A Laboratory Study of Hot Carbon Dioxide Injection into Fractured and Conventional Cores

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Abstract:
CO₂ injection into oil reservoirs has been widely accepted as an effective technique for enhanced oil recovery. This study deals with a new Carbon Dioxide (CO₂) EOR technique, “HOT CO₂” injection in conventional and fractured cores which includes combination of thermal and drive mechanisms. Laboratory tests were conducted on conventional and fractured cores. Permeability and porosity of conventional and fractured cores were measured. CO₂ gas with low and constant rate was injected into the cores and injection continued until no oil produced, the process was immiscible. After that hot CO₂ with the same condition injected into the cores and enhanced oil recovery from each core was determined. Also hot CO₂ with the same condition injected into the cores which flooded by water (brine) completely previous and enhanced oil recovery from each cores was determined to study which reservoirs were better candidate for hot CO₂ injection. The results showed that injection of hot CO₂ into the cores that flooded with CO₂ previously was more feasible and could recover residual oil significantly. Also, results showed that hot CO₂ injection was feasible method to enhanced oil recovery in conventional core but in fractured it was not. Produced oil was increased by using Soak-Alternating-Gas method (SAG) in fractured core.

Keywords:
Hot CO₂; EOR; Immiscible; Fractured core; Conventional core; Soaking
1. Introduction
Carbon dioxide flooding is an effective enhanced oil recovery process. It appeared in 1930’s and had a great development in 1970’s [1]. Over 30 year’s production practice, CO₂ flooding has become the leading enhanced oil recovery techniques for light and medium oils [2]. CO₂ injection has been widely used for recovering oil from reservoirs due to its easy solubility in crude oil and its ability to swell the net volume of oil and thereby reduce oil viscosity by a vaporizing-gas-drive mechanism [3]. The quantity of hydrocarbons that can be recovered from a reservoir is influenced by several characteristics of the reservoir including reservoir rock properties, reservoir pressure and temperature, physical and compositional properties of fluid and structural relief, to name a few. However, the predominant factor in deciding the success of a CO₂ flood is the reservoir heterogeneity. Injected gas tends to flow in the highly permeable fractures, instead of the normally expected displacement path. These fractures are often responsible for early and excessive breakthrough of CO₂, thus greatly affecting the economics of the project [4]. The physical properties and PVT behavior of CO₂ with most reservoir oils is qualitatively different from other gases considered in gas injection IOR projects. Pure CO₂ has a critical point at a temperature and pressure 1071 psia and 87.91 °F respectively, which is within the temperature range of light oil and medium oils which cooled by water flooding and the shallower viscous oil fields. CO₂ densities can approach 1g/cc and may be greater than oil at most reservoir conditions, giving scope for designing different types of injection strategy.
Many factors have been found contributory to the oil recovery in CO₂ flooding. These mainly include:
- Low interface tensions
- Viscosity reduction
- Oil swelling
- Formation permeability improvement
- Solution gas flooding
- Density change of oil and water [2].
Hot CO₂ flooding heats the reservoir at the same time in partially miscible with oil. The operating temperature of hot CO₂ depends upon the reservoir temperature and oil properties. It is above the critical point of CO₂ phase diagram as shown in three phase diagram in Figure 1 [7].
The main objective of this work has been to investigate the feasibility of hot CO\textsubscript{2} injection and Soak-Alternating-Gas method (SAG) by using hot CO\textsubscript{2} in conventional and fractured core, focusing on the heat transfer of hot CO\textsubscript{2} and hydrocarbons in conventional core and on the heat transfer of hot CO\textsubscript{2} and hydrocarbons between the fracture and the matrix. Also hot CO\textsubscript{2} injects into the cores which are flooded with water and CO\textsubscript{2} previous, to study which reservoirs are better candidate for hot CO\textsubscript{2} injection. In this study a new method has been used for fracturing the cores.

2. Materials and Methods
For a reservoir with along CO\textsubscript{2} injection history, the reservoir temperature will be reduced a little. The highest reduction is seen in the proximity of injection wells. In this study, the temperature set at 100 °C to represent the temperature of the CO\textsubscript{2} flooded zones. The pressure was one atmosphere because the process was immiscible. The full details of the core samples, fluids and experimental set up are given in the following sections.

2.1. Core samples
In this study, two cores were used. The structure of two cores was the same with length of 35 cm and diameter of 4.2 cm. One of the cores as a fractured model contains a fracture in its middle. The properties and dimensions of the cores are summarized in Table 1.
2.2. Fluid samples
Oil which was used in all experiments in this study was prepared from Maroon reservoir at south of Iran. Oil composition was given in Table 2. Brine was prepared in laboratory. The composition of brine was given in Table 3 which is similar to the composition of reservoir brine. Injected gas was pure CO$_2$.

