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# The Impact of Gas-Assisted Gravity Drainage on Operating Pressure in a Miscible $CO_2$ Flood

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## Abstract

We investigated the combined contributions of gravity drainage and miscibility as recovery mechanisms during $CO_2$ flooding. The effects of gravity stable and unstable $CO_2$ fronts under immiscible, near miscible and miscible displacements of crude oil by $CO_2$ are presented. We contrast our results in porous media, with slim tube experiments, core floods, and bead packed tubes.

Standard slim-tube, vertically and horizontally oriented bead packed tubes, as well as vertical and horizontal reservoir core flood experiments, were used to investigate the role of the gravitational forces in improving oil recovery under different conditions regarding the crude oil – $CO_2$ miscibility. Three crude oils with different minimum miscibility pressure (MMP) values were used in this study.

Our results show the gravity drainage mechanism has a much greater significance than previously thought when compared to the effects of phase behavior or the miscibility alone. Not surprisingly, vertically stable, downward displacement resulted in better performance compared to horizontal displacement in all cores and bead packed tubes in our experiments. Recovery is only slightly higher in the gravity stable floods when miscibility is achieved. However, in immiscible and near miscible displacements, recovery is significantly higher in the gravity stable floods, reaching up to 90% RF at 250 psi below the MMP value, compared to only 33% in horizontal floods. Our results suggest that achieving miscibility is not necessary to obtain high recovery efficiency during a gravity-stable displacement. Breakthrough is reached faster in horizontal floods as a consequence of fingering and gravity override.

This work challenges the paradigm that miscibility is required to achieve high recovery factors during $CO_2$ flooding, and highlights the overlooked role of gravity drainage as a displacement mechanism. This finding has an essential impact on field operations as it allows for lower operating pressures in $CO_2$ flooding processes under stable gravity displacement that will result in positive impact on economics. The relevance of our results is exacerbated by the current low crude oil price environment.

# Introduction

### Carbon Dioxide – Enhanced Oil Recovery ($CO_2$ – EOR)

For decades, carbon dioxide flooding has been a widely used enhanced oil recovery (EOR) technique. Field projects continue to show good incremental oil recovery in response to $CO_2$ injection and its use has consistently grown in recent years becoming the most used EOR method in the US (Koottungal 2012).

$CO_2$ injection is favored over other types of gas injections because it can significantly reduce oil viscosity, swells the oil due to its high solubility in hydrocarbons, and decreases override effects (Adel 2016). $CO_2$ also has a comparatively lower compression cost and a lower minimum miscibility pressure (MMP) compared to most other injection gas. The density of $CO_2$ is considerably closer to the average light oil density than most other solvents at reservoir conditions, making $CO_2$ less prone to gravity segregation compared to other gases at similar conditions. Another beneficial effect of $CO_2$ is the likelihood of higher gravity segregation in the high water saturation zones of the reservoir than in the higher oil saturation zones.

Moreover, $CO_2$ injection is also appealing from an environmental perspective. The injection of $CO_2$ into oil reservoirs has the additional benefit of reducing global warming effects through $CO_2$ sequestration and benefits from governmental tax benefits, favoring $CO_2$ over other injection gases (Tovar et al. 2014). The implementation $CO_2$ – EOR is categorized into three processes: Continuous Gas Injection, Water Alternating Gas, and Gas-Assisted Gravity Drainage.

***Continuous Gas Injection Process (CGI).*** Gas injection is used in the tertiary recovery stage to enhance production from waterflooded reservoirs using $CO_2$ to improve the microscopic sweep efficiency ($E_D$) through the swelling of oil, reduction of viscosity and decrease of interfacial tension (IFT) (Schechter et al. 1994). During the CGI process, the reservoir is flooded horizontally using vertical wells for both gas injection and oil production. However, due to the lower density of the $CO_2$ compared to oil and the effects of the gravity override, the $CO_2$ tends to rise to the top of the pay zone and contrast in permeability of sedimentary layers which results in fingering and poor volumetric sweep efficiency. Also, the low viscosity of the injected gas leads to an unfavorably high mobility ratio (M). High mobility ratios lead to poor sweep efficiencies, meaning that the injected gas contacts less reservoir oil. Hence, making flood profile control the most significant limitation for continuous horizontal gas floods.

***Water Alternating Gas Process (WAG).*** The Water Alternating Gas (WAG) process is another EOR method used in the tertiary recovery stage to enhance production (Zhang et al. 2018). Although $CO_2$ has a higher microscopic sweep efficiency ($E_D$) than water, the volumetric sweep efficiency ($E_V$) of water is greater than that of $CO_2$ in horizontal flooding operations. By alternating slugs of water and $CO_2$, the WAG process tends to homogenize the injected fluid front thereby increasing the exposure of $CO_2$ to a greater fraction of the reservoir resulting in significant improvement of oil recovery. However, as presented by Rao et al., a review of 59 fields WAG projects have only yielded to recovery improvements of 5 to 10%.

The problem with this approach is that oil recovery is affected by severe gravity segregation due to the natural affinity of the injected water to underride and the affinity of the injected gas to override as is presented in Fig. 1a. (Rao et al., 2004)

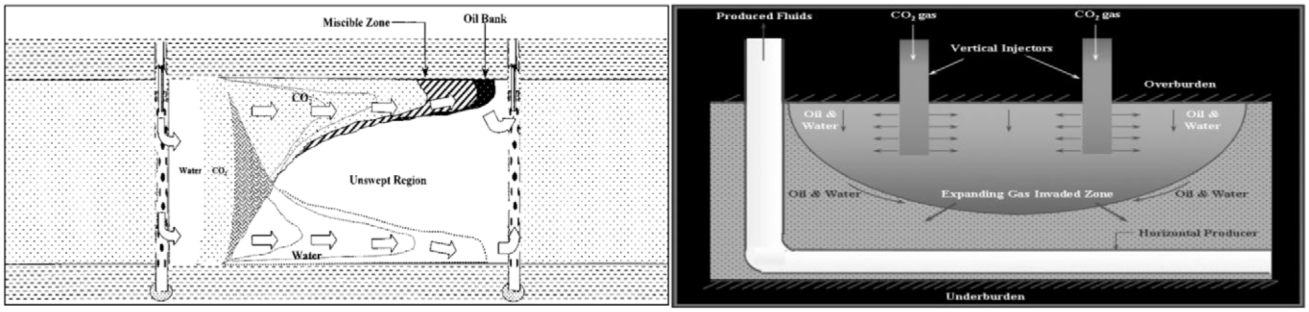


**Figure 1—(a – left) A more realistic schematic of the WAG process (b – right) Conceptual diagram of Gas-Assisted Gravity Drainage (Rao et al. 2004)**

