Numerical Study of CO2 injection and the Role of Viscous Crossflow in Near-Miscible CO2-WAG

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Keyword: CO2-EOR; Near Miscible; Viscous Crossflow; Fine-scale Simulation.
Abstract
CO₂ Water-Alternating-Gas injection (CO₂-WAG) is still a challenging task to simulate and predict accurately, due to the complex interaction of CO₂/oil phase behaviour, 3-phase flow and the heterogeneity of the porous medium. In this paper, we focus specifically on the regime of viscous fingering flow in CO₂-WAG in heterogeneous systems because of its importance in elucidating this complex interaction. This work presents a detailed simulation study of both immiscible and near-miscible CO₂-WAG and continuous CO₂ displacements with unfavourable mobility ratios for 1D and 2D systems. 2D heterogeneous permeability fields were generated as Correlated Random Fields (CRF) with specified degrees of heterogeneity (permeability range, described by the Dykstra-Parsons coefficients, $V_{DP}$) and structures (defined through the dimensionless correlation range, $R_L = \lambda/L$).

Our central aim is to improve the modelling of CO₂ displacement in the transition from immiscible to miscible flows in CO₂-WAG processes. To do so, two key physical mechanisms that occur during near-Miscible WAG (nMWAG) processes have been studied in detail, namely compositional effects (denoted as Mechanism 1, $M_{CE}$) and low-interfacial-tension (IFT) film flow effects (denoted as Mechanism 2, $M_{IFT}$). The low IFT effects in $M_{IFT}$ manifest themselves in an increased mobility of oil phase due to enhanced film formation and flow processes. This latter mechanism ($M_{IFT}$) is modelled as an increased oil relative permeability using different well-known models (Betté and Coats) parameterized by the gas/oil IFT ($\sigma_{go}$), calculated in the simulation from the compositional PVT model via a built-in correlation (the McLeod-Sugden equation, in this case). A range of various combinations of oil-stripping effects ($M_{CE}$) and IFT effects ($M_{IFT}$) has been tested to evaluate the potential impact of each mechanism on the flow behaviour such as the local displacement efficiency and the ultimate oil recovery. Oil bypassed by viscous fingering/local heterogeneity, can be efficiently recovered by WAG in the cases where both $M_{CE}$ and $M_{IFT}$ are taken into account (as opposed to either mechanism being considered alone). We also show that the way these two distinct but related mechanisms ($M_{CE}$ and $M_{IFT}$) operate in near miscible conditions cannot be observed in (i) a simple 1D system such as a slim tube experiment, or (ii) in a heterogeneous system under continuous CO₂ injection.

Using tracer analysis in our simulations, we demonstrate that a major recovery mechanism in near-miscible WAG displacement is viscous crossflow between non-preferential (bypassed) flow-paths and preferential flow-paths (i.e. between the viscous fingers). Due to the significance of IFT effects (the $M_{IFT}$ mechanism), we also present...
comparative results from two of the IFT-dependent relative permeability models (Betté and Coats) showing the impact of each model on the simulation of the near-miscible WAG flow behaviour.

Introduction
CO₂-WAG has been shown in the field to be one of the most effective Enhanced Oil Recovery (EOR) methods over the last few decades (Alvarado and Manrique, 2010; Lake et al., 2014). Under certain conditions, CO₂ can be miscible (or multi-contact miscible) with the crude oil without forming an interface and this significantly improves the displacement performance (Stalkup, 1983; Hartman and Cullick, 1994; Christensen et al., 2001). However, it has been argued that, even for “so called miscible flooding”, true miscibility is hardly achieved during field applications, and multi-contact miscibility is the most common case (Skauge and Sorbie, 2014). Ren et al. (2015) performed a systematic assessment of oil displacement by CO₂ in Jilin oil field. They reported that a large pressure drop could occur in a process, which was designed to be miscible, due to the existence of low-permeability zones, particularly near the producers. This leads to the loss of miscibility in their case and resulted in a near-miscible/immiscible process. In other words, many CO₂-WAG processes may be in the regime of “near-miscibility”, which involves complex multiphase flow (water, oil and gas) and the process of inter-phase mass transfer or “oil stripping” (referred to as M_CE and described by a PVT model using an equation of state, EOS).

According to Danesh (1998) and Orr (2007), when CO₂ is injected to displace oil, a set of mutual interactions start to occur as CO₂ dissolves into oil and oil components are vaporised into the gas phase (oil lighter component stripping), i.e. compositional effects (M_CE). In previous work, we presented a numerical study on purely compositional effects for this single mechanism (i.e. M_CE only) acting alone. This is essentially the application of conventional compositional simulation (Wang et al., 2019). Besides M_CE, as the pressure increases and the system comes closer to miscibility, a situation we describe as “near-miscible”, another oil recovery mechanism involving enhanced oil layer flow occurs (Sohrabi et al., 2008a). During the process of component transfer under near-miscible conditions, the interfacial tension (IFT) between the gas and the oil (σ_gb) is continuously changing and leads to improvement in oil mobility, i.e. IFT effects (M_ITF). Sorbie and van Dijke (2010) cited experimental observations and presented theoretical evidence that significant hydrocarbon film/layer flow occurs at gas/oil IFT (σ_gb) above miscibility, i.e. σ_gb ~ 1 - 3 mN/m. Note that this magnitude of σ_gb might be considered as “immiscible”,
but here we define it “near-miscible” since this is where the enhanced film flow effects start to occur. The \( M_{\text{IFT}} \) mechanism is modelled as an increase in hydrocarbon relative permeability in our study in precisely these conditions of “near miscibility”, defined by a gas/oil IFT parameter \( (\sigma_{go}^0) \). That is, as the compositional simulation proceeds, the quantity \( \sigma_{go} \) is calculated locally and, when \( \sigma_{go} < \sigma_{go}^0 \), the IFT model is deployed in the simulation (and the effect of this \( M_{\text{IFT}} \) “onset” parameter is studied in our work for \( \sigma_{go}^0 \) values in the range \( \sigma_{go}^0 = 0.1 - 5 \text{mN/m} \)). In the calculations presented, we will show how the combined/separate \( M_{\text{CE}} \) and \( M_{\text{IFT}} \) mechanisms affect the flow behaviour and oil recovery, both in continuous \( \text{CO}_2 \) injections and in \( \text{CO}_2\text{-WAG} \) processes. Figure 1 shows a schematic diagram with the range of possible mechanistic combinations (\( M_{\text{CE}} \) and \( M_{\text{IFT}} \)) that can occur (at least theoretically) in \( \text{CO}_2 \) (or in any other gas) displacement processes.

