Experimental Analysis of CO₂-Sequestration Efficiency During Oil Recovery in Naturally Fractured Reservoirs
J.J. Trivedi and T. Babadagli, SPE, University of Alberta

Abstract
With urgent need of greenhouse gas sequestration and booming oil prices, underground oil/gas reservoirs seems the only value added choice. A great portion of current CO₂ injection projects in the world is in naturally fractured reservoir. The matrix part of these reservoirs constitutes the major oil storage unit and this oil is targeted during CO₂ injection. It is our intention to show that this media could also be used as permanent CO₂ storage unit while recovering oil in it. These reservoirs, however, are complex in nature and the physics of the matrix-fracture interaction process during CO₂ injection is still not known to great extend.

To ease the complex nature of the problems, experiments were performed on artificially fractured (single) Berea sandstone cores saturated with n-decane. CO₂ was injected at constant rates into the fracture while maintaining the high pressure into the core and the system. Injection and production data were monitored and collected using continuous data logging system. After continuous injection diffusion of CO₂ was allowed to occur by shutting down the system for a specific period of time and then following a blowdown period to produce oil recovered by diffusion from matrix to fracture. At different pressure steps, produced liquid was analyzed using gas chromatography while the produced gas measured using continuous flow meter. The CO₂ storage capacity of the rock with change in the pressure and the amount of oil recovered during blow down period was analyzed.

The results of the continuous injection experiments were used to obtain diffusion coefficients by matching the simulation results. Using dimensionless analysis and matrix-fracture diffusion groups, a critical number for optimal recovery/sequestration was obtained. The pressure decay behavior during the shutdown was analyzed in conjunction with the gas chromatograph analysis of produced oil sample collected during blowdown after the quasi-equilibrium reached during pressure decay. This led to insights into the governing mechanism of extraction/condensation and miscibility for recovering lighter to heavier hydrocarbons during pressure depletion from fractured reservoirs.

Introduction
Although there exists considerable amount of experimental work on modeling matrix-fracture interaction using first contact miscible solvents to mimic fully miscible CO₂ injection (Burger and Mohanty, 1997; Burger et al. 1996; Gabitto, 1998; Firoozabadi and Markeset, 1994; Trivedi and Babadagli, 2008a), experimental studies using CO₂ as solvent are limited. Mostly Berea sandstones are used in these researches because of their readily availability, ease of cleaning and homogeneous structures. Studies using fractured carbonate rocks or low permeable matrix are rare (Karimaie et al. 2007; Darvish et al. 2006a and 2006b). In one of its kind experimental work, Chakravarthy et al. (2006) used polymer gels to show the effect of delayed breakthrough during immiscible CO₂ injection into fractured Berea cores. Improved recovery was observed during huff-and-puff performance in miscible range over immiscible injection of CO₂ (Asghari and Torabi 2007; Torabi and Asghari 2007). Because of the complexity and duration involved into the diffusion experiments as well as limitations of simulators to precisely predict the multiphase diffusion/mass transfer functions, the previous attempts to understand the physical mechanism are highly valuable. None of these works, however, considered the sequestration aspect during EOR. In the first part of this study, we performed dynamic diffusion experiments to show that oil recovery from the matrix can be enhanced as well as greenhouse gas storage can be accomplished by optimizing flow dynamics. In the second part, we provided a quantitative analysis showing the efficiency limits of the process.
Importance/Role of diffusivity in miscible and immiscible matrix-fracture transfer process

Different miscible injection processes using carbon dioxide, nitrogen, flue gas, natural gas, or other hydrocarbon gases such as methane, ethane, propane and butane as solvent were tested for the purpose of enhanced oil/gas recovery. One of the most important issues in common is that they all dissolve into the oil phase by diffusion mechanism. The efficiency of the mixing or dissolving is typically measured or characterized by a mutual diffusion coefficient of solvent into the oil phase. Solute transport in rough fractures is controlled by diffusion as well as advective processes. The fracture dispersion coefficient and effective matrix diffusion coefficient are the most important parameters for matrix oil recovery. In fractured porous media, the matrix diffusion is of primary importance in the processes such as geological disposal of nuclear waste, contaminant transport during ground water contamination, enhanced oil recovery in naturally fractured reservoirs and greenhouse gas sequestration in fractured geological formations.