***Gas-Assisted Gravity Drainage (GAGD).*** The gas-assisted gravity drainage EOR process overcomes the limitations faced by the conventional horizontal gas injection processes such as the continuous gas injection and the water alternating gas EOR methods.

The schematic concept of the gas-assisted gravity drainage process is presented in Fig. 1b. A horizontal producer well is drilled at the bottom of the pay zone, and the existing vertical wells are used for gas injection, providing steady gravity displacements and uniform reservoir sweep. As a result of gravity segregation, the injected $CO_2$ into the vertical wells accumulates at the top of the pay zone and displaces the reservoir oil downwards draining the horizontal producer that is spanning numerous injection wells. Gravity segregation also plays an essential role in postponing the $CO_2$ breakthrough to the producer.

The $CO_2$ invaded zone maximizes the volumetric sweep efficiency (Ev) as it starts growing in all directions, and begins to sweep larger and larger volumes of the reservoir.

## Objective

The purpose of this work is to investigate the relative contributions of gravity drainage in improving oil recovery under different conditions regarding crude oil – $CO_2$ miscibility. The effects of gravity stable and unstable $CO_2$ fronts under immiscible, near miscible and miscible displacements of crude oil by $CO_2$ are considered. We contrast our results in porous media, with slim tube experiments, core floods, and bead packed tubes. Vertically and horizontally oriented bead packed tubes, as well as vertical and horizontal reservoir core flood experiments.

## Description of Experimental Procedures and Equipment

Three crude oil samples from the Wellman Unit, the North Burbank Unit (NBU) and the Oklahoma/Texas Panhandle presented in Table 1 were selected for and used in this study. These fields, where $CO_2$ – EOR has been successfully implemented for over a decade, show great potential for the implementation of GAGD to optimize their performance (Schechter et al. 1998) as will be discussed in later sections.

**Table 1—Description of the crude oil samples used**

| | Crude Oil Samples | | |
|---|---|---|---|
| | Wellman Unit | North Burbank Unit | Oklahoma/Texas Panhandle |
| **API °** | 42 | 35 | 30 |
| **Reservoir Temp (°F)** | 150 | 122 | 152 |
| **MMP (psig)** | 1605 | 1373 | 1980 |

Standard slim-tube, vertically and horizontally oriented bead packed tubes, as well as vertical and horizontal reservoir core flood experiments, were used to investigate the role of gravity forces in improving oil recovery under different conditions regarding the crude oil – $CO_2$ miscibility.

**Minimum Miscibility Pressure Determination**

Minimum miscibility pressure (MMP) is one of the most crucial parameters in any gas injection project. The MMP is the lowest pressure at which the injected gas and the reservoir oil become miscible through a multi-contact process at the reservoir temperature (Elsharkawy et al. 1992).

The MMP can be determined using several methods that are categorized as experimental or computational. In the laboratory, the slim tube experiment, the rising bubble method, and the method of vanishing interfacial tension are the most common (Adel 2016). However, the vanishing interfacial tension and the rising bubble methods do not entirely address the multi-contact mechanisms (Teklu et al. 2012). Therefore, the slim tube method is considered as the most accurate way to determine the MMP. It simulates the 1-D displacement of the reservoir crude oil by the injected $CO_2$ through a porous medium and fully accounting for the thermodynamic phenomenon, the effect of displacement efficiency and phase behavior taking place in the $CO_2$ – oil system inside a sand packed stainless steel coil. This method, being one dimensional, avoids the unfavorable conditions such as gravity override, unfavorable viscosity ratios and fingering, making this method the most accurate way to determine the MMP.

Generally speaking, the slim tube experiment procedure consists of injecting $CO_2$ to contact and displace the reservoir crude oil that saturates a grain packed coil at stabilized conditions of pressure and temperature that resemble those in the reservoir. Elsharkawy *et al*. (1992) defined the MMP value as the intersection between the two lines defined by the recovery factor as a function of pressure, both under miscible and immiscible conditions (Adel 2016). All recovery factors are measured at 1.2 PV of injected gas. To standardize the slim tube experiments, long coil lengths and low injection rates have been recommended in literature to avoid composition variations, effects of fingering and to ensure a stable thermodynamic front (Elsharkawy *et al*., 1992).

Fig. 2 represents the schematic of the experimental apparatus. An 80 ft slim tube coil was used for the minimum miscibility pressure determination experiments. The coil is made of stainless steel with an inside diameter of 0.25 in, a thickness of 0.063 in, and is packed with 100 – 150 mesh Ottawa sand.