Figure 1 Schematic diagram of the possible mechanistic processes that may occur in a \( \text{CO}_2 \) (gas) displacement process at immiscible and near-miscible conditions.

A further motivation for this study is to analyze the overall outcome when these mechanisms are incorporated in the commonly used methods of IFT-dependent relative permeability, i.e. Coats (1980) and Betté et al. (1991). We believe that this detailed analysis of the modelling process of the oil displacement by \( \text{CO}_2 \) at near-miscible conditions within fine-scale models will lead to the development of more rigorous ways to simulate large-scale \( \text{CO}_2\text{-EOR} \) processes. The complete dataset and results of this study are available online as a model case example for testing out potential upscaling techniques for compositional flows in heterogeneous systems. The DOI for this supplementary material is \( 10.17861/fc1e90bb-9d3f-4a6c-9170-7b7fe10ec7b9 \).
Literature Review

Longeron (1980) and Bardon (1994) performed a series of core flooding tests to investigate the IFT effects on relative permeability using binary fluid mixtures. They concluded that the residual oil saturation is highly dependent on the value of IFT between gas and oil, especially when it is lower than 0.1 mN/m. Very importantly, the relative permeabilities to both oil and gas became linear as IFT approached zero. The system used by these workers was a simple hydrocarbon mixture, which was fully vaporized by the CO$_2$. However, for oils with significant quantities of heavier components (C10+) as used in this work, the system is never fully miscible in that the stripping of the lighter components leaves behind a much heavier oil (higher molecular weight). Therefore, the “gas” and “oil” relative permeabilities never attain this linear form; indeed, in our more complex system we show below that the gas/oil IFT ($\sigma_{go}$) goes through a minimum during the displacement.

Coats (1980) developed a compositional model to simulate gas displacement taking account of both compositional effects and IFT effects. His method of modelling compositional problems has been widely applied since then and has been coded into commercial software, such as Eclipse 300 (Schlumberger, 2018) and CMG/GEM (CMG, 2019).

Betté et al. (1991) modified Coats model and performed a series of numerical simulations to evaluate IFT effects on fluid behaviour. Their method of simulating IFT effects has been also well accepted and incorporated in GEM/CMG. In their study, they claimed that IFT effects barely affect the ultimate recovery and we show that this is sometimes correct under certain conditions, but is not generally true, and we explain the conditions where IFT effects (which we refer as the M$_{IFT}$ mechanism) may or may not be important. In fact, the IFT effects in the study by Betté et al. (1991) were probably masked by the much more dominant compositional effects. They only simulated continuous injection of CO$_2$ into 1D models and cores, and they did not simulate WAG. We agree with their finding and present below that, continuous gas injection of CO$_2$ does not show any significant M$_{IFT}$ effect, and that the effect is negligible in linear (1D) systems. More importantly, we go on to show in this work that IFT effects are much more significant in near-miscible WAG processes in 2D heterogeneous systems, and by implication, in 3D heterogeneous systems.
Sohrabi et al. (2004; 2008a; 2008b) designed a series of WAG tests to evaluate IFT effects at the pore-scale. They showed that if the IFT between oil and gas is reduced to the level of \( \sigma_{go} \sim 1 \text{-} 3 \text{ mN/m} \), very good oil recovery can be obtained through either a thick oil film (oil wetting) or an oil layer (water wetting). In other words, the local displacement efficiency can be greatly improved by means of a “thick oil film”, even though the IFT is not an ultra-low level (i.e. \( \sigma_{go} \sim 1 \text{-} 3 \text{ mN/m} \) and not necessarily as low as say, \( \sigma_{go} \sim 0.001 \text{ mN/m} \)).

Sorbie and van Dijke (2010) proposed a consistent pore-scale theory of phase flow for the transition from immiscible to miscible conditions with respect to the impact of IFT effects on the contact angles. They modified the equations originally proposed by Al-Siyabi et al. (1999) to account for this low IFT (but not ultra-low) transition. They concluded that such an “oil film” mechanism is particularly important during near-miscible WAG, where IFT could be reduced to \( \sigma_{go} \sim 1 \text{-} 3 \text{ mN/m} \), i.e. near-miscible conditions. As explained above, this leads to a precise definition of “near-miscible” in this work; i.e. when the \( \sigma_{go} \) calculated (in the PVT module of the compositional simulation) becomes \( \sigma_{go} < \sigma_{go}^0 \), then the M\(_{\text{IFT}}\) mechanism is invoked and the Coats or Betté model is deployed. In this study, we have a particular focus on this near-miscible zone, where both IFT effects (\( \text{M}_{\text{IFT}} \)) and compositional effects (\( \text{M}_{\text{CE}} \)) can be important.

Kamali et al. (2014) conducted a laboratory and numerical study on the fluid behaviour during continuous CO\(_2\) injection. They reported that the displacement performance of their core flooding experiments under near-miscible and miscible conditions were almost equal. Later, they extended their study to WAG to seek co-optimizations of CO\(_2\) storage and EOR (Kamali et al., 2017). They highlighted the dependence of gas/oil relative permeability on the status of miscibility and pointed out its importance when modelling WAG displacements.

Skauge and Sorbie (2014) produced a review on the flow mechanisms at different scales during the process of WAG injection. They pointed out the strong link between pore-scale physics, the core-scale and field-scale oil recovery mechanisms. As motivated by their study, we therefore suppose that the increase in relative permeability with decreasing IFT is related to the “oil film” mechanism (\( \text{M}_{\text{IFT}} \) in Figure 1), although the simulator simply represents it as an enhanced oil phase relative permeability.
Yao et al. (2016) conducted a numerical study to assess the potential of CO\textsubscript{2} flooding in the enhanced recovery for a certain oil reservoir. They reported a great change in IFT during the whole injection process due to mass transfer. They claimed that the displacement performance could be improved by IFT reduction, especially in the subsequent water injection cycle. In a recent paper, Jahanbakhsh et al. (2018) compared the IFT effects on relative permeability of all three phases between immiscible and near-miscible WAG. They concluded that both oil and gas relative permeability could increase with decreasing IFT and therefore the oil recovery is significantly improved. However, they did not explicitly differentiate the mechanisms between the low-IFT effect (M\textsubscript{IFT} in our jargon) and the oil stripping effect (M\textsubscript{CE}).

The above review is presented to put the current study into the context of earlier work, which is mostly focused on the combined compositional and IFT effects, i.e. the respective M\textsubscript{CE} and M\textsubscript{IFT} mechanisms, during the transition from immiscible to near-miscible displacement. Our survey of the literature indicates important aspects of the modelling of flow behaviour under low-IFT (but not ultra-low) condition have not been fully appreciated or investigated. This is particularly true where strong compositional effects (M\textsubscript{CE}), IFT effects (M\textsubscript{IFT}), heterogeneities and multiphase flow are all involved, such as in near-miscible CO\textsubscript{2}-WAG processes. We stress that this combination of mechanisms/conditions is not unusual in these reservoir processes.