Experimental methods to measure diffusivity could be direct or indirect. Direct method is the one which requires the compositional analysis of the diffusing species while the indirect method involves in measuring the parameters affected by diffusion such as volume change, pressure variation or solute volatization. As reported in literature, direct methods are time consuming and expensive (Sigmund 1976; Upreti and Mehrotra 2002). Recently, several studies reported new approaches for indirect method (Upreti and Mehrrota, 2002; Riazi, 1996; Tharanivasan et al., 2004; Zhang et al., 2000; Sheikha et al., 2005). These methods typically measure the change in pressure due to gas diffusion into liquid. Most of the research works until now did not consider the flow (or hydrodynamics) in the porous media while calculating the diffusion coefficient. In this study we obtained diffusion coefficients by simulating and matching the CO$_2$ gas injection into oil saturated fractured porous media experimental results. Diffusion/dispersion into fractured porous media was then quantified by newly defined dimensionless groups.

Experimental components

Core properties and core preparation

Cores were cut through the center in the direction of longitudinal axis using the special saw (Figure 1). The cores were then weighted and placed in a desiccator filled with oil. The desiccator was connected to a vacuum pump. The core was saturated under constant vacuum for 48 hours. The weight of the core after saturation was measured. Porosity of the matrix was calculated from the difference in the weight of saturated and unsaturated core. The porosity of Berea sandstone cores ranges from 19 to 21 %. The porosity of Midale cores ranges from 27 to 31 %. The average permeabilities are 500 mD and 10 mD for Berea sandstones and the Midale sample, respectively.

Diffusion cell (Core holder)

The diffusion cell is a 21 in. long and 3 inch in diameter steel made core holder. It is capable of holding cores up to 21 inches in length and 2 inches in diameter. Both ends have ferrule assembly by installing ferrule to the end caps with screws. The rubber sleeve is installed around both ferrules. The sleeve-ferrule assembly is inserted into the holder body from one side. The other ferrule assembly is then installed and tightened. The core is inserted through ferrule into the rubber sleeve using spacers if needed. Core lengths can be reduced by using spacers and by using the length adjustment available in the retainers.

The annulus between the outer diameter of the sleeve and the inner diameter of the body is filled with the hydraulic oil which is used to supply overburden using hydraulic hand pump. The maximum pressure rating of the cell is 4000 psi and maximum temperature is 100 ^{o}C. The holder has an inlet for applying overburden pressure around the rubber sleeve. The radial stress is applied to the core using high pressure nitrogen cylinder from the overburden line. The both end of has three 1/8” holes. One of the holes at the inlet touching the center where fracture is located is used as an injection port, the other two for pressure transducer and pressure relief valve. Similarly at the production end the hole touching the fracture is used as a production port. The experimental set-up is shown in Figure 2.

Injection set-up

Two ISCO 500D pumps were used for injection of oil and CO$_2$. The ISCO syringe pumps can operate at flow rates as low as 0.01 ml/min. The maximum pressure rating for the pump is 3750 psi at 200 ml/min. The pumps can be set to operate either at constant flow or at constant pressure using a controller attached. 500 mL capacity piston type (Model 500D) that can maintain constant flow to within +/- 0.5%. The liquid CO$_2$ cylinder has pressure only 850 psi. The accumulator of the pump has a capacity of only 508 ml. Therefore, every time after the refill, the syringe pumps were used to increase the pressure up to the desired level. N$_2$ cylinder supplying constant pressure using high pressure regulator at the overburden line is used to apply the loads and stresses. In some experiments water using ISCO pump was used to supply overburden pressure. ISCO pumps are connected to RS-232 serial interface for controlling and operating parameters using the LabVIEW program.

Production system

Production unit is comprised of a back pressure regulator, a custom made separator and a flow meter unit. A KPB series medium to high pressure piston-sensing back pressure regulator provided by Swagelok was used. The regulator is connected to the production line coming out at bottom of the core holder. By closing and opening of the regulator knob desired pressure
inside the core holder was maintained. A separator is connected to back pressure regulator for oil and gas separation coming through the backpressure regulator. Separated oil is collected into a graduated cylinder on an electric balance while the amount of gas coming out was passed through a volume/mass flow meter.

**Data acquisition system (DAQ)**

Data acquisition from the thermocouples and pressure transducers is performed using the National Instruments DAQ-9172 module equipped with NI Bus 9211 and 9215, which is connected to a host PC. The LabVIEW software is used to monitor the entire process and perform the appropriate programs for I/O applications. All the necessary data, as listed below, are collected using this system. ISCO pumps and weight balance are connected through RS-232 serial interface for controlling and operating parameters using the LabVIEW program, while the flow meter is connected through s-video to RS-232 converter interface. The flow rate, amount of volume injected and pump pressure data from the ISCO pump, gas mass/volume flow from the flow meter, pressure data through transducers connected at the injection and production line and weight data from the electric balance are collected at different time steps using LabVIEW program.