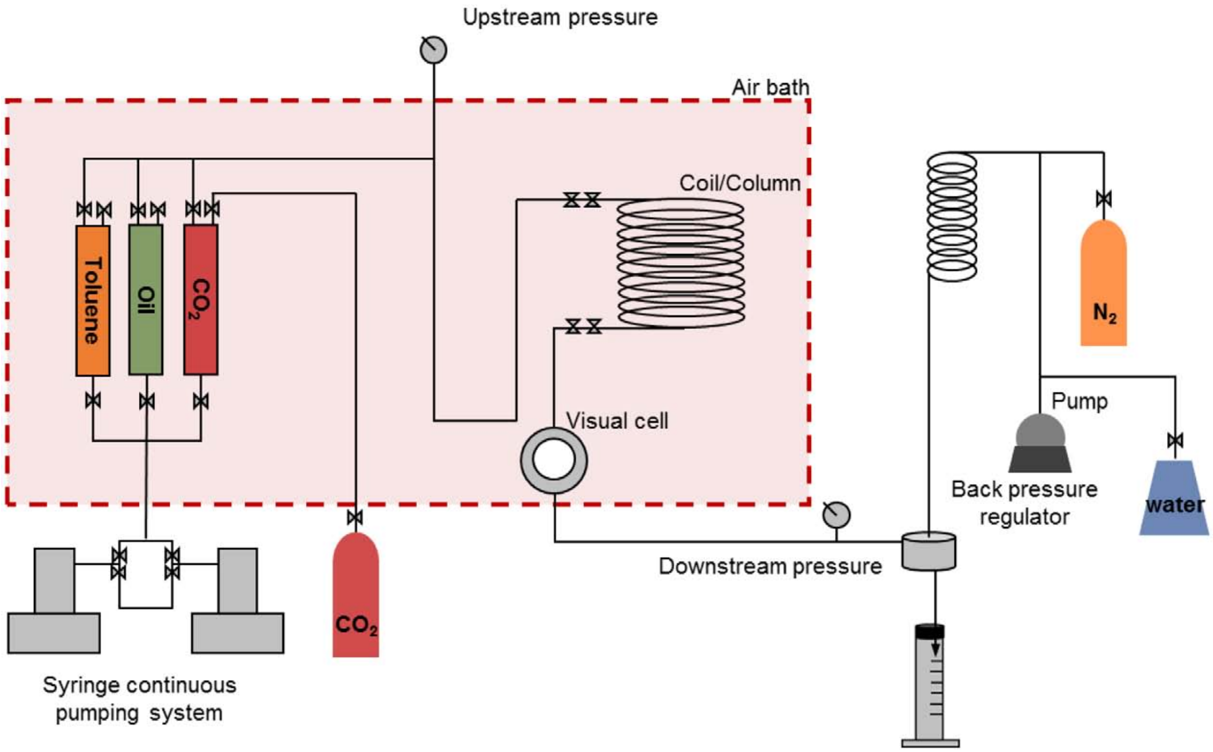


**Figure 2—Schematic of the core flooding experiments used for the Gas-Assisted Gravity Drainage**

To guarantee the porous media is clean and dry before each run, 2 pore volumes (PV) of toluene are injected at a rate of 0.2 $cm^3$/min followed by 2 PV of supercritical $CO_2$ at a rate of 0.06 $cm^3$/min. After the stabilization of pressure and temperature, 2 PV of the dead crude oil are injected at a rate of 0.2 $cm^3$/min to guarantee the system is fully saturated. Following this, 1.2 PV of $CO_2$ is pumped at a rate of 0.06 $cm^3$/min to displace the oil.

The effluents are measured along the duration of the experiment to calculate the recovery factor at each pressure. The resulting recovery factors are plotted as a function of the pressure, and two regions are identified. The immiscible region, where the recovery factor is a strong function of pressure, and the miscible region, where the recovery factor is a weak function of pressure. The MMP of each sample was determined by fitting a straight line through each group of data points representing either the miscible or the immiscible region and solving for the interception point of the two trend lines.

## Bead Packed Tube-flooding Experiments

A large diameter tubing packed with 100 mesh glass beads with a porosity value of 35% and a permeability value of 1.2 Darcy was used to perform five total experiments. After evacuating the tubing, brine was injected into the porous media to saturate it fully. The PV and porosity values were calculated by measuring the brine volume that was taken into the tubing.

Brine was then displaced by injecting 1.5 PV of crude oil at a reservoir equivalent rate of 1ft/D leaving behind 25% irreducible water saturation ($S_{w\,irr}$). In the following experiments, only the Wellman Unit crude oil sample was used, which has an MMP value of 1605 psig.

Three testing pressure values were selected for the displacements of crude oil by $CO_2$ under immiscible, near miscible and miscible conditions. Three gravity stable experiments were performed by injecting $CO_2$ into the top of the vertically oriented tubing at pressures of 1400, 1550 and 1800 psig.

Two additional experiments at a pressure of 1400 psig were performed. One experiment was done gravity unstable by percolating $CO_2$ from the bottom to the top of the vertically oriented tubing, and the last experiment was done by orienting the bead packed tube in a horizontal position to examine the effect of both the flow direction and orientation.

## Core-flooding Experiments

Vertical and horizontal reservoir core flood experiments were used to investigate the role of the gravitational forces in improving oil recovery under different conditions regarding the crude oil – $CO_2$ miscibility. Heterogeneous Berea sandstone core samples with a diameter of 1 in and a length of 6 in were used during the coreflooding experiments. The North Burbank Unit and the Oklahoma/Texas Panhandle crude oil samples were used. For each crude oil sample, three gravity stable (vertical) and three horizontal corefloods were performed at the same operating pressures for the displacements of crude oil by $CO_2$ under immiscible, near miscible and miscible conditions. The different combinations of crude oil samples, core plug orientations, and pressure conditions resulted in the performance of a total 12 coreflooding experiments that are presented in Table 2.

**Table 2—Summary of all core flooding experiments performed**

| | Crude Oil Sample | MMP (psig) | Core Orientation | Miscibility Status | Operating Pressure (psig) |
|---|---|---|---|---|---|
| Core flooding Experiments | North Burbank Unit | 1373 | Horizontal | Immiscible displacement | 1100 |
| | | | | Near miscible displacement | 1300 |
| | | | | Miscible displacement | 1600 |
| | | | Vertical | Immiscible displacement | 1100 |
| | | | | Near miscible displacement | 1300 |
| | | | | Miscible displacement | 1600 |
| | Oklahoma/Texas Panhandle | 1980 | Horizontal | Immiscible displacement | 1700 |
| | | | | Near miscible displacement | 1900 |
| | | | | Miscible displacement | 2200 |
| | | | Vertical | Immiscible displacement | 1700 |
| | | | | Near miscible displacement | 1900 |
| | | | | Miscible displacement | 2200 |

First, the core is packed into a core holder, and a confining pressure of 500 psig is applied. The core holder is then submitted to vacuum conditions for one hour, and synthetic brine is allowed to flow into the core to fully saturate it ($S_w$ = 100%). The PV and porosity values can now be calculated by measuring the volume of the brine that is taken into the core. The porosities of the 12 core plugs used range from 20 to 23%. The permeability values, which ranged from 300 to 400 md, were provided by the vendor of the core plugs.