Table 2
Oil composition (%)

<table>
<thead>
<tr>
<th>Component</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$IC_4$</th>
<th>$NC_4$</th>
<th>$IC_5$</th>
<th>$NC_5$</th>
<th>$C_6$</th>
<th>$C_7^+$</th>
<th>$H_2S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>48.45</td>
<td>9.223</td>
<td>5.144</td>
<td>0.867</td>
<td>2.507</td>
<td>1.032</td>
<td>1.289</td>
<td>2.129</td>
<td>29.36</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
Brine composition

<table>
<thead>
<tr>
<th>Component</th>
<th>$KCl$</th>
<th>$MgCl_2$</th>
<th>$CaCl_2$</th>
<th>$NaCl$</th>
<th>$H_2O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (g)</td>
<td>0.3</td>
<td>4.3</td>
<td>32</td>
<td>36</td>
<td>927.4</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3. Matrix and fracture system
Both cores were conventional at the first. For fabricating a fractured core, one of the cores was selected and was cut in the middle and the space between two half of the core was filled by glass wool with 2 mm diameter. The artificial fracture acted similar to actual fracture. The glass wool had no effect on the surface area of the middle of core and did not affect on the fluid which was used later for saturating the core. This was investigated by measuring core permeability before and after using glass wool. The middle of core was filled with sealing material had zero permeability and core had its initial permeability of 0.11 D. The glass wool was a porous media with high permeability so in the middle of the core it was acted like a real fracture.
2.4. Initial Saturations
The pore volume was measured by saturating cores with brine. The oil with a composition as shown in Table 2 was then injected into the cores at a rate of 0.5 \( \text{cm}^3/\text{min} \). In this case the cores were vertically and oil was injected from the top of the cores. In the conventional core, oil break through was observed after 69.06 \( \text{cm}^3 \) of brine were produced. The total volume of oil was injected into the core was 145.5 \( \text{cm}^3 \) (1.5 PV) and the total volume of brine was produced from the conventional core was 81.8 \( \text{cm}^3 \). In the fractured core, oil break through was observed after 97.78 \( \text{cm}^3 \) of brine were produced. The total volume of oil was injected into the core was 204.28 \( \text{cm}^3 \) (1.5 PV) and the total volume of brine was produced from the fractured core was 115.3 \( \text{cm}^3 \). Thus, the initial water saturation, \( S_{W_i} \) for conventional and fractured cores were 15.66% and 15.06% respectively. Also, initial oil saturation, \( S_{O_i} \) for conventional and fractured cores were 84.34% and 84.94% respectively. This initialization was done at 25\(^\circ\) C and the pressure was one atmosphere.

2.5. Experiments
Highly heterogeneous reservoirs with variable lateral and vertical permeability characteristics can cause potential problems during CO\(_2\) injection. The injection gas tends to finger ahead into areas with high mobility ratios. This results in the gas forming preferential paths and “bypassing” large volumes of oil [5], [6]. CO\(_2\) Flooding process involves very complicated phase behavior, which depends on the temperature, pressure and fluids properties of a certain reservoir.

The potential of CO\(_2\) storage combining EOR is high; approximately 60 %PV injected CO\(_2\) can be retained in the reservoir at the CO\(_2\) breakthrough if reinjection is not considered. This suggests a “gross” CO\(_2\) retention efficiency of approximately 60 %PV at CO\(_2\) breakthrough if separation and reinjection is not considered after the breakthrough. Reservoirs with high concentrations of vertical fractures should be avoided due to CO\(_2\) injection losses out of zone and, or early CO\(_2\) breakthrough reducing sweep efficiency [7]. To generate accurate predictions by field simulations of CO\(_2\) injection into conventional and fractured reservoirs, a set of CO\(_2\) injection experiments at condition near reservoirs conditions should be performed to check EOR mechanisms.

