CO₂ Geological Storage Coupled with Water Alternating Gas for Enhanced Oil Recovery

Hutthapong Yoosook, Kreangkrai Maneeintr*

Carbon Capture, Storage and Utilisation Research Laboratory, Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330 Thailand
krengkrai.M@chula.ac.th

Due to the climate change and global warming, the concern about CO₂ emission into the atmosphere has been raised in many industries such as oil and gas business. The sources of CO₂ include natural gas processing and other processes. The current technology to mitigate CO₂ is carbon capture, storage and utilisation. At the same time, oil production is expected to increase due to the higher consumption. CO₂ geological storage in depleting oilfield coupled with enhanced oil recovery can be a better technology to meet both requirements. The excellent example of this technology is the Weyburn Project in Canada that can store CO₂ and produce more oil as well as prolong the reservoir life. From this successful project, the technology is studied by applying it with the depleting oilfield for both oil production and CO₂ storage in the North of Thailand by using simulation model. It becomes the objective of this research, which is to evaluate CO₂ geological storage coupled with water alternating gas (WAG) for enhanced oil recovery as well as to study the effects the parameters, such as total hydrocarbon pore volume (HCPV) injection and WAG ratio, on oil production and CO₂ consumption and sequestration for enhanced oil recovery, with the added benefit of carbon sequestration. CMG software from Computer Modeling Group Ltd. is used to create the 3D simulation model to predict the CO₂ storage in the geological formation. From the simulation, the results reported that oil can be produced up to 125,976 m³ of oil or 57% recovery, CO₂ consumption is 66,261 m³ of gas and CO₂ utilisation is approximately 0.53 m³ of gas per m³ of oil. The main parameters for WAG process is WAG ratio in that oil production increases as WAG ratio increases. CO₂ consumption increases with total HCPV injection. The results of this study can be applied to develop the CO₂ enhanced oil recovery (EOR) in the depleting oilfield in the North of Thailand for both oil production and CO₂ storage.

1. Introduction

In recent years, many industries have been highly concerned about the reduction in Greenhouse Gases emission, especially carbon dioxide (CO₂) due to the threat of climate change (Gallo et al., 2002). One of the most effective method to reduce CO₂ emission is Carbon Capture and Storage (CCS), which is the capturing and injecting of CO₂ to underground storage in depleted oil reservoirs (Metz et al., 2005). CO₂ has the capability to enhance oil recovery with a recovery potential of an additional 15 - 20 % of the original oil in place after primary and secondary recovery due to its miscibility mechanism (Global Energy Institute, 2012). The additional extraction of oil will provide more space available for CO₂ storage in long term. The use of CO₂ for enhanced oil recovery (EOR) resulted in exceeding benefits to improve oil production with the extending of project’s life. It helps to minimise the environmental impact by reducing CO₂ emission in atmosphere and storing it in an underground depleted reservoir (Mathias et al., 2009).

Water alternating gas (WAG) processes is one of the various techniques to enhance oil recovery by injecting CO₂ alternated with water. This technique is related to the injection of a CO₂ slug into oil reservoir, followed by a slug of water that serves as the chasing fluid that help maintain reservoir pressure, displace the injected CO₂ and crude oil, adjust flood front to be more stable, reduce mobility of CO₂, and increase injectivity (Donaldson et al., 1989). This cycle is repeated as operational design. The WAG process fundamentally consists two mechanisms, including the injected CO₂ reacts with crude oil thereby reducing the oil viscosity consequently making the oil can flow easily due to miscible and immiscible effects. The second mechanism is where the
alternating water injection can maintain reservoir pressure and help to reduce the amount of CO\textsubscript{2} consumption (Ghahfarokhi et al., 2016). The objective of this research is to evaluate CO\textsubscript{2} geological storage coupled with WAG for EOR and to study the effects the parameters, such as total hydrocarbon pore volume (HCPV) injection and WAG ratio, on oil production and CO\textsubscript{2} consumption and storage.

