40, *Petroleum Recovery Inst., Calgary*.
- Martin, D. F. & Taber, J. J. (1992). Carbon dioxide flooding. *Journal of Petroleum Technology*, 44(04), 396-400.
- Mulliken, C. A., & Sandler, S. I. (1980). The prediction of CO₂ solubility and swelling factors for enhanced oil recovery. *Industrial & Engineering Chemistry Process Design and Development*, 19(4), 709-711.
- Naar, J., Wygal, R. J., & Henderson, J. H. (1962). Imbibition relative permeability in unconsolidated porous media. *Society of Petroleum Engineers Journal*, 2(01), 13-17.
- Orr Jr, F. M. (1980). Simulation of the one-dimensional convection of four-phase, four-component mixtures. Topical report, June 1980. [CO2FLD] (No. DOE/ET/12082-8). New Mexico Inst. of Mining and Technology, Socorro (USA). New Mexico Petroleum Recovery Research Center.
- Orr Jr, F. M., & Silva, M. K. (1987). Effect of oil composition on minimum miscibility pressure-part 2: correlation. *SPE Reservoir Engineering*, 2(04), 479-491.

- Orr Jr, F. M., Silva, M. K., & Lien, C. L. (1983). Equilibrium phase compositions of CO₂/crude oil mixtures-Part 2: Comparison of continuous multiple-contact and slim-tube displacement tests. *Society of Petroleum Engineers Journal*, 23(02), 281-291.
- Parvazdavani, M., Masihi, M., & Ghazanfari, M. H. (2013). Gas-oil relative permeability at near miscible conditions: An experimental and modeling approach. *Scientia Iranica*, 20(3), 626-636.
- Peaceman, D. W., & Rachford Jr, H. H. (1962). Numerical calculation of multidimensional miscible displacement. *Society of Petroleum Engineers Journal*, 2(04), 327-339.
- Peng, D. Y., & Robinson, D. B. (1976). A new two-constant equation of state. *Industrial & Engineering Chemistry Fundamentals*, 15(1), 59-64.
- Perrine, R. L. (1963). A unified theory for stable and unstable miscible displacement. *Society of Petroleum Engineers Journal*, 3(03), 205-213.
- Pope, G. A., & Nelson, R. C. (1978). A chemical flooding compositional simulator. *Society of Petroleum Engineers Journal*, 18(05), 339-354.
- Rathmell, J. J., Stalkup, F. I., & Hassinger, R. C. (1971, January). A laboratory investigation of miscible displacement by carbon dioxide. Fall meeting of the society of petroleum engineers of AIME. *Society of Petroleum Engineers*.
- Rutherford, W. M. (1962). Miscibility Relationships in the Displacement of Oil by light hydrocarbons. *Society of Petroleum Engineers Journal*, 2(04), 340-346.
- Sebastian, H. M., Wenger, R. S., & Renner, T. A. (1985). Correlation of minimum miscibility pressure for impure CO₂ streams. *Journal of Petroleum Technology*, 37(11), 2-076.
- Shokrollahi, A., Arabloo, M., Gharagheizi, F., & Mohammadi, A. H. (2013). Intelligent model for prediction of CO₂-reservoir oil minimum miscibility pressure. *Fuel*, 112, 375-384.
- Simon, R. & Graue, D. J. (1965). Generalized correlations for predicting solubility, swelling and viscosity behavior of CO₂-crude oil systems. *Journal of Petroleum Technology*, 17(01), 102-106.
- Teja, A. S., & Sandler, S. I. (1980). A Corresponding States equation for saturated liquid densities. II. Applications to the calculation of swelling factors of CO₂-crude oil systems. *AIChE Journal*, 26(3), 341-345.
- Wang, G. C. (1982). Microscopic Investigation of CO₂, Flooding Process. *Journal of Petroleum Technology*, 34(08), 1-789.
- Welge, H. J., Johnson E. J., Ewing, S. P. Jr., and Brinkman, F. H. (1961). The Linear Displacement of Oil from Porous Media by Enriched Gas. *Journ. Petro Tech.*, 13(08), AIME, 787-796
- Wilson, J. F. (1960). Miscible Displacement-Flow Behavior and Phase Relationships for a Partially Depleted Reservoir, *Trans AIME*, 219, pp. 223-228
- Wolsky, A. M., & Jankowski, D. J. (1986). The Value of CO₂; Framework and Results. *Journal of petroleum technology*, 38(09), 987-994.
- Yellig, W. F., & Metcalfe, R. S. (1980). Determination and Prediction of CO₂ Minimum Miscibility Pressures. *Journal of Petroleum Technology*, 32(01), 160-168.
- Yuan, H., Johns, R. T., Egwuenu, A. M., & Dindoruk, B. (2005). Improved MMP correlation for CO₂ floods using analytical theory. *SPE Reservoir Evaluation & Engineering*, 8(05), 418-425.
- Li, F. F., Yang, S. L., Chen, H., Zhang, X., Yin, D. D., He, L. P., & Wang, Z. (2015). An improved method to study CO₂-oil relative permeability under miscible conditions. *Journal of Petroleum Exploration and Production Technology*, 5(1), 45-53.
- Soave, G. (1972). Equilibrium constants from a modified Redlich-Kwong equation of state. *Chemical Engineering Science*, 27(6), 1197-1203.
- Redlich, O., & Kwong, J. N. (1949). On the Thermodynamics of Solutions. V. An Equation of State. Fugacities of Gaseous Solutions. *Chemical reviews*, 44(1), 233-244.
- Whitson, C. H., & Brulé, M. R. (2000). Phase behavior. Richardson, TX: Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers.
- Hoffman, A. E., Crump, J. S., & Hocott, C. R. (1953). Equilibrium constants for a gas-condensate system. *Journal of Petroleum Technology*, 5(01), 1-10.
- Brooks, R., & Corey, T. (1964). Hydraulic Properties of Porous Media. *Hydrology Papers*, Colorado State University.
- Lohrenz, J., Bray, B. G., & Clark, C. R. (1964). Calculating viscosities of reservoir fluids from their compositions. *Journal of Petroleum Technology*, 16(10), 1-171.
- Deffrenne, P., Marle, C., & Pacsirszki, J. (1961, January). The determination of pressures of miscibility. Fall Meeting of the Society of Petroleum Engineers of AIME. *Society of Petroleum Engineers*.
- Awang, M., & Ali, S. M. (1980, January). Hot-Solvent Miscible Displacement. In Annual Technical Meeting. Petroleum Society of Canada.
- Sigmund, P. M., Kerr, W., & MacPherson, R. E. (1984, January). A laboratory and computer model evaluation of immiscible CO₂ flooding in a low-temperature reservoir. In SPE Enhanced Oil Recovery Symposium. *Society of Petroleum Engineers*.
- Kuo, S. S. (1985, January). Prediction of miscibility for the enriched-gas drive process. In SPE Annual Technical Conference and Exhibition. *Society of Petroleum Engineers*
- Eakin, B. E., & Mitch, F. J. (1988, January). Measurement and correlation of miscibility pressures of reservoir oils. In SPE annual technical conference and exhibition. *Society of Petroleum Engineers*.
- Ahmed, T. H. (1994, January). Prediction of CO₂ minimum miscibility pressures. In SPE Latin America/Caribbean Petroleum Engineering Conference. *Society of Petroleum Engineers*.
- Ghomian, Y., Pope, G. A., & Sepehrnoori, K. (2008, January). Development of a response surface based model for minimum miscibility pressure (MMP) correlation of CO₂ flooding. In SPE Annual Technical Conference and Exhibition. *Society of Petroleum Engineers*.
- Alomair, O., & Iqbal, M. (2014, April). CO₂ minimum miscible pressure (MMP) estimation using multiple linear regression (MLR) technique. In SPE Saudi Arabia Section Technical Symposium and Exhibition. *Society of Petroleum Engineers*.