Fig. 3 represents the schematic of the experimental setup and apparatus used for the gravity stable (GAGD) corefloods. The horizontal corefloods are also performed using the same apparatus, and the same setup, except for the orientation of the core holder which is horizontal.

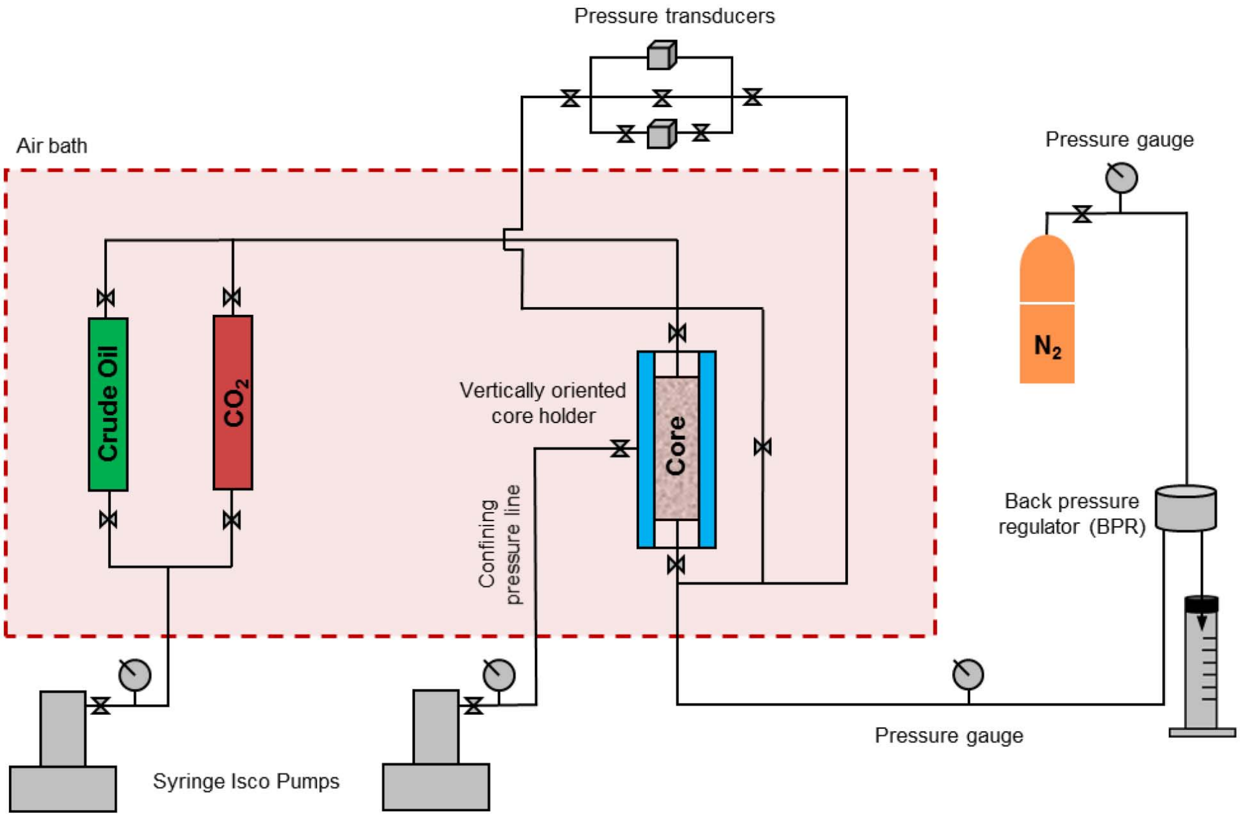


**Figure 3—Schematic of the core flooding experiments used for the Gas-Assisted Gravity Drainage**

After the core holder is mounted in the core holder, the air bath temperature is set to the corresponding crude oil's reservoir temperature (122 or 155 °F) which is allowed at least 10 hours to stabilize. The back pressure is set to the desired operating pressure, and the irreducible water saturation ($S_{w\ irr}$) is then established by injecting 1.5 PV of crude oil at a rate of 1ft/D to displace the synthetic brine. Finally, 1.4 PV of $CO_2$ is injected, and the effluents are measured along the duration of the experiment to calculate the recovery factor (%OOIP).

## Results and Discussions

### Minimum Miscibility Pressure Determination

The MMP values of the $CO_2$ – crude oil systems from the Wellman Unit, the North Burbank Unit, and the Oklahoma/Texas Panhandle were determined using an 80-ft slim tube. The results of the slim tube experiments for the minimum miscibility pressure determination for each of the three crude oil samples used are presented in Table 3 and Figs. 4, 5 & 6.