The cores were placed horizontally in the oven. The whole setup is shown in Figure 2.
In the first step the conventional core was targeted. The temperature of oven was set at 100°C and CO₂ which was at room temperature (25°C) was injected into the conventional core at a rate of 0.5 \( \text{cm}^3/\text{min} \). The volume of injected CO₂ and cumulative produced fluids and breakthrough time were measured. The CO₂ injection was continued until no oil produced in outlet. After that the heater which was in the direction of CO₂ injection turned on and CO₂ temperature increased to 120°C. Hot CO₂ was injected into the conventional core and the volume of injected CO₂ and cumulative produced fluids and breakthrough were measured too. Results showed that the amount of produced oil and water significantly increased and the breakthrough time was reduced slightly. Next experiment was done on the fractured core to indicate feasibility of hot CO₂ injection in fractured core. The temperature of oven was set at 100°C and CO₂ was injected into the fractured core at a rate of 0.5 \( \text{cm}^3/\text{min} \) and 25°C. All the process was similar to the conventional core runs. The volume of injected CO₂ and cumulative produced fluids and breakthrough were measured. The CO₂ injection was continued until no oil was produced in outlet. After that the heater which was in the direction of CO₂ injection turned on and CO₂ temperature increased to 120°C. Hot CO₂ was injected into the fractured core and the volume of injected CO₂ and cumulative produced fluids which consist of oil, water and CO₂ were measured too. Unexpected results were observed; after finishing CO₂ injection and starting the hot CO₂ injection, the produced oil was low. It showed that the fracture was acted as a channel and hot CO₂ moved in the fracture because of high permeability of fracture and low viscosity of hot CO₂.

The best candidate to produce residual oil in the matrix is a new method which is Soak-Alternating-Gas (SAG). SAG method has been conceptualized based on continuous CO₂ flooding, cyclic CO₂ stimulation, and WAG techniques for conditions where water injectivity is poor and water is not available. The goal of this new method is to optimize the CO₂ process by using periodic soak periods in a continuous flood to maintain the effectiveness of transition zone at the flood front, maximize the amount of oil swelling/mobilizing behind the flood front, and cause the oil mobilization behind the flood front to occur as close to the flood front as possible, thus forming an “extended” flood front. This would create greater mobility control in the CO₂ flooding process without the use of WAG, reduce the travel distance needed to achieve optimal miscibility, and increase the mass transfer between CO₂ and oil without adding additional CO₂ [8]. SAG method was used in
fractured core. Hot CO₂ was injected into the fractured core which had been flooded with CO₂ completely. In the next step, input and output of the core holder were closed and soaking happened. Heat transferred from hot CO₂ to matrix around the fracture and viscosity of oil in the matrix decreased, also a little miscibility occurred because of high temperature so mobility of oil increased and oil started to move into the fracture. Figure 3 shows heat transfer from fracture to matrix and oil movement schematically. After 30 minutes the injection of hot CO₂ was restarted and oil started to produce again.

Next experiment was done on the conventional and fractured cores to study which reservoirs were candidate for hot CO₂ injection. Initial saturation was done on the two cores like previous experiment. The temperature of oven was set at 100 °C and brine which was at room temperature (25 °C) was injected into the conventional core at a rate of 0.5 cm³/min. The volume of injected brine and cumulative produced fluids and break through time were measured. The water injection was continued until no oil produced in outlet. After that hot CO₂ at 120 °C was injected into the conventional core and the volume of injected CO₂ and cumulative produced fluids and break through were measured too. These processes were done on the fractured core and volume of cumulative injected and produced fluids and break through were measured too. These data compared to each other to distinguish which reservoirs were better candidate for hot CO₂ injection, the reservoirs which flooded with water or CO₂.

3. Results and Discussions:
The results show that CO₂ injection is feasible method to enhanced oil recovery in conventional core. Figure 4 shows the cumulative oil which has produced by flooding CO₂ at a rate of 0.5 cm³/min in conventional core. This figure represents in conventional core after 295 %PV of CO₂ injection, cumulative produced oil is 50.8 %PV.
The breakthrough of CO\(_2\) has happened after 61 %PV of CO\(_2\) injection. Early breakthrough is the most problem of CO\(_2\) injection. Figure 5 shows the volume of oil which has produced by flooding hot CO\(_2\) in conventional core. As Figure 5 shows after 295 %PV of CO\(_2\) injection, the cumulative produced oil is 11.8 %PV. The breakthrough of hot CO\(_2\) has happened after 45 %PV of hot CO\(_2\) injection. Thus, hot CO\(_2\) breakthrough occurs earlier than CO\(_2\). High mobility of hot CO\(_2\) causes the earlier breakthrough. These results represent that CO\(_2\) and hot CO\(_2\) injection are proper methods in conventional core.

