Introduction

Fossil fuel remains an important energy source for the rest of the 21st century, particularly with a growing global population and fast economic development. Oil has been identified as the important low-carbon fossil fuel to meet the increased energy demand. However, the recovery factor of oil resources is low (<40%) [1, 2] after primary and secondary recovery stages, so there is enormous motivation to improve recovery cost effectively, and with environmentally friendly techniques if possible. Carbon dioxide (CO₂) injection is recognised as an important means of enhanced oil recovery (CO₂-EOR) [3] as well as a potential mitigation strategy for the greenhouse gas effect [4]. Thus, CO₂-EOR if often considered as an attractive option to reduce the cost associated with CO₂ geo sequestration in deep geological storage media.

Carbon dioxide flooding may be categorized as either immiscible, near-miscible or miscible based on the operating pressure, temperature, and the type and composition of the in-situ crude oil. The possible chemical and thermodynamic events (e.g. exchange of mass) occurring during a CO₂ flood tend to make the displacement processes microscopically efficient [5]. Such a microscopic displacement efficiency [6] can lead to a prolonged reservoir life by 15–20 years and recover an additional 15.0-20.0% of the oil initially in place [7]. However, the very high viscosity and moderate density contrasts of a CO₂ flood present significant impediments to achieving a reasonable macroscopic sweep efficiency for the flood [8]. The above-mentioned disparity in fluid properties tend to result in development of highly dispersed and non-conforming displacement processes that often lead to major uncertainty in predicting the performance of the CO₂-EOR. The poor macroscopic efficiency of a gas flood, in general, could be improved by the deployment of various economically and technically viable conformance control techniques as proposed in the literature and demonstrated in some pilot and field applications. For instance, water alternating gas (WAG) injection is one of the proposed methods to mitigate frontal advance instabilities [9]. According to Christensen, Stenby [10], who reviewed over 50 WAG projects, about 57% of WAG injections have been performed in sandstone reservoirs resulting in 5.0 10.0% incremental oil recovery. The benefits of the WAG injection scheme are realised through a number of mechanisms such as reduction in the relative permeability to gas and gas entrapment in the high permeability zones. During CO₂-EOR, these features not only divert the injectants into lower permeability zones leading to improved macroscopic sweep of the flood but also put the excellent microscopic sweep attainable by CO₂ injection into use in the otherwise bypassed oil-rich low permeability zones. Despite the promising performance of the WAG flooding, extreme reservoir heterogeneity may still pose a challenge to its development under in-situ conditions. In the context of hydrocarbon reservoirs, heterogeneity may translate into a spatial variation in the characteristics of the subsurface fluid-rock system such as porosity, thickness, saturation, wettability and permeability or a combination of these. Nevertheless, stratification and the often-associated permeability variation is frequently recognised as the primary drive behind the underperformance of fluid-fluid displacements performed in hydrocarbon reservoirs [11]. The reservoir heterogeneity may deteriorate the conformance of a displacement by accelerating the worsening effects of the viscous fingering and channelling resulting in the premature breakthrough (BT) of the injectant and reduced sweep efficiency [12, 13]. On the other hand, as also demonstrated by published literature results, viscous, capillary, gravity and dispersive forces may contribute to the crossflow phenomenon [14-16] that may positively impact on the sweep efficiency. The presumed positive contribution of the crossflow during a gas flood in layered porous media may be realized via reduced viscous channelling and ensuing delayed BT as well as reduced gas to liquid ratio during the post-BT period. Given the relevance of the addressed topic, not yet well covered in all its aspect in the present scientific literature, a reproducible and elaborate laboratory approach to assess and scrutinize the potential effects of permeability heterogeneity on the displacement performance of immiscible CO₂ injection is proposed in this work. The results obtained can contribute significantly towards improving our current understanding of contributing factors during CO₂-EOR and CO₂ geological storage in active/depleted and often heterogeneous hydrocarbon reservoirs.

Experimental Work

**Equipment, elements and experimental conditions:** Core flooding experiments were performed using a reservoir condition core flooding setup (A detailed description of the specifications and attributes of
this setup can be found in previous published work [17]). A synthetic brine of 32,000 ppm salinity prepared using analytical grade reagents supplied by Sigma Aldrich (20 g NaCl, 7 g KCl and 5 g CaCl₂.2H₂O per 1000 mL of distilled water) along with n-C₁₀ (99 mol%, Sigma Aldrich) and high purity supercritical CO₂ (99.9 wt%, BOC Gases) were used as the experimental fluids. The experiments performed at 9.65 MPa, 26.9 MPa and 343 K pore pressure, confining stress and temperature, respectively. The MMP (minimum miscibility pressure) of CO₂/n-C₁₀ at 344 K is about 12.6 MPa [18]. Thus, CO₂ would be immiscible with n-C₁₀ at the experimental conditions used here.

Core sample preparation and Experimental procedure: Three homogeneous core plugs, namely, Grey Berea, Bandera Brown and Kirby with nominal porosities of 18, 19 and 23% and nominal permeabilities of 0.1, 0.020 and 0.008 (μm)² respectively. These homogeneous core plugs of differing permeabilities were cut axially into two longitudinal halves. The heterogeneous samples were then constructed simply by combining the longitudinal sample to construct a layered sample. Further information regarding sample construction is available in our previously published paper [13]. The standard procedures and protocols available in the published literature [7, 19] were used to design the flooding procedure in this work. To conduct a flooding experiment, after the attainment of the residual water saturation (Sₑ), 4–6 PVs of formation brine was used to flood the sample at 4 mL/min to achieve the residual n-C₁₀ saturation. Then, WAG injection commenced straight away by injection CO₂ and brine in consecutive slugs at the flow rate of 1 mL/min (determined according to the criteria set out in the literature [20]) utilizing a WAG ratio of 1:1 and the slug sizes of 0.15 PV.