**Table 3—Summary of test pressures and oil recoveries for the determination of MMP of each $CO_2$ – crude oil system**

| | Wellman Unit | | North Burbank Unit | |
|---|---|---|---|---|
| **Miscibility Status** | **Test Pressure (psig)** | **Oil Recovery (% of OOIP)** | **Test Pressure (psig)** | **Oil recovery (% of OOIP)** |
| Miscible | 3500 | 92.7 | 3500 | 95.0 |
| | 2800 | 89.5 | 2500 | 92.0 |
| | 2200 | 86.6 | 1800 | 89.9 |
| Immiscible | 1000 | 51.0 | 1000 | 66.3 |
| | 750 | 36.4 | 750 | 51.3 |
| | 500 | 23.6 | 500 | 36.3 |

| | Oklahoma/Texas Panhandle | |
|---|---|---|
| **Miscibility Status** | **Test Pressure (psig)** | **Oil Recovery (% of OOIP)** |
| Miscible | 4500 | 91.3 |
| | 3500 | 89.23 |
| | 2500 | 87.24 |
| Immiscible | 1600 | 50.18 |
| | 1400 | 34.9 |
| | 1200 | 19.62 |

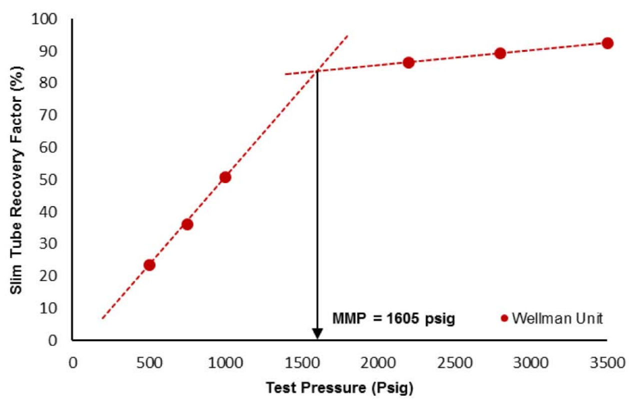


**Figure 4—Recovery vs. pressure in the slim tube for the Wellman oil**

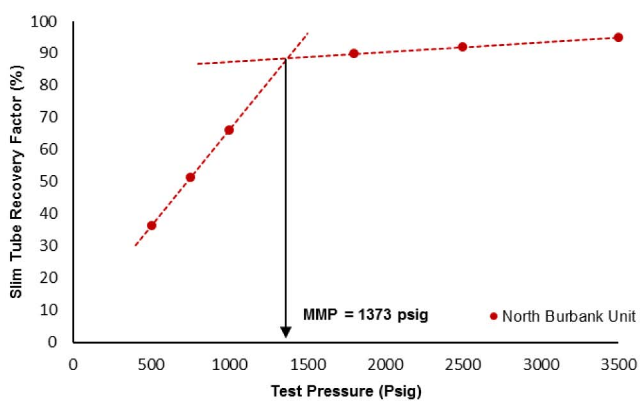


**Figure 5—Recovery vs. pressure in the slim tube for the NBU oil**

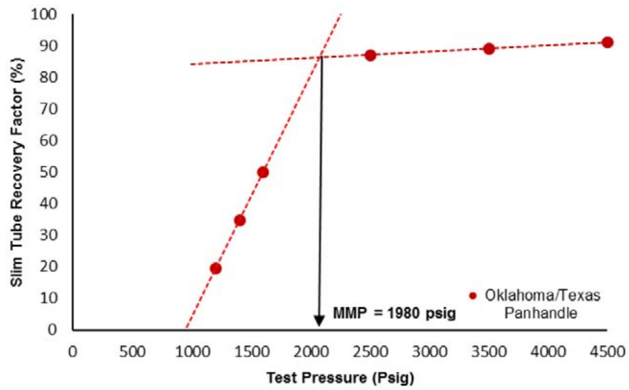


**Figure 6—Recovery vs. pressure in the slim tube for the Oklahoma/Texas Panhandle oil**

The recoveries measured at the lower pressure data points show a strong dependency on pressure, which indicates that miscibility has not yet been reached. On the contrary, at the higher pressure data points, the recovery factors are not strongly affected by the increase of pressure, indicating that miscible behavior has been reached.

A straight line is fitted through each group of data points representing either the miscible or the immiscible region. The MMP is determined by solving the intersection of the two linear trend lines.

Performing three measurements both above and below the MMP enables an immediate quality assessment of the consistency of all runs and guarantees that the data points are inside the linear trends and not in the transition (Adel et al. 2016).

## Bead Packed Tube-flooding Results

This section presents bead packed tube $CO_2$ experiments that were used to evaluate the individual role and contribution of miscibility as well as gravity drainage as displacement mechanisms.

***Miscibility Impact in Gravity Stable $CO_2$ Floods.*** Three experiments were performed at stable gravity by injecting $CO_2$ into the top of the vertically oriented tubing saturated with Wellman Unit crude oil that has a minimum miscibility value of 1605 psi. The experiments were performed at immiscible, near miscible and miscible displacements pressures of 1400, 1550 and 1800 psig and a reservoir temperature of 151 °F. The results of these experiments are summarized in Fig. 7 and Table 4.