An additional and rather surprising part of the literature, which has been overlooked in considering the mechanism of the near-miscible WAG processes, is the contribution of viscous crossflow to the recovery mechanism. Zapata and Lake (1981) conducted a theoretical analysis of viscous crossflow in a stratified model for an immiscible 2-phase (water and oil or polymer and oil) system. They pointed out the importance of the crossflow to the sweep efficiency and therefore the ultimate oil recovery. Gardner and Ypma (1984) presented both experimental (core flooding) and theoretical results to investigate the interaction between phase behaviour and macroscopic-bypassing in a viscous-dominated system. They claimed that both the local displacement efficiency and the volumetric sweep could be affected by fingering flow due to viscous instabilities. Viscous crossflow has also been studied in some detail in the context of polymer flooding recovery mechanisms as discussed in Sorbie (2013). Al-Bayati et al. (2018) conducted an experimental study to investigate the effect of core-scale heterogeneity on the oil recovery of
miscible CO₂ flooding. They claimed that the effects of viscous crossflow is related to the improved oil recovery in their layered samples. A recent paper by Sorbie and Skauge (2019) discussed viscous crossflow in both polymer and WAG processes where the findings referred to for WAG are those presented here. In this study, the relevance of viscous crossflow to near-miscible WAG will become evident from the results presented below.

**Methodology**

**Fluid properties and relative permeability**

Table 1 shows the data for a seven-component light oil with a Minimum Miscibility Pressure (MMP) of 125 bar and a viscosity of 0.16 mPa·s which was used in our study. The bubble point pressure was, \( P_b = 38.5 \) bar at 53 °C. The full fluid data used for the generation of a Peng-Robinson equation of state (EOS) and details of the numerical setup can be found in our previous paper (Wang *et al.*, 2019).

<table>
<thead>
<tr>
<th>Component</th>
<th>( \text{CO}_2 )</th>
<th>( \text{N}_2 ) to ( \text{CH}_4 )</th>
<th>( \text{C}_2 ) to ( \text{C}_7 )</th>
<th>( \text{C}<em>8 ) to ( \text{C}</em>{12} )</th>
<th>( \text{C}<em>{13} ) to ( \text{C}</em>{19} )</th>
<th>( \text{C}<em>{20} ) to ( \text{C}</em>{30} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mole fraction</strong></td>
<td>1.2%</td>
<td>11.7%</td>
<td>19.5%</td>
<td>22%</td>
<td>28.2%</td>
<td>9.4%</td>
</tr>
<tr>
<td><strong>Viscosity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.16 mPa·s</td>
<td></td>
</tr>
<tr>
<td><strong>MMP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>125 bar</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Oil compositions and properties; *calculated by the simulator using the correlation by Jossi *et al.* (1962).

The oil/water and oil/gas two-phase relative permeability curves used here are shown in Figure 2. Note that a relatively high \( S_{\text{org}} \) (to immiscible gas displacement) is chosen here (\( S_{\text{org}}=0.33 \)) to give a higher target oil for near-miscible CO₂ displacement, with the aim of emphasizing the magnitude of effects occurring in the transition from immiscible to miscible conditions on the ultimate oil recovery. The Stone 2 method (Aziz and Settari, 1979) is applied in our study to calculate the relative permeability when three mobile phases are present during WAG injection. In this paper, hysteresis effects are not included but are currently under analysis for subsequent publications.
Figure 2 Oil-water and oil-gas relative permeability curves.

**Modelling of relative permeabilities as interfacial tension ($\sigma_{go}$) changes**

Formulas for the Coats’ model (modified version in the GEM simulator)

As mentioned earlier, the IFT-dependent model proposed by Coats has been the most widely used model to incorporate the effects of the $M_{IFT}$ mechanism. The method developed by Coats (1980) entails an interpolation between immiscible and fully miscible relative permeability functions (i.e. the linear relationships). The weighting function ($f$) with a specified critical gas/oil IFT, $\sigma_{go}^0$, is introduced to control the contribution of the IFT effects. The gas/oil IFT ($\sigma_{go}$) was calculated by the simulator as part of the compositional simulation using the McLeod-Sugden equation (CMG, 2019). If the actual local calculated $\sigma_{go}$ is above the threshold value ($\sigma_{go}^0$), the initial immiscible relative permeabilities of the gas and oil phases are used. If $\sigma_{go} < \sigma_{go}^0$, the relative permeability of oil and gas will be modified accordingly (as shown below) and they will gradually become linear functions as $\sigma_{go}$ approaches zero. As seen in Equation 1 and Equation 2, the smaller the weighting factor ($f$), the greater the impact IFT effects will have on the relative permeabilities. The exponent “n” involved in Equation 3, which is typically at a level of 0.1-0.5, was set to 0.5 here (although a wide range of values has been simulated in this work).

A modified Coats’ IFT-dependent model, which is available in the commercial software CMG/GEM (CMG, 2019), was used in this work and is defined by Equation 1 to Equation 8. Note that a separate parameter- hydrocarbon permeability ($K_{rh}$) was introduced in this method. $K_{rh}$ is the average of the initial gas and oil relative
permeabilities, capturing the concept of miscibility ($\sigma_{go} \sim 0.001$ mN/m) where oil and gas should become one single phase (CMG, 2019).

\begin{align*}
K_{rog} &= f \times K_{ro} + (1 - f) \times K_{rh} \times \overline{S_o} & \text{Equation 1} \\
K_{rg} &= f \times K_{rg} + (1 - f) \times K_{rh} \times \overline{S_g} & \text{Equation 2} \\
The parameter $f = 1$, if $\sigma_{go} > \sigma_{go}^0$ \\
&= (\alpha_{go} / \alpha_{go}^0)^n$, otherwise. & \text{Equation 3} \\
\overline{S_o} &= \frac{1 - S_g - S_{wc} - S_{org}^*}{1 - S_{wc} - S_{org}^*} & \text{Equation 4} \\
\overline{S_g} &= \frac{S_g - S_{gcr}^*}{1 - S_{wc} - S_{gcr}^*} & \text{Equation 5} \\
S_{org}^* &= f \times S_{org}^{imm} & \text{Equation 6} \\
S_{gcr}^* &= f \times S_{gcr}^{imm} & \text{Equation 7} \\
K_{rh} &= 0.5 \times (K_{row} + K_{rg}) & \text{Equation 8}
\end{align*}

Formulas for the model of Betté et al.