Results and Discussion

Impact of Permeability heterogeneity: Given the homogeneous case (PR=1) sample tested in this work, in addition to three different heterogeneity levels of strong, moderate and weak were simulated as corresponding to PR values of 12.5, 5 and 2.5, respectively. It is clear that the results reported in Table 1 shows that the ultimate RF is the highest for the homogeneous sample (at PR=1, RF=78.1%). In this sample, the flood front is expected to move steadily during the WAG flooding distributing the injected fluids spatially even across the entire thickness of the sample. This behaviour would not only delay the BT but also result in a more sustained high recovery rate throughout the experiment. While the initial pre-BT oil recovery trends for the remaining three heterogeneous samples all resemble that of the homogeneous sample, the instant of BT, RF at BT as well as the ultimate RF are different across various cases. In other words, as the PR increases, BT occurs earlier resulting in lower recoveries. As can be seen from Table 1, the RF at BT for PR=1 is 22.0% followed by 16.0%, 14.0% and 8.0% for the PRs of 2.5, 5 and 12.5, respectively. Also, the ultimate RF decreases from 71.9% to 65.1% and then 60.5% as the PR increases consecutively. The observed decreasing trend in RF against PR has also been reported by other researchers previously [12, 17]. This behaviour is very likely caused by the increasing tendency of the injected fluids to penetrate the high permeability layer preferentially and circumvent the low permeability layer as the PR increases. Similar outcomes have been reported in the analytical and experimental investigations performed by other researchers [15].

<table>
<thead>
<tr>
<th>PR</th>
<th>Heterogeneity level</th>
<th>Injected PV’s at breakthrough</th>
<th>RF (%) at breakthrough</th>
<th>Sₑ (%)</th>
<th>Ultimate RF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Homogeneous</td>
<td>0.227</td>
<td>22.0</td>
<td>16</td>
<td>78.1</td>
</tr>
<tr>
<td>2.5</td>
<td>Weak</td>
<td>0.139</td>
<td>14.0</td>
<td>21</td>
<td>71.9</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
<td>0.109</td>
<td>12.0</td>
<td>25</td>
<td>65.1</td>
</tr>
<tr>
<td>12.5</td>
<td>Strong</td>
<td>0.087</td>
<td>8.0</td>
<td>28</td>
<td>60.5</td>
</tr>
</tbody>
</table>

Impact of crossflow: In a layered system, the occurrence and contribution of crossflow would be controlled by the degree of interlayer communication something that was controlled in our
experiments by placing either a thin Teflon sheet (to prevent communication) or tissue papers (to promote communication) in between the two halves of our layered samples.

As expected, Figure 1 reveals that for both cases of communication and non-communicating layered systems, RF consistently decreases as PR increases. However, such a trend seems to be steeper for the case of communicating layers where crossflow is permitted to occur. Such an effect is against the common belief that the crossflow would tend to contribute positively towards improving oil recovery in a layered system as confirmed by our previous results for the case of continuous CO₂ flooding [17]. This contradiction may find support in the dynamic mechanisms responsible for the enhancing effect of WAG flooding on oil recovery. In general, with or without crossflow, as the first WAG slug (i.e. 0.15 PV of CO₂ in our experiments) is injected, the CO₂ mostly bypasses the low permeability layer as it finds it easier to penetrate and flow through the high permeability one. However, the following slug of water injected would entrap some of the CO₂ in the high permeability layer and reduce relative permeability to CO₂ forcing more of the subsequently injected slugs to flood the lower permeability layer [21]. However, in the absence of crossflow due to the lack of communication between layers, any injectants delivered to the low permeability layer would be kept there and improve the sweep of the layer while if crossflow is permitted, fluids may initially flood this layer but then they would be diverted towards the high permeability zone as the preferential flow path. Therefore, higher oil recoveries may be expected in the case non-communicating layers (i.e. lack of crossflow).

![Graph](image.png)

**Figure 1.** Impact of crossflow on the ultimate oil recovery in layered core samples.

### Conclusions

Reservoir heterogeneity is a critical aspect of a hydrocarbon reservoir that affects the performance of a displacement in an underground system, thus hydrocarbon yield [12, 16, 22]. The results of this study initially demonstrate and quantify the negative effect of heterogeneity level (PR) of layered samples on oil recovery with higher PR resulting in lower ultimate RF. For example, increasing PR from 2.5 to 12.5 resulted in nearly 12.0% decrease in RF. This deterioration of RF is mainly attributed to the worsening effect of high permeability layer acting as a preferential flow channel for injectants as the PR increases which also brings the BT times forward. Our experimental study also enabled us to evaluate the effect of crossflow on RF. The results indicate that the occurrence of crossflow has a negative effect on RF. The elimination of crossflow having positive effects on RF is attributed to a better conformance control as well as the higher dominance of the viscous driving forces under such conditions.
References

4. Saeedi, A., Experimental study of multiphase flow in porous media during CO2 Geo-Sequestration