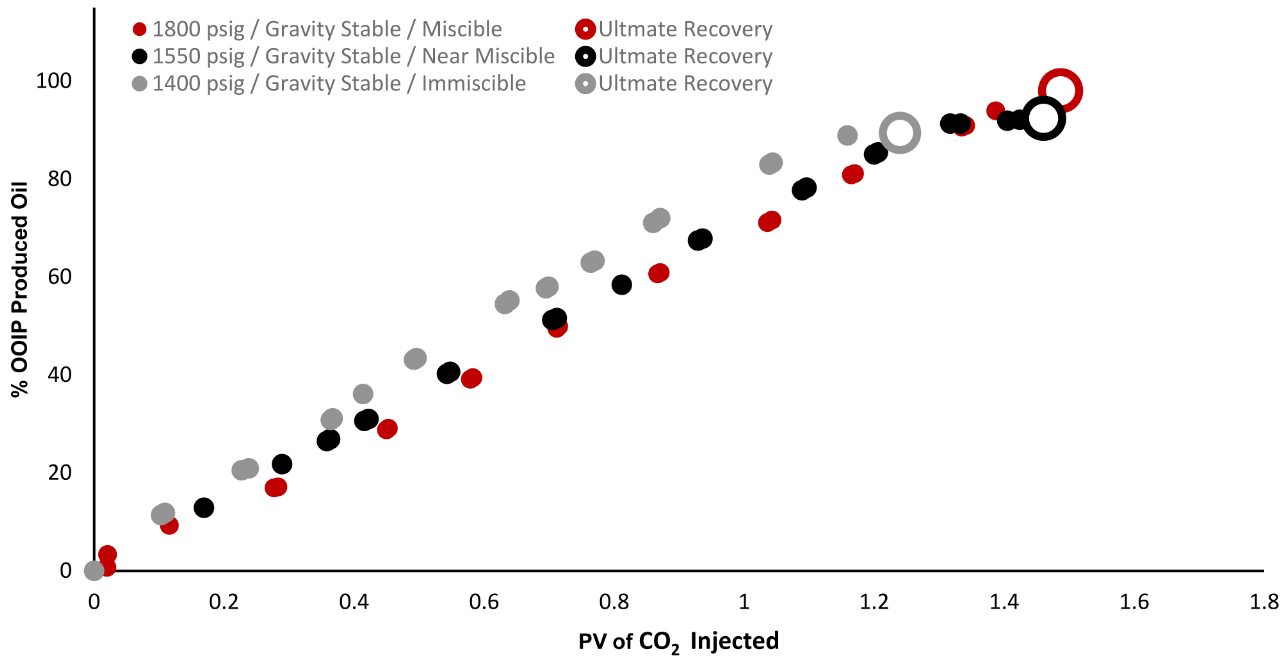


**Figure 7—Recovery curves for gravity stables tube tests at different miscibility conditions**

**Table 4—Summary of test pressures and oil recoveries for the determination of MMP of each $CO_2$ – crude oil system**

| Test Pressure (psig) | Miscibility Status | $CO_2$ Flow | PV of $CO_2$ Injected at EUR | % OOIP produced oil at EUR |
|---|---|---|---|---|
| 1800 | Miscible | Gravity Stable | 1.487 | 98.0 |
| 1550 | Near Miscible | Gravity Stable | 1.476 | 92.4 |
| 1400 | Immiscible | Gravity Stable | 1.240 | 89.4 |

The stable gravity $CO_2$ injection into the bead packed tubing resulted in excellent recovery under all miscibility conditions, with an 89% recovery factor (RF) below the MMP and a 98% RF above MMP as Fig. 7 demonstrates.

The reduction in pressure of 200 psig below the MMP did not have a significant effect on the recovery factors for gravity stable flood. Our results suggest that achieving miscibility is not necessary to obtain high recovery efficiency when a gravity-stable displacement is in place.

***Evaluation of Gravity Forces under Immiscible $CO_2$ Displacements.*** Two additional experiments at an immiscible pressure of 1400 psig were performed. One experiment was done with unstable gravity by flowing $CO_2$ from the bottom to the top of the vertically oriented tubing, and the last experiment was done by orienting the bead packed tube in a horizontal position to examine the effects of the direction and orientation of the $CO_2$ injection. The results of these experiments are summarized in Fig. 8 and Table 5.

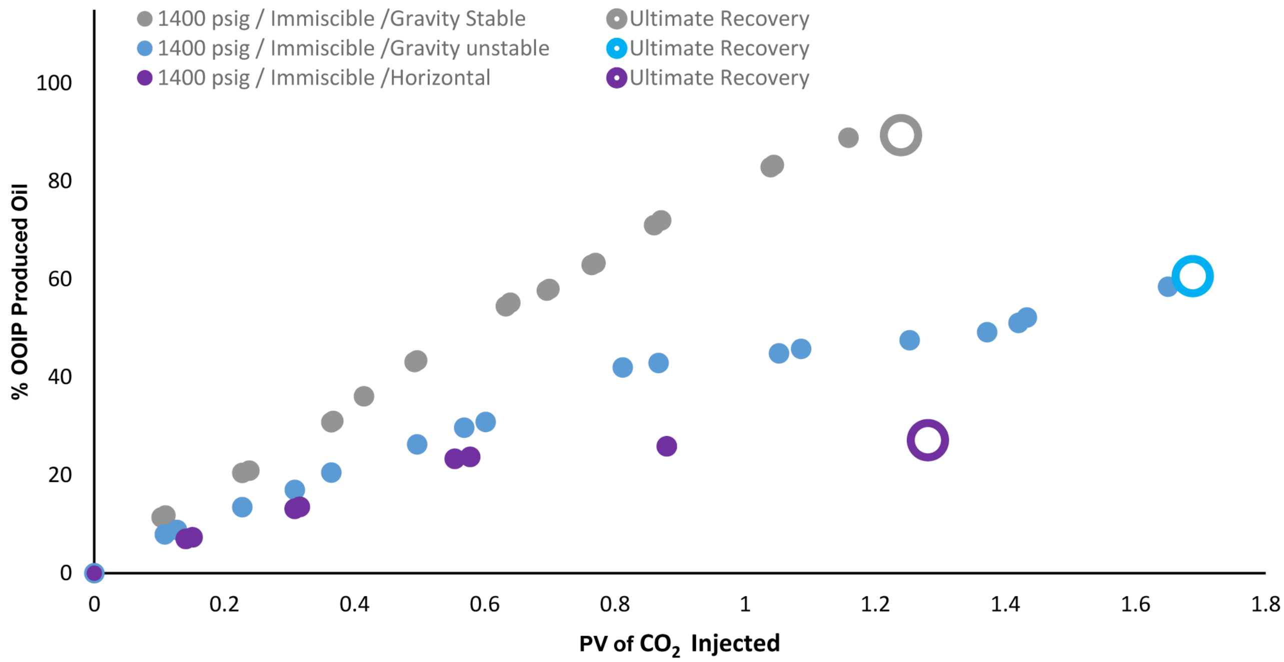


**Figure 8—Recovery curves for immiscible $CO_2$ tube floods at different orientations**

**Table 5—Summary of test pressures and oil recoveries for the determination of MMP of each $CO_2$ – crude oil system**

| Test Pressure (psig) | Miscibility Status | $CO_2$ Flow | PV of $CO_2$ Injected at EUR | % OOIP produced oil at EUR |
|---|---|---|---|---|
| 1400 | Immiscible | Gravity Stable | 1.240 | 89.4 |
| 1400 | Immiscible | Gravity Unstable | 1.688 | 60.6 |
| 1400 | Immiscible | Horizontal | 1.281 | 27.1 |

Under immiscible conditions, the stable gravity $CO_2$ injection into the bead packed tubing resulted in the best EUL recovery of 89 %. Unstable gravity injection resulted in an EUL of 60.6%, and the hospital injection performed the least with an EUL of only 27.1% as shown in Table 5. Breakthrough is reached faster in the horizontal flood as a consequence of fingering and gravity override.