**Experimental procedure**

The cores were cut and dried in the oven to remove the water content. Before this, the Midale cores were subjected to a cleaning process using the Soxhlet device. Dried core was cut into two pieces in the longitudinal direction using a diamond saw and the sides of the cores were smoothened. The cut cores were weighted and coated with aluminum foil except the two ends. Two pieces of cut cores were put in the desiccator filled with n-decane/Midale crude oil and connected to the vacuum pump assembly. Cores were saturated under vacuum for 48 hours. The weight of the core after saturation was measured. Porosity of the matrix was calculated from the difference in the weight of saturated and unsaturated core. Saturated two core pieces were held together and the fractured core was placed into the core holder assembly. Once the prepared core is placed into the core holder and injection/production lines are connected properly, overburden pressure using high pressure nitrogen cylinder was applied. The overburden was always kept 300 psi higher than the injection pressure. Oil was injected into the fractured core at the desired pressure until the flow rate stabilizes while keeping the back pressure fully closed. Core was saturated for 24 hrs to achieve complete saturation. The pump was switched to constant flow and oil was injected at desired flow rate and system pressure was maintained by adjusting the opening of the back pressure regulator. Once the back pressure regulator is set, the oil injection was stopped and pressure inside the CO2 pump was increased 50 to 100 psi higher than the desired experimental pressure. Then, the CO2 pump was switched to run at constant rate flow.

In one of the Midale core experiments, sudden change in pressure was observed while injecting oil into the core situated in the core assembly as discussed earlier. Hence core was removed from the holder before even starting the CO2 injection and we found the core completely crushed into pieces. Upon repetition of the same problem, we modified the design using a lead metal cover jacket surrounding the core and only exposing the fracture portion. The overburden and core pressure was increased simultaneously so that the core was not exposed to sudden pressure change.

**Continuous CO2 diffusion for oil recovery**

CO2 was injected at different very low rates: 5ml/hr, 10ml/hr and 20 ml/hr with an injection pressure of 1200 psi and backpressure regulator operating at 1200 psi, a near miscible/miscible pressure condition for CO2/n-decane system for the Berea sandstone cases. To study the CO2 behavior at immiscible condition, one experiment at the injection rate of 5ml/hr and was carried out at 950 psi core pressure by keeping initial injection pressure and backpressure regulator at 950 psi. Another pressure, 1400 psi, was selected to obtain fully miscible (above miscible) displacement and compare the results with other two cases. At 1400 psi, one CO2 injection rate (10 ml/hr) was tested. For the Midale core experiments, injection was carried out at 10 ml/hr rate while keeping the core pressure 950 psi and 1700 psi in two different cases. At 950 psi, Midale crude oil is immiscible with CO2 while at 1700 psi it is at near miscible condition. The system was continuously supplied with constant overburden pressure of 1500 psi using water injection using ISCO pump in all the experiments except in case-8 where overburden was maintained at 1850 psi. Pressure variations and amount of oil/gas production were closely monitored and logged during the experiment run.

**Blow down**

After the continuous injection was stopped, the production valve at the bottom of the core-holder and the backpressure valve were closed. The system was fully shut-down for 36 hrs. During this period CO2 and oil diffusion and back diffusion took place. Change in pressure at the injection/production ends was monitored. After 36 hrs, production valve and back pressure was opened to produce CO2 and oil. Production continues until the pressure inside the core lowers to 250 psi. The shut-down and pressure blow down cycle was then repeated for every 250 psi pressure steps. The amount of oil and CO2 production were measured at every pressure steps to determine the CO2 sequestration capacity at particular pressure and ultimate oil recovered after the blow down.
Experimental results and discussion

Figures 3 and 4 show the amount of oil produced with respect to the reservoir (core) pressure during the project life. It can be seen that the production trend for all cases of injection follows modified hyperbolic relationship \((y_0 + aP/(b + P))\) with the core pressure. As seen from the graphical representation of oil recovery with blow-down pressure, most of the oil is produced during the first cycle of blowdown period up to 750 psi. For Cases 7 and 8, where CO2 was injected at 10 ml/hr into Midale core saturated with Midale oil at pressure 950 psi and 1700 psi respectively, the recovery increased until the pressure reduction reaches 400 psi, which is lower than the Berea sandstones. The pressure stabilization for Case 8 was around 1100 psi during shut down higher than Berea. After the first blowdown, the recovery at 800-700 psi for the Cases 7 and 8 are almost the same even though, at the end of during continuous injection, 1700 psi initial pressure (case 8) showed ~8% higher recovery with less amount of CO2 PV injection.