Another widely used method for modelling the effect of IFT on the gas and oil phase relative permeabilities was proposed by Betté et al. (1991) and is defined by Equation 9 and Equation 10. This model uses the same rationale for triggering/controlling IFT effects as the Coats’ model and it also imposes an interpolation between immiscible (initial) and miscible hydrocarbon relative permeabilities ($K_{rh}$) using the weighting function ($f$) and the hydrocarbon permeability ($K_{rh}$). Differing from Coats model, the residual oil saturation is not explicitly defined in Betté model. A discussion of these models on the flow behaviour is presented below.

\begin{align*}
K_{rot} &= f \times K_{ro} + (1 - f) \times K_{rh} \times (S_o/(1 - S_w)) & \text{Equation 9} \\
K_{rgt} &= f \times K_{rg} + (1 - f) \times K_{rh} \times (S_g/(1 - S_w)) & \text{Equation 10}
\end{align*}
Comparison between two models

Figure 3 Relative gas and oil permeability of an example with varying \((\sigma_{go}/\sigma_{go}^0)\) ratio, Betté model (left) and Coats model (right).

Figure 3 shows a range of relative-permeability curves varying \((\sigma_{go}/\sigma_{go}^0)\) ratio using the Betté model and the Coats model. Results in Figure 3, show that for both models the relative permeabilities approach linearity with decreasing \(\sigma_{go}\) (as \(\sigma_{go}/\sigma_{go}^0\) ratio decreases) and these two sets of curves are quite similar. However, there are discrepancies between oil relative permeability curves, which may have a significant impact on the final flow behaviour in WAG processes. Here, we take the \((\sigma_{go}/\sigma_{go}^0)\) ratio of 0.1 \((f = 0.32\) assuming the exponent of \(n\) as 0.5) as an example to be plotted in Figure 4 using semi-log scale to illustrate these differences:

1. Based on the same initial input of immiscible relative permeabilities (Figure 2), the IFT-dependent oil relative permeabilities produced from the Coats model are generally lower than those produced from the Betté model. This discrepancy between the oil relative permeabilities for each model increases with gas saturation (i.e. decreasing oil saturation) as shown in Figure 4. On the other hand, there is little discrepancy between gas relative permeabilities produced from two models, see Figure 4.

2. It is also shown in Figure 5 that the residual oil saturation (i.e. \(S_{or}\) where the \(k_{ro} = 0\)) in the Coats model has a definite value which is proportional to the \((\sigma_{go}/\sigma_{go}^0)\) ratio (see Equation 4). On the other hand, the residual oil saturation in the Betté model goes immediately to zero under IFT effects, see Figure 5. In other words, oil is always mobile \((k_{ro}>0)\) in the Betté model as long as the IFT effects are triggered (i.e. \(\sigma_{go} < \sigma_{go}^0\)). This is because of the nature of the method used for modelling IFT effects in Betté model (Equation 9 and Equation 10). This
method has no further treatment of the residual oil saturation. Because of the contribution of the non-zero gas relative permeability to $K_{rh}$, the consequent oil relative permeability is therefore not zero, although it may often have a very low value (e.g. 0.001-0.05).

Figure 4 An example of relative permeabilities with a $\sigma_{go}/\sigma_{go}^0$ ratio of 0.1.

Figure 5 Residual oil to gas versus $\sigma_{go}/\sigma_{go}^0$ ratio.
**1D model**

Figure 6 Schematic of 1D numerical test.

In order to determine the threshold value ($\sigma_{go}^0$) for the subsequent 2D models, 1D numerical simulations (near miscible and immiscible) were performed to track the interfacial tension between oil and gas ($\sigma_{go}$) during the whole injection process. Both IFT-dependent models were applied to investigate the effects of different relative-permeability treatment on the displacement performance. As seen in Figure 6, the length of the 1D model here (50m) was longer than a conventional to slim-tube model reduce possible fluctuations in the numerical results. More importantly, the results achieved in these 1D tests can be directly compared to the subsequent 2D tests with the same “well spacing”.

**2D areal heterogeneous model**

A small 50m x 10m ($\Delta x=\Delta y=0.05m$) heterogeneous permeability field was generated with a level of permeability heterogeneity defined by the Dykstra-Parsons coefficient (Dykstra and Parsons, 1950) and dimensionless correlation range ($R_L=\lambda/L$), where $\lambda$ is the correlation range and L is the system length (Jensen et al., 2000). This model of the permeability field, which is effectively the size of a single grid block in a full field model, is shown in Figure 7. The relatively short correlation range ($R_L=0.1$), this field was chosen to trigger possible fingering flow, but avoid “channeling” flow; i.e. where there is an obvious single high permeability channel through the system. The full details of the model are given in Table 2. Both wells were horizontal and were perforated along the width of the model. The injector in our tests was set to inject displacing fluid at a rate of 0.4 pore volumes/day (PV/d) and the producer was controlled by setting the minimum bottom-hole pressure. Both continuous CO$_2$ injection and WAG injection (slugs of CO$_2$/water/CO$_2$/water etc.) were modelled with the injection strategy given in Table 3.
Figure 7 Permeability Field A ($V_{DP}=0.7$, $R_L=0.1$) used to trigger fingering flow in gas displacement either by continuous CO$_2$ injection or in WAG.

<table>
<thead>
<tr>
<th>Porosity</th>
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<tr>
<td>Average permeability (md)</td>
<td>1000 md</td>
</tr>
<tr>
<td>Dykstra-Parsons coefficient</td>
<td>0.7</td>
</tr>
<tr>
<td>Dimensionless correlation range</td>
<td>0.1</td>
</tr>
<tr>
<td>Initial pressure (kPa)</td>
<td>Immiscible: 7000 Near-miscible: 12000</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>53</td>
</tr>
<tr>
<td>Initial saturations</td>
<td>$S_w = 0.1; S_o = 0.9; S_g = 0$</td>
</tr>
</tbody>
</table>

Table 2 Data for 2D models.