2. Simulation

In this study, GEM (2011) software by Computer Modelling Group Ltd. is used as a tool to construct the 3D reservoir model and to evaluate the performance of WAG technique in various scenarios. The homogeneous reservoir model is created based on a reservoir segment in Fang oil field, Thailand. This model consists of two layers of shale formation above and below reservoir to ensure that the injected CO\textsubscript{2} will not leak from the sandstone formation while injecting CO\textsubscript{2} at high pressure. Total area of this model is 145,161 m\textsuperscript{2} with total thickness of 27.4 m which include 9.1 m of above and below shale formation, and 9.1 m of sandstone formation. The pattern of production well and injection well in this model is quarter five-spot pattern that comprises one injection well and one production well at the opposite corner of model and the well spacing is 538.9 m. The dimensions of model together with location of two wells are displayed in Figure 1. The reservoir properties of this models are summarised in Table 1. There are 29 components in this reservoir and the API gravity of the reservoir fluid is about 31° API.

![Figure 1: Dimensions of reservoir model with location of two wells](image)

**Table 1: Reservoir properties using for created reservoir model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Dimension</td>
<td>25 x 25 x 6</td>
<td>block</td>
</tr>
<tr>
<td>Reservoir Size</td>
<td>381 x 381 x 9.14</td>
<td>m</td>
</tr>
<tr>
<td>Top of Reservoir</td>
<td>1,347.2</td>
<td>m</td>
</tr>
<tr>
<td>Reservoir Thickness</td>
<td>9.14</td>
<td>m</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.25</td>
<td>fraction</td>
</tr>
<tr>
<td>Horizontal Permeability</td>
<td>150</td>
<td>mD</td>
</tr>
<tr>
<td>Vertical Permeability</td>
<td>15</td>
<td>mD</td>
</tr>
<tr>
<td>Reservoir Pressure</td>
<td>4.69</td>
<td>MPa</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>62.2</td>
<td>°C</td>
</tr>
</tbody>
</table>

3. Results

3.1 Effect of WAG HCPV injection

The effect of HCPV injection on the performance of CO\textsubscript{2} WAG is investigated by performing five runs of 0.10, 0.15, 0.20, 0.25, and 0.30 HCPV within ten years of production. The relationship between oil recovery factor and producing time for all cases is shown in Figure 2. The results indicated that higher oil recovery factor can be obtained by injecting with higher HCPV injection due to CO\textsubscript{2} EOR mechanisms. However, the injection of higher HCPV required more amount of CO\textsubscript{2}. Higher HCPV injection provide more oil recovery factor with additional amount of CO\textsubscript{2} storage into the reservoir.
3.2 Effect of WAG ratio

The effect of WAG ratio on oil recovery factor is also investigated by conducted 5 runs as following: WAG 1 : 1, 1 : 2, 2 : 1, 3 : 1, and continuous CO₂ flooding. Results of these runs is presented in Figure 3 that the highest oil recovery factor of 45 % is obtained by using WAG 2 : 1 or 3 : 1. Continuous CO₂ flooding shows poor performance (18 % oil recovery factor) which in line with the conclusion of previously research (Zekri et al., 2011). The poor performance of continuous CO₂ flooding could be described to the low volumetric sweep efficiency as a result of unfavorable mobility ratio that cause of early breakthrough and viscous fingering. Theoretically, increasing of WAG ratio is able to improve the performance of WAG method due to the volumetric sweep efficiency improvement (Attanucci et al., 1993). However, increasing of WAG ratio to be higher than 3 : 1 would not rise the oil recovery factor because of the limitation of formation fracture pressure.
3.3 Effect of number of cycle and WAG cycle time