Immiscible gas injection is usually unfavorable due to several mechanisms such as capillary forces from interfacial forces between immiscible fluids, viscous forces caused by adverse mobility ratios, and gravity segregation caused by the natural affinity of the injected gas to override due to density differences. By changing the orientation and direction of $CO_2$ injection, we see the impact of gravity forces improving oil recovery, especially below the MMP.

## Core-flooding Experiments

The results of the12 coreflooding experiments using different combinations of crude oil samples, core plug orientations, and pressure conditions are presented in Table 6, Fig. 9 and Fig 10.

Table 6—Summary of test pressures and oil recoveries for the core flooding experiments

| Core Orientation | North Burbank Unit Test Pressure (psig) | North Burbank Unit Oil Recovery (% of OOIP) | Oklahoma/Texas Panhandle Test Pressure (psig) | Oklahoma/Texas Panhandle Oil recovery (% of OOIP) |
|---|---|---|---|---|
| Horizontal | 1100 | 33.5 | 1700 | 29.8 |
| | 1300 | 62.5 | 1900 | 50.4 |
| | 1600 | 92.2 | 2200 | 87.6 |
| Vertical | 1100 | 90.4 | 1700 | 89.5 |
| | 1300 | 94.6 | 1900 | 91.3 |
| | 1600 | 97.1 | 2200 | 94.2 |

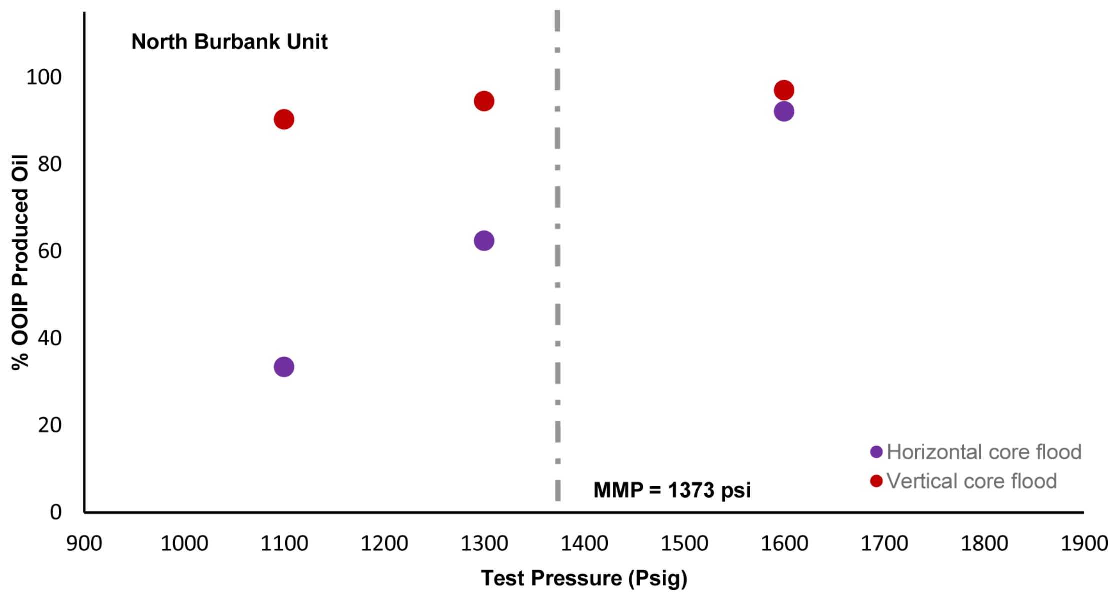


Figure 9—$CO_2$ core flood results for the NBU oil under immiscible, near miscible and miscible displacements

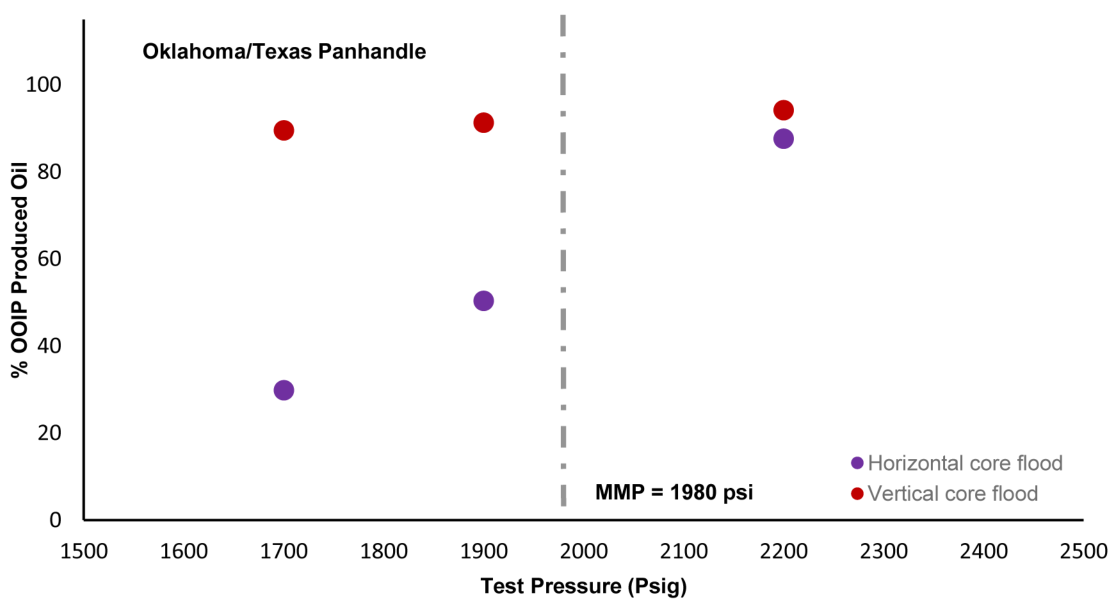


Figure 10—$CO_2$ core flood results for the Oklahoma/Texas Panhandle oil under immiscible, near miscible and miscible displacements