This was for the first time hot CO\(_2\) injected into the fractured core. Figure 6 shows the cumulative oil which was produced by flooding CO\(_2\) at a rate of 0.5 cm\(^3\)/min in fractured core. This figure shows that in the fractured core after 260 %PV of CO\(_2\) injection, cumulative produced oil is 44.6 %PV. The CO\(_2\) breakthrough happened after 32 %PV of CO\(_2\) injection. In this case, fracture with high permeability causes rapid breakthrough of CO\(_2\).
After fractured core was flooded by CO₂ completely, hot CO₂ injected into the fractured core. Produced oil was low, so SAG method was used and after soaking the fractured core by hot CO₂, oil started to produce. Figure 7 shows cumulative produced oil after soaking the core for 30 minutes. This figure shows after 77 %PV of hot CO₂ injection, the produced oil is 4 %PV and after 257 %PV hot CO₂ injection, the produced oil is 4.57 %PV. This is for the first time SAG method was used in fractured core by hot CO₂ and results show that hot CO₂ injection by use of the SAG method is feasible EOR process in fractured reservoirs.

Also the results show that hot CO₂ injection is more feasible method to enhanced oil recovery in the reservoirs that floods by CO₂ previously. Hot CO₂ injected into the conventional core which had flooded with water previously. Figure 8 shows the cumulative oil which was produced by water flooding at a rate of $0.5 \text{cm}^3/\text{min}$ in conventional core and Figure 9 shows it in fractured core. These figures represent that in conventional core after 347 %PV of water injection, cumulative produced oil is 58 %PV and in fractured core after 285 %PV of water injection cumulative produced oil is 50 %PV.
Figure 8. Produced oil versus water injection in conventional core.

Figure 9. Produced oil versus water injection in fractured core.
The breakthrough of water happened after 73 %PV in conventional and 62 %PV in fractured core. Figure 10 shows the volume of oil which was produced by hot CO\textsubscript{2} flooding in conventional core which completely flooded by water previously. As Figure 10 shows after 295 %PV of hot CO\textsubscript{2} injection, the cumulative produced oil is 5.3 %PV.

![Figure 10](image)

**Figure 10.** Enhanced oil recovery versus hot CO\textsubscript{2} injection in conventional core after flooding by water injection.

The breakthrough of hot CO\textsubscript{2} happened after 48 %PV injection. Hot CO\textsubscript{2} injected into the fractured core which was flooded by water previously. The results show that the produced oil after hot CO\textsubscript{2} flooding is low. These results represent that cores which are flooded with CO\textsubscript{2} previous are better candidate for hot CO\textsubscript{2} injection than the cores which are flooded by water. Water injection reduces reservoirs temperature so in thermal processes the reservoirs which are flooded with water, the CO\textsubscript{2} injection are not feasible.

Hot CO\textsubscript{2} Flooding can cover wide range of oil which includes high API gravity oil; also it can be applied to variety of reservoir which includes sandstone, dolomites and cherts. Mobility of hot CO\textsubscript{2} is more than CO\textsubscript{2} so it can flood the zones that CO\textsubscript{2} can not. Hot CO\textsubscript{2} flooding increases the mobility of oil comparative to CO\textsubscript{2} flooding. In fractured reservoirs, SAG method by using the hot CO\textsubscript{2} is feasible method especially in shallow reservoirs and the reservoirs which injection and production wells distance are small because of heat loses.

All EOR process has limitations on their applicability. These limitations have derived partially from laboratory test.

1. Naturally and economically availability of CO\textsubscript{2}.
2. High permeable zones and fractures reduce break through time and also decrease efficiency of hot CO\textsubscript{2} injection.
3. High temperature of CO\textsubscript{2} causes corrosive problems.
4. Heating CO\textsubscript{2} has high cost.
5. A large gas cap or aquifer is usually an unfavorable factor.
4. Conclusions
CO₂ gas has been injected into the conventional and fractured cores and amount of produced fluids and breakthrough time have been measured. After that hot CO₂ was injected into the each core and enhanced oil recovery and breakthrough time were determined. Results show that hot CO₂ injection is a feasible method to enhanced oil recovery in conventional core but in the fractured is not feasible. Recovery was increased by soaking the fractured core with hot CO₂. Therefore, soaking with hot CO₂ can be a feasible EOR process in fractured reservoirs. Results show that hot CO₂ injection is a good candidate in the reservoirs that floods with CO₂ previous but in the reservoirs those floods with water is not feasible method to enhanced oil recovery because water injection reduces the reservoir temperature. Heat content of CO₂ is low so hot CO₂ injection is not feasible method in deep reservoirs because of heat losses. Application of hot CO₂ flooding shows that it reduces the viscosity of medium or heavy oils and partially mixes with oil to increase the swelling factor which ultimately increases the recovery factor with respect to CO₂ flooding. Also, soaking hot CO₂ method can be uses in the fractured reservoirs which distance of injection and production wells are small. In this study for the first time, hot CO₂ was injected into a fractured core and SAG method by hot CO₂ was used in this core.
References:
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