<table>
<thead>
<tr>
<th>Continuous injection (1PVI)</th>
<th>1 PVI continuous CO$_2$ injection at reservoir conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAG injection (2 PVI)</td>
<td>1$^{st}$ water cycle 1$^{st}$ gas cycle 2$^{nd}$ water cycle 2$^{nd}$ gas cycle 3$^{rd}$ water cycle</td>
</tr>
<tr>
<td>0.4 PVI water 0.4 PVI CO$_2$ 0.4 PVI water 0.4 PVI CO$_2$ 0.4 PVI water</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Injection strategy (PVI = pore volume injected).
The central objective of choosing a 2D model of the type shown here and of the scale, i.e. the size of a relatively small grid block in many WAG simulations, is to allow us to model all of the multi-scale physics from the core scale (continuum scale with $\Delta x = 0.05$ m) to the scale of the field (a grid block) such that the calculation is fully converged. According to Arya et al. (1988) and Sorbie and Mackay (2000), the grid resolution of our model allows a level of dispersion (dispersivity $\sim \Delta x / 2$), which is typical of a homogenous core scale, also $\Delta x << \lambda$, ($\Delta x / L = 0.05/50 = 0.001 << R_L = \lambda / L = 0.1$). Therefore, grid refinement will not produce any changes to the simulated quantities and we are at the scale where additional effects such as capillary pressure, relative permeability hysteresis, gas/oil trapping etc., can be modelled in a fully converged manner with the same grid. Indeed, all of these effects have been incorporated into the calculation and the effects of all of these on near miscible WAG will be described in a future publication.

**Pseudo tracer analysis**

In addition, a pseudo tracer simulation was carried out to demonstrate some of the mechanistic flow features in our 2D models. Specifically, when it was suspected from our original simulations that viscous crossflow (Zapata and Lake, 1981; Sorbie and Skauge, 2019) may be an important mechanism in near-miscible WAG process, we wished to test this hypothesis directly by labelling the bypassed oil after the first gas flood. This analysis involved injecting a certain amount of tracer oil, which had same EOS data as initial oil. The “$C_8$ to $C_{12}$” (the component with the most mole fraction) was renamed as $C_8^*$ and served as a tracking target. All the other simulation parameters were the same as the ones in previous simulations. The main details of the design of our tracer simulations are as follows:

1. All EOS parameters of this tracer oil ($C_8^*$) were exactly same as the initial oil, thus the oil phase behaviour was identical.
2. The tracer oil was injected into a chosen position in a non-preferential (bypassed) flow route (identified from 2D simulations without injecting tracer first), with the aim of tracking the flow behaviour in the bypassed zone.
3. The tracer was not injecting tracer at the start of the WAG floods (at $t = 0$) in order to minimize the impacts from the initial water cycle, where the stable displacing front can greatly distribute the tracer and therefore complicate the investigation the IFT effects. A very small amount of tracer was injected into the chosen bypassed grid block at a rate of $1/12000$ PV/hour for 2 hours ($1/6000$ PV in total). Such injection was conducted either at the beginning of the simulation for the CO$_2$ continuous injection floods (i.e. at $t = 0$) or the beginning of the first gas
cycle during WAG (i.e. at $t = 0.4$ PV). We found that such a slow and small amount of tracer injection had a negligible impact on the overall flow pattern, compared with the simulations with no tracer.

4. The whole injection process of tracer was designed to avoid any contacts with CO$_2$ to guarantee C8* only exists in the oil phase before the injected CO$_2$ arrives.

Results will now be presented from a series of numerical simulations to assess and differentiate the impacts of the $M_{CE}$ and $M_{IFT}$ mechanisms on the flow behaviour and oil displacement characteristics during CO$_2$ injection. We investigate any possible differences in simulation results from the two models which describe the $M_{IFT}$ mechanism, i.e. Betté et al. (1991) and Coats (1980), in order to improve the modelling the transition from immiscible to miscible oil displacement by CO$_2$. To follow the structure and logic of what our results are attempting to demonstrate, the results are presented in the steps outlined in Table 4.

<table>
<thead>
<tr>
<th>Step</th>
<th>Model dimension</th>
<th>Injection scheme &amp; Mechanisms included</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1D</td>
<td>Continuous CO$_2$ injection:</td>
<td>To determine the threshold value of interfacial tension for modelling IFT effects; To assess the impact of $M_{IFT}$ on the oil recovery in a 1D homogenous model.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Neither $M_{CE}$ nor $M_{IFT}$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>2. $M_{CE}$ acting only</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>3. Both $M_{CE}$ and $M_{IFT}$</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>2D areal</td>
<td>Continuous CO$_2$ injection:</td>
<td>To investigate the impact of $M_{IFT}$ on the oil recovery during continuous injection.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Neither $M_{CE}$ nor $M_{IFT}$</td>
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<tr>
<td></td>
<td></td>
<td>2. $M_{IFT}$ acting only</td>
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</tr>
<tr>
<td>#3</td>
<td>2D areal</td>
<td>Continuous CO$_2$ injection:</td>
<td>To investigate the combined impact of $M_{CE}$ and $M_{IFT}$ on the oil recovery during near-miscible continuous injection.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. $M_{CE}$ acting only</td>
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<tr>
<td></td>
<td></td>
<td>2. Both $M_{CE}$ and $M_{IFT}$</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>2D areal</td>
<td>CO$_2$-WAG</td>
<td>To investigate the combined impact of $M_{CE}$ and $M_{IFT}$ on the oil recovery during near-miscible WAG displacement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. $M_{CE}$ acting only</td>
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<tr>
<td></td>
<td></td>
<td>2. Both $M_{CE}$ and $M_{IFT}$</td>
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</tr>
<tr>
<td>#5</td>
<td>Tracer analysis (2D)</td>
<td>Continuous and CO$_2$-WAG</td>
<td>To investigate the role of viscous crossflow in the recovery of bypassed oil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. $M_{CE}$ acting only</td>
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<tr>
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<td>2. Both $M_{CE}$ and $M_{IFT}$</td>
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</tbody>
</table>

Table 4 Outline of numerical tests performed and objectives of each stage.
Results and Discussions

1. Determination of threshold value for modelling IFT effects

In order to determine a suitable threshold value of $\sigma_{go}^0$ to use when modelling IFT effects to reflect the “film flow” mechanism ($M_{IFT}$), a representative cell (3/10 of the 1D system length from the injector) was selected to track its IFT throughout the whole process of immiscible and near-miscible displacement. This is the #1 step of simulations in Table 4. The results in Figure 8 (blue line) show that, the gas/oil IFT ($\sigma_{go}$) first decreases from $\sim 7 \text{ mN/m}$ to $\sim 3 \text{ mN/m}$ and then increases again up to $\sim 6 \text{ mN/m}$ under immiscible conditions. This behaviour is a result because of CO$_2$ dissolution and minor oil component stripping when CO$_2$ contacts the oil. On the other hand, the results in Figure 8 for the near-miscible flooding case clearly lead to a much wider range of IFT values during the whole process (from 0.01 to 10 mN/m). This is very well known from conventional compositional simulations. In the early stages of the displacement, CO$_2$ and oil are approaching miscibility through the mass transfer process, and $\sigma_{go}$ sharply decreases. Such a change in IFT which is a consequence of the component transfer, also leads to an increased oil relative permeability ($M_{IFT}$) as soon as $\sigma_{go} < \sigma_{go}^0$. With further contacts between CO$_2$ and oil, $\sigma_{go}$ again increases and the fluids become immiscible. This is because the light-medium oil components have been mostly vaporized/stripped leaving the remaining oil consisting mainly of heavier components, thus the CO$_2$/remaining oil IFT increases to a high value since this oil is immiscible with the CO$_2$. This phenomenon is well-known and is extensively described in the literature (Orr, 2007; Wang et al., 2019). In addition, these effects impose a further complexity as they must also interact with the flow behaviour in heterogeneous systems in the preferential and non-preferential flow paths. Indeed, in the results below, we demonstrate that “different mechanisms work in different places for different processes”.
Figure 8 IFT in the representative cell at near-miscible conditions.