Number of WAG cycle can affect the oil recovery factor in CO2 WAG process. The most favourable WAG cycle is one cycle, that is shown in Figure 4. The highest oil recovery factor occurs in the minimum WAG cycle case because the largest amount of CO2 and water are injected into the reservoir in only one cycle, allowing the pressure in the reservoir to be above the minimum miscibility pressure (MMP) and miscibility effects would occur. The addition of more WAG cycle provides lower oil recovery factor due to the same amount of CO2 and water are separately injected into the reservoir, which is insufficient to maintain the reservoir pressure to be higher than MMP. The shorter WAG cycle time provides the highest oil recovery factor due to the effect of the number of cycle that is already mentioned. The effect of WAG cycle time on oil recovery factor is presented in Figure 5. The highest oil recovery is obtained when slugs of CO2 and water are injected in the shortest time with the lowest number of cycle due to the greatest reservoir pressure as compared to other scenarios.

Figure 4: The effect of number of cycle on oil recover factor

Figure 5: The effect of WAG cycle time on oil recover factor
3.4 Sensitivity Analysis

The sensitivity study is performed as a series of simulation to investigate the impacts of these operating parameters on CO₂ WAG method in ten years. The comparison of these parameters is presented in Figure 6, based on the incremental oil recovery factor. As shown, the most important parameter is WAG ratio, followed by number of cycle, WAG cycle time, and total HCPV injection. The range for the incremental oil recovery factor at ten years of production is 28.5% to 45% of original oil in place (OOIP).

![Figure 6: Sensitivity analysis of oil recovery factor in WAG process](image)

3.5 Comparison to Primary Recovery

From the simulation, the results reported that the oil can be produced was 125,976 m³ of oil or 57% recovery with CO₂ WAG technique, comparing to the primary production with merely 2.92% of OOIP. CO₂ WAG technique would obviously be the effective process to achieve the incremental oil production up to 54.08% of OOIP above primary production. CO₂ consumption of CO₂ WAG technique is 66,261 m³ of gas that entire injected CO₂ is stored in reservoir by replacing of residual oil. The CO₂ utilisation of this method is 0.53 m³ of gas per m³ of oil. Finally, the comparing results of CO₂ WAG process and primary production is presented in Figure 7 and Table 2.

![Figure 7: Comparison of oil recovery factor between CO₂ WAG and primary production](image)
Table 2: The comparison between CO₂ WAG method and primary production

<table>
<thead>
<tr>
<th>Method</th>
<th>Recovery Factor (%)</th>
<th>Cumulative Oil Production (m³ of oil)</th>
<th>Cumulative CO₂ Injection (m³ of gas)</th>
<th>CO₂ Storage (m³ of gas)</th>
<th>CO₂ Utilisation (m³ of gas per m³ of oil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ WAG</td>
<td>57.00</td>
<td>125,976</td>
<td>66,261</td>
<td>66,261</td>
<td>0.53</td>
</tr>
<tr>
<td>Primary Production</td>
<td>2.92</td>
<td>6,458</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4. Conclusions

Alternating slugs of CO₂ and water contain the capability to enhance oil recovery due to oil viscosity reduction, reservoir pressure maintenance, sweep efficiency improvement, trapped-gas effect, and crude displacement by CO₂ and water. The increasing of WAG ratio is able to develop the WAG performance by the injected slugs of water, which can improve the volumetric sweep efficiency. However, the injection of CO₂ without alternating of water provides poor EOR performance due to low volumetric sweep efficiency that can be caused by the early breakthrough, viscous fingering, and gravity overriding effect.

In term of sensitivity analysis, WAG ratio and HCPV injection should be highly concerned in WAG design because these parameters can have direct effect to the oil recovery factor and CO₂ consumption. The smallest number of WAG cycle together with the shortest WAG cycle time should be selected for effective design because they will provide the highest reservoir pressure that can maintain miscible mechanism. The CO₂ WAG process should be stopped at the time when the first CO₂ is produced because the CO₂ flood front is initially reaching the production well and almost the whole CO₂ is stored into the reservoir.

Acknowledgments

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Reference


Global Energy Institute, 2012, CO₂ enhanced oil recovery, Global Energy Institute, Washington, DC, USA.