Recovery is only slightly higher in the gravity stable floods when miscibility is achieved. However, in immiscible and near miscible displacements, recovery is significantly higher in the gravity stable floods, reaching up to 90.4% and 89.5% RF at 250 psi below the MMP value, compared to only 33.5% and 29.8% RF in horizontal floods. Breakthrough is reached faster in horizontal floods as a consequence of fingering, and gravity override, bypassing the oil through that $CO_2$ created flow channel and leaving most of the oil untouched.

Figs. 9 and 10 compare the recovery-pressure relationship in the stable gravity environment and the horizontal $CO_2$ core floods at immiscible, near miscible, and miscible conditions. For gravity stable floods, the reduction in pressure to below MMP did not have a significant effect on recovery. Our results suggest that achieving miscibility is not necessary to obtain high recovery efficiency when a gravity-stable displacement is in place.

## Conclusions

1. Breakthrough is reached faster in the horizontal floods compared to the gravity stable floods as a consequence of fingering and gravity override.
2. Gravity drainage has a significant impact on improving oil recovery, especially below the MMP.
3. The reduction in pressure of 200 psig below the MMP did not have a significant effect on the recovery factors in the laboratory $CO_2$ assisted gravity drainage coreflooding.
4. Our results suggest that achieving miscibility is not necessary to obtain high recovery efficiency when a gravity-stable displacement is in place.
5. This work challenges the paradigm that miscibility is required to achieve high recovery factors during $CO_2$ assisted gravity drainage flooding, and highlights the overlooked role of gravity drainage as a displacement mechanism.
6. This finding has an essential impact on field operations as it allows for lower operating pressures in $CO_2$ flooding processes under stable gravity displacement that will result in positive impact on economics.

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## Nomenclature

| | |
|---|---|
| EOR | Enhanced oil recovery |
| CCI | Continuous gas injection |
| $CO_2$ | Carbon dioxide |
| $E_D$ | Microscopic displacement efficiency |
| $E_V$ | Volumetric sweep efficiency |
| EOR | Enhanced oil recovery |
| EUR | Estimated ultimate recovery |
| GAGD | Gas assisted gravity drainage |
| IFT | Interfacial tension |
| M | Mobility ratio |
| MMP | Minimum miscibility pressure, psig |
| NBU | North Burbank Unit |

OOIP Oil originally in place
PV Pore volumes
RF Recovery factor
$S_w$ Water saturation
$S_{w\ irr}$ Irreducible water saturation
WAG Water alternating gas

## References


Adel, I.A. 2016. A Reliable and Rapid Technique for the Laboratory Determination of the Minimum Miscibility Pressure for CO2–Light Crude Oil Systems Using the Slim Tube Method. MS Thesis, Texas A&M University.

Adel, I.A., Tovar, F.D., and Schechter, D.S. 2016. Fast-Slim Tube: A Reliable and Rapid Technique for the Laboratory Determination of Mmp in CO2 - Light Crude Oil Systems. Paper presented at the SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, USA. Society of Petroleum Engineers. DOI: 10.2118/179673-MS.

Elsharkawy, A.M., Poettmann, F.H., and Christiansen, R.L. 1992. Measuring Minimum Miscibility Pressure: Slim-Tube or Rising-Bubble Method? Paper presented at the SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, USA. Society of Petroleum Engineers. DOI: 10.2118/24114-MS.

Koottungal, L. 2012. Miscible CO2 Now Eclipses Steam in Us Eor Production. *Oil and Gas Journal* **110** (4).

Rao, D., Ayirala, S., Kulkarni, M. et al. 2004. Development of Gas Assisted Gravity Drainage (GAGD) Process for Improved Light Oil Recovery. *In SPE/DOE Symposium on Improved Oil Recovery*. Tulsa, Oklahoma, USA: Society of Petroleum Engineers. ISBN 1555639887.

Schechter, D., Zhou, D., and OrrF. Jr, 1994. Low Ift Drainage and Imbibition. *Journal of Petroleum Science and Engineering* **11** (4): 283–300.

Schechter, D.S., Grigg, R., Guo, B. et al. 1998. Wellman Unit CO2 Flood: Reservoir Pressure Reduction and Flooding the Water/Oil. In SPE Annual Technical Conference and Exhibition: Society of Petroleum Engineers. ISBN 1555631568.

Teklu, T.W., Ghedan, S.G., Graves, R.M. et al. 2012. Minimum Miscibility Pressure Determination: Modified Multiple Mixing Cell Method. Paper presented at the SPE EOR Conference at Oil and Gas West Asia, Muscat, Oman. Society of Petroleum Engineers. DOI: 10.2118/155454-MS.

Tovar, F.D., Eide, O., Graue, A. et al. 2014. Experimental Investigation of Enhanced Recovery in Unconventional Liquid Reservoirs Using CO2: A Look Ahead to the Future of Unconventional Eor. Paper presented at the SPE Unconventional Resources Conference, The Woodlands, Texas. Society of Petroleum Engineers. DOI: 10.2118/169022-MS.

Zhang, F., Saputra, I.W.R., Niu, G. et al. 2018. Upscaling Laboratory Result of Surfactant-Assisted Spontaneous Imbibition to the Field Scale through Scaling Group Analysis, Numerical Simulation, and Discrete Fracture Network Model Paper presented at the SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, USA. Society of Petroleum Engineers. DOI: 10.2118/179673-MS.