The results in Figure 8 demonstrate the range of gas/oil IFT values which can occur for both the immiscible (narrow, \( \sim 7 \) to \( 3 \) mN/m) and near-miscible (wide, \( \sim 7 \) to \( 0.01 \) mN/m) cases. In order to investigate the effect of the film-flow \( \text{M}_{\text{IFT}} \) mechanism, simulations were carried out for a range of “onset” \( \sigma_{go}^0 \) values (0.1, 5 and 10 mN/m) to examine the role and magnitude of this mechanism on the oil recovery in the near-miscible 1D oil displacements by continuous CO\(_2\) injection. As shown in Figure 9, the IFT effects on the near-miscible displacement in the model were found to be minor regarding the oil recovery. This is because the oil-stripping mechanism (\( \text{M}_{\text{CE}} \)) is very efficient and has already been able to recover most of the oil in the 1D system and therefore leaves little target oil for IFT effects (\( \text{M}_{\text{IFT}} \)) to work on. For a similar reason, the discrepancy between two models (Betté and Coats) under near-miscible conditions is also negligible. What should also be highlighted here is that the remaining oil saturation mostly consists of the heavy components (higher viscosity) with very poor mobility, which also leads to increasing IFT as the flood progresses. This will further hinder the oil phase flow (poor mobility), leading to a fairly limited incremental oil recovery. In other words, the oil stripping effects (\( \text{M}_{\text{CE}} \)) have greatly masked and restricted IFT effects (\( \text{M}_{\text{IFT}} \)) and are therefore dominant during the oil displacement by CO\(_2\) under continuous injection in 1D under near-miscible conditions. We noted above that Betté et al. (1991) had already described this effect. However, given our finding below, they did not point out that 1D-model experiments are actually a very
poor way of examining the IFT effects (the M_{IFT} mechanism) in continuous gas injection; worse still, such experiments actually **miss** these effects.

![Diagram](image.png)

**Figure 9** Recovery factor based on Coats (blue) and Betté (red) with various values of threshold interfacial tension ($\sigma_{go}$).

### 2. Impact of M_{IFT} on the oil recovery during continuous injection

We now consider continuous CO$_2$ injection with only the IFT mechanism (M_{IFT}) working alone in the 2D heterogeneous model described above; these are the step #2 simulations in Table 4. In fact, this is a highly unlikely case physically since it requires the IFT to decrease but without significant compositional effects; this case is shown as Case C in the phase diagram in Figure 10. However unphysical this case is, it allows us to examine the effect of all combinations of mechanism for completeness; in this respect, we note that all three other cases A, B and D in Figure 10 are physically plausible and can occur.

Figure 10 shows the distributions of gas saturation after 0.5PV of CO$_2$ injection under purely immiscible (no IFT effects) conditions, and with IFT effects using Betté and Coats models, each with an onset value of $\sigma_{go}^0 = 10$ mN/m. As expected, fingering flow of gas occurs in the system due to the highly unfavourable mobility ratio. For the same amount of CO$_2$ injection at reservoir conditions, cases with IFT effects show slightly decreased macroscopic sweep efficiencies, i.e. somewhat more severe viscous fingering. This is because the oil mobilized by IFT effects within the gas fingers can then be recovered allowing even more injected gas to flow into these fingering regions. The
consequent higher gas saturation leads to more aggressive gas fingers and therefore aggravates the imbalance of the fluid flow between preferential routes in the gas fingers (as indicated by oval shapes in Figure 10) and the non-preferential bypassed routes. Figure 11 shows that the oil saturation after 1PV of injection for the same cases as in Figure 10. The results in Figure 11 show that, in the non-preferential routes, the oil is even more poorly recovered (i.e. bypassed) than the base case (no IFT effects), whereas the oil in the preferential routes can be more efficiently produced.

Figure 10 Snapshots of gas saturation with 0.5PVI of CO₂ at immiscible conditions.

Figure 11 Snapshots of oil saturation with 1PVI of CO₂ at immiscible conditions.
The oil recovery results in Figure 12 (at 1PV of continuous CO₂ injection), show that the combined IFT effects of poorer sweep but lower remaining oil in the preferential paths lead to a very limited improved oil recovery compared to the base case without IFT effects (Betté: 3.5%, Coats: 2.4%). In addition, the local displacement efficiency in the preferential routes near the injector are slightly better based on the Betté model than on the Coats model. This is simply because of the different treatment of residual oil saturation between two models and matches our observations made in the previous calculations based on 1D model. However, this discrepancy does not make much difference in the oil recovery between the two models after 1 PVI, which is a typical volume for continuous CO₂ injection in laboratory (Betté et al., 1991). This is because, even with the Betté model, the newly mobilized oil is still of very low permeability and therefore not sufficient to be recovered with a certain amount of continuous CO₂ injection (see Figure 12).

![Figure 12 Oil recovery with/without IFT effects at immiscible conditions after 1PV CO₂ continuous injection.](image)

**3. Combined impact of Mₐₙ and Mᵢₛ on the oil recovery during continuous injection**

We now consider the combined effects of the two mechanism of compositional/stripping (Mₐₙ) and IFT (Mᵢₛ) during continuous CO₂ injection into the 2D heterogeneous model; these are the step #3 calculations in Table 4.

According to Sohrabi et al. (2004) and Sorbie and van Dijke (2010), oil layer flow is an important flow mechanism during near-miscible gas displacement. They found that although gas-oil interfacial tension is not ultra-low (e.g. at a level of σₒ₉ ~ 1 - 3 mN/m), significant oil flow can still be observed through oil layer drainage. In order to evaluate the significance of such effects, the threshold IFT, σₒ₉₀ in our simulations is set to 5 mN/m for the following 2D areal near-miscible CO₂ displacements. That is, we now investigate the effect of combined mechanisms (Mₐₙ
and $M_{IFT}$) on the flow behaviour, when viscous instability and heterogeneity are involved under continuous CO$_2$ injection.