SAŽETAK

Simulacijski model metode EOR utiskivanja CO₂ uskom cijevi

Simulacijski model duge, uske cijevi (*slim-tube*) kreiran je u svrhu validacije eksperimenta i ugađanje jednadžbe stanja, a potencijalno i kao alat za brzo i pouzdano određivanje minimalnoga tlaka miješanja (MMP) uz uvjet da je razvijena jednadžba stanja za razmatranu naftu. Brojne analize osjetljivosti napravljene su mijenjanjem sastavnih varijabli simulacijskoga modela (broj ćelija, Correyjevi eksponenti krivulja relativnih propusnosti, promjena brzine utiskivanja te termodinamičkoga (PVT) modela). Minimalni tlak miješanja dobiven simulacijom određen je kao sjecište dviju različitih krivulja u funkciji utisnoga tlaka i kumulativnoga iscrpka pri svakome tlačnom koraku. Vidljivo je da u pogledu određivanja minimalnoga tlaka miješanja postoji dobra podudarnost s laboratorijskim podacima, no uz nešto podcijenjen konačni iscrpak nafte u osnovnome testiranom modelu. Moguće je izdvojiti „X-tip” relativnih propusnosti kao potencijalni izvor odstupanja koje su u modelu korištene istovjetno, pri svim tlačnim koracima (za nemješive te djelomično i potpuno mješive uvjete). Konačno, finim ugađanjem binarnih interakcijskih parametara u simulacijskome modelu te promjenom relativnih propusnosti za nemješive uvjete moguće je postići vrlo dobro slaganje s eksperimentalnim podacima.

Ključne riječi

minimalni tlak miješanja, uska cijev, jednadžba stanja, metode povećanja iscrpka nafte (EOR), utiskivanje CO₂

Authors Contribution

Domagoj Vulin is credited for the research hypothesis and development of the simulation model used throughout this work. **Marko Gačina** developed the EOS used in the simulation model, performed simulations and their interpretation. **Valentina Biličić** researched the literature and performed MMP correlation comparison.