Figure 13 shows a snapshot of the gas distribution in the system after 0.5 PV of CO$_2$ continuous injection and Figure 14 shows the remaining oil distribution after 1PV of CO$_2$ injection; the three cases shown are for the near-miscible case (fixed $M_{CE}$) with/without IFT effects described by each of the Betté and Coats models. A comparison of Figure 10a (immiscible conditions) and Figure 13a (compositional effects, $M_{CE}$ only) shows how the oil-stripping mechanism affects flow behaviour. For the same pore volume of CO$_2$ injected, the gas saturation is much higher in the near-miscible case than in the immiscible case in the preferential routes (as indicated by the oval shapes). Under near-miscible conditions, the oil components have been mostly vaporized into the CO$_2$ and thus flow in the gas phase. As a result, the greatly increased gas saturation will form more aggressive gas fingers under near-miscible conditions than under immiscible conditions. More interestingly, IFT effects mobilize some oil, which leads to a slightly worse macroscopic sweep efficiency. Both mechanisms are working in tandem to recover the oil in the preferential routes (as indicated by the oval shapes) but forming more severe gas fingers at the same time, as seen in Figure 13 (a-c). As a result, the oil in the preferential routes can be more efficiently produced, whereas the oil in the non-preferential routes is even more poorly recovered than in the base case. The results in Figure 15 show that the oil recovery after 1PV of continuous CO$_2$ injection has been modestly increased by the IFT effects (~ 4 - 5%), but only by a very limited amount due to viscous instability forming dominant gas fingers. As expected, there is a minor discrepancy regarding the ultimate oil recovery between Betté and Coats, due to the dominant stripping effects (oil components flow in gas phase). Both of these models for the IFT effect ($M_{IFT}$) indicate that there is a significant amount of bypassed oil in the non-preferential routes.
Figure 13 Snapshots of gas saturation with 0.5PVI of CO$_2$ under near-miscible conditions.

- a. No IFT effects
- b. $\sigma^{0}_{ga} = 5$ mN/m with Betté
- c. $\sigma^{0}_{ga} = 5$ mN/m with Coats

Figure 14 Snapshots of oil saturation with 1PVI of CO$_2$ under near-miscible conditions.

- a. No IFT effects
- b. $\sigma^{0}_{ga} = 5$ mN/m with Betté
- c. $\sigma^{0}_{ga} = 5$ mN/m with Coats
Figure 15 Oil recovery after 1PV continuous CO₂ injection with/without the account of IFT effects ($σ_0 = 5$ mN/m).

4. Combined impact of $M_{CE}$ and $M_{IFT}$ on the oil recovery during CO₂-WAG

We now address the issue of the bypassed oil left in the non-preferential routes due to the dominant gas fingers, formed in continuous CO₂ injection, as shown in Figure 14 above. The relatively minor effect in terms of oil recovery in continuous CO₂ injection, even when both stripping/compositional effects ($M_{CE}$) and IFT effects ($M_{IFT}$) are present, has led us to consider WAG injection, which is expected to improve the stability of the displacing front. WAG simulations including both the $M_{CE}$ and $M_{IFT}$ mechanisms are described in the step #4 set of simulations in Table 4. A range of numerical simulations of near-miscible WAG displacement with the aforementioned injection strategy (Table 3) was conducted with/without IFT effects as shown below.

Figure 16 show the remaining oil saturation at various stages of the WAG simulations comparing near-miscible cases (always with $M_{CE}$ acting) both with and without the IFT effects ($M_{IFT}$) included. The figures on the left show the results without IFT effects ($M_{CE}$ only), and those in the middle and right columns with IFT effects (i.e. combined $M_{CE}$ and $M_{IFT}$), for both Betté and Coats models. As expected, WAG is able to improve macroscopic sweep very efficiently both with and without IFT effects. Very importantly, both the Betté and the Coats models give essentially the same prediction that the overall displacement performance is significantly enhanced through the IFT effects ($M_{IFT}$). In contrast to the case of continuous injection, the local displacement efficiency, particularly in the non-preferential routes, can be very effectively improved in the case of WAG displacement. As seen in the
corresponding oil recovery results in Figure 17, the recovery from the second water and second gas injection cycle have been instantly and greatly improved due to the additional IFT effects ($M_{\text{IFT}}$). As a result, the improvement in total due to the $M_{\text{IFT}}$ mechanism in the oil recovery is approximately 17%. Note that IFT effects have no impact on the fluid behaviour and oil recovery in the first water injection cycle (W1). In other words, the remaining oil saturation and oil recovery at the end of W1 are identical for all these three cases.

Figure 16 Track of remaining oil saturation throughout the 2PVI of WAG with compositional effects acting only (left column), IFT effects based on Betté model (middle column) and IFT effects based on Coats model (right column).
Figure 17 Incremental oil recovery of each cycle with compositional effects acting only (grey), IFT effects based on Betté model (red) and IFT effects based on Coats model (blue).

The significance of the IFT effects \( \Delta \text{IFT} \) during near-miscible \( \text{CO}_2 \)-WAG injection has been clearly pointed out so far. We now address the question: how \( \Delta \text{IFT} \) can effectively change the flow pattern during WAG displacement but have minor impacts on the flow behaviour during the continuous \( \text{CO}_2 \) displacement. The reason we address this issue explicitly is that, although oil can be mobilized by IFT effects and be displaced by a stable displacing front, the consequent oil relative permeability (near the zone of residual oil) is still very low and we might expect that it should take long time (or much injection) for this incremental oil to be produced; but this is evidently not the case.

With the same amount of injection (2PV WAG in total here), both models give a same prediction that \( \Delta \text{IFT} \) can have an immediate effect and the oil recovery has been quickly and efficiently enhanced during the second water cycle (W2: 0.8PV-1.2PV) and second gas cycle (G2: 1.2PV-1.6PV). This implies that there must be some other flow features triggered/amplified by IFT effects in our 2D heterogeneous models. In fact, from our observed simulation results, we conjectured that this very efficient recovery mechanism had the hallmarks of a viscous crossflow mechanism; i.e. it was quite large and quick. Thus, we set out to test this hypothesis.

5. Tracer analysis

The results of our simulations show that there is a significant and relatively fast mobilization of oil when both of the \( \Delta \text{CE} \) and \( \Delta \text{IFT} \) mechanisms work together, and we surmise that this is due to crossflow. To test this hypothesis,
we performed a tracer simulation, to investigate the flow trajectory of the oil in the non-preferential routes (i.e. the bypassed oil) during WAG with both mechanisms present ($M_{CE}$ and $M_{IFT}$). The tracer test is referred to as step #5 in Table 4. Since there was negligible difference in the WAG results between Betté and Coats models, the tracer analysis was only performed using the Coats model. As noted in Methodology section, we injected a small amount of tracer into a non-preferential route to observe the tracer distribution throughout the whole injection process. Figure 18 shows the mole fraction of this tracer in the oil at the end of injection (1/6000 PV in total).

![Figure 18](image)

Figure 18 The snapshots at the end of tracer injection.

As seen in Figure 19 a - d, we compare the snapshots of the tracer distribution after a certain amount of injection in four cases, i.e. at the end of continuous injection (Figure 19 a & b) and at the end of the second gas cycle of WAG injection (Figure 19 c & d). All simulations show that the tracer migration is strongly affected by crossflow. It is evident from the results in Figure 19a ($M_{CE}$ only) and Figure 19b (both $M_{CE}$ and $M_{IFT}$ mechanism), that IFT effects have a fairly limited impact on the oil crossflow during the continuous CO$_2$ displacement. The continuous gas injection does not change the flows through the severe gas fingering and thus the bypassed oil remains in the non-preferential routes, despite the fact that the oil relative permeability may be somewhat increased. For this reason, a significant amount of remaining oil can still be found between gas fingers, i.e. in the non-preferential routes, no matter whether we include or exclude IFT effects ($M_{IFT}$) during the continuous CO$_2$ injection. The tracer results
are therefore completely consistent with the earlier findings that continuous CO$_2$ injection is rather similar when either just M$_{CE}$ or both M$_{CE}$ and M$_{IFT}$ mechanisms are present.

As for WAG injection processes, the results in Figure 19c for the case with compositional effects only (M$_{CE}$ only) do not lead to significant (oil/tracer) crossflow in the system, and subsequently, there is very limited production from the by-passed regions. However, comparison of the tracer results in Figure 19c and Figure 19d (near-miscible WAG injection without and with IFT effects) clearly shows the extent of crossflow has been significantly enhanced by the IFT effects during WAG displacement. The oil permeability in the non-preferential routes enhanced by the IFT effects may now crossflow, when water (more viscous) is injected, from the non-preferential routes into the preferential flowing routes. Water injection is required since this process is highly dependent on a stable displacing front in order to maximize the crossflow. Therefore, the case of near-miscible WAG displacement with IFT effects has by far the most extensive tracer migration and therefore the greatest crossflow (Figure 19d). This explains why IFT effects can greatly modify the displacement performance and rapidly improve the oil recovery in the case of near-miscible WAG with IFT effects, but have a minor impact in all of the other cases.
Finally, we explain why there is only a negligible discrepancy between the Betté and Coats models when simulating near-miscible WAG. This is because IFT effects in the non-preferential routes can be very strong due to the fact that the mass exchange process between oil and gas is still at early-middle stage. In other words, $\sigma_{go}$ is sufficiently low to make the residual oil close to zero (based on Coats) and thus make the two models produce almost the same results.

**Summary and Conclusions**

The central objective of this paper is to study the balance and interactions of the different mechanistic contributions to the physics occurring during oil displacement by CO$_2$ (both continuous and WAG). Mechanism 1 ($M_{CE}$) is the oil stripping/compositional effect and Mechanism 2 ($M_{IFT}$) is the near-miscible IFT effect on oil relative permeability. Using sufficiently fine-scale models, we explain how these mechanisms interact with each other and affect the sweep and local displacement efficiency in the fingering flow regime. We believe that studying the key processes separately leads to a greater insight into the physics of CO$_2$ displacement. From the point of view of modelling, we identify the key discrepancy between Coats and Betté models, aiming to provide insight into the simulation of the transition from immiscible to near-miscible systems. Although the results achieved in this numerical study have not yet been tested in the laboratory, they clearly indicate how important these mechanisms are and the corresponding experiments could be carried out in the future. Here are four key observations from the range of numerical simulations presented here.

1. Incremental oil recovery is insensitive to IFT effects ($M_{IFT}$) during continuous CO$_2$ injection in our cases. This is because both $M_{CE}$ (oil stripping effects) and $M_{IFT}$ (IFT effects) are working in tandem to recover the oil in the preferential routes, but forming more severe gas fingers at the same time leading to more imbalanced flow paths. The final result of the competing IFT effects of poorer sweep but lower residual oil in the preferential paths leads to a relatively limited increased oil recovery.

2. It has been found that IFT effects ($M_{IFT}$) could have a great impact on the fluid behaviour and the oil recovery in near-miscible WAG displacements. With a stable displacing front during WAG, the oil mobilized by IFT effects in the non-preferential routes flows (viscous crossflow) into the neighboring preferential routes and is then recovered rapidly by strong compositional effects ($M_{CE}$). Our simulations confirm that the efficiency of near miscible WAG arises because of the efficient operation of these combined $M_{CE}$ and $M_{IFT}$ mechanisms.
3. Although the treatments of the residual oil saturation under IFT effects are different between the Betté and Coats models, there is only negligible discrepancy between these two models when simulating near-miscible WAG. This is because $\sigma_{go}$ in the bypassed oil zone is sufficiently low to make the residual oil close to zero (based on Coats). Therefore, the two models (Betté and Coats) produced almost the same results in our cases.

4. We believe we have demonstrated how the different mechanisms (oil stripping, $M_{CE}$ and IFT effects, $M_{IFT}$) work in different places (preferential and non-preferential routes) for different processes (continuous CO$_2$ injection and WAG) under different conditions (immiscible and near miscible).

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List of symbols

$f$ - Weighting factor for IFT effects
$K_{rg}$ - Gas relative permeability
$K_{rgt}$ - Total gas relative permeability (under IFT effects)
$K_{ro}$ - Oil relative permeability
$K_{rot}$ - Total oil relative permeability (under IFT effects)
$K_{rw}$ - Water relative permeability
$M_{CE}$ - Oil stripping effects
$M_{IFT}$ - Interfacial tension effects
$n$ - Exponent of the equation for weighting factor
$R_L$ - Dimensionless correlation range
$S_g$ - Gas saturation

$S_o$ - Oil saturation

$S_{or g}$ - Residual oil saturation to gas

$S_{or w}$ - Residual oil saturation to water

$S_w$ - Water saturation

$S_{wc}$ - Connate water saturation

PVI - Pore volume injection

$V_{dp}$ - Dykstra-Parsons coefficient

$\sigma_{go}^0$ - Threshold value when IFT effects are triggered

$\sigma_{go}$ - Interfacial tension between oil and gas
References