The normalized recovery factor (R.F. = % Recovery / PV Inj) based on per volume of CO2 injected was presented in Figures 9 and 10. It is a log-log representation of R.F. with PV of CO2 injected during the continuous injection period. The Cases 5 and 6 follow a similar trend and are parallel in nature. But 20 ml/hr injection rate has a higher R.F. value. Here the difference in initial injection pressure does not have much difference in values hence difficult to reach any sound conclusion. But in Figure 8, where initial injection pressure are 950 psi and 1700 psi, the difference in the R.F. clearly suggests the miscible process having advantage over immiscible case. After ~0.3 PV of CO2 injection, the R.F. for both cases approaches to the same value. Hence, further continuations of miscible process can impair the economics of the project due to high compression cost of CO2 to achieve miscible condition. At this point switching to maintaining lower pressure would be more economical.

To check the viability of storage during pressure reduction for oil production, we showed the results of CO2 production at different pressures in Figures 5 and 6. CO2 storage at different pressures for the same cases are given in Figures 7 and 8 after the continuous injection was stopped. Up to 600 psi, it follows a linear trend of CO2 storage reduction but below 600 psi the storage drops drastically. The trend of CO2 storage with blowdown pressure for the Midale cores initially saturated with dead Midale crude oil is also shown in Figure 8. The detailed results and discussion of the experiments are presented in another study (Trivedi and Babadagli 2008c).

When a non-equilibrium gas comes in contact with a liquid phase in a constant volume and constant temperature system, the system will approach to a new equilibrium state with changed pressure and temperature condition governed by diffusion process. The time required to reach this new equilibrium condition depends on the diffusion coefficient of the gas into the liquid phase. The amount of gas transferred into the oil phase depends on gas solubility while the transfer rate is governed by diffusion coefficient. During the continuous injection of CO2 into oil saturated porous media, injection was stopped when the oil production was very low compared to gas production. At this stage, the phase at the injection and production ports located at the centre of the core where the fracture is lying was occupied mainly by CO2. During the shutdown period after the continuous injection was stopped caused a drop in pressure. As shown in Figure 11, during shutdown the pressure declined and reached a stable value, a point of quasi-equilibrium. This clearly suggests the diffusion of CO2 into the hydrocarbon phase. During this period, mobilization of heavier hydrocarbon component of the oil occurs. This phenomenon is due to increased extraction/condensation, a result of diffusion and solubilization.

The pressure decay behavior was observed and used by many authors (Upreti and Mehrotra, 2002; Riazi, 1996; Tharanivasan et al., 2004; Zhang et al., 2000; Sheikha et al., 2005; Fjelde et al., 2008) to calculate solvent gas/CO2 diffusivity into heavy oil/bitumen as well as into light hydrocarbons. In this method, more commonly known as pressure decay method, two pairs of fluids are place in a closed chamber (Sapphire cell) at test conditions and pressure response of the constant volume system are modeled by applying appropriate boundary conditions to calculate diffusion coefficients. So far, we have not come across any work where interaction between any phase (gas, liquid or supercritical) of a gas and oil saturated porous media was used to study pressure decay method hence the interpretation of the results during our experiments are more critical and valuable. The value of diffusion coefficient is dependent on the final equilibrium pressure and times required to reach this pressure. The steeper the pressure decline with time, the higher the value of diffusion coefficient. As seen in Figure 11, in the Case 7, where injection of CO2 was at immiscible condition into Midale carbonate core, the pressure decay behavior was not observed. In contrast, for the Case 8, the decay was observed as near miscible condition was maintained during CO2 injection but still it was not as steep decline as observed for the Cases 4, 5 and 6. This discrepancy is due to diffusion characteristics in different rock types: Berea sandstones (Cases 4 to 6) and Midale carbonates (Cases 7 and 8). Also in the Case 6 the decay is gradual, while in the Cases 4 and 5 the decay is very steep. Injection in the Case 6 was stopped earlier and the total amount of CO2 injected was much lower due to injection/production at higher rates compared to the Cases 4 and 5. Hence, indicating that shutdown after slower rate injection for a longer period of time will yield higher diffusion and higher amount of oil recovered during the first blowdown compared to a faster rate injection for a shorter period of time. This conclusion is complemented by oil production with pressure depletion shown in Figure 3 for the Case 4 and 6.

During the first blow down period after the first shutdown, significant amount of oil production was noticed while further consecutive shutdowns were ineffective for production. The reason being, during the first shutdown, the quasi-equilibrium is reached as the pressure stabilizes after the decay. This means that further solubility of gas into oil phase is very much reduced. To increase the oil production requires addition of fresh gas phase to create non-equilibrium into the system which subsequently will increase the solubility as well as the rate of molecular transfer controlled by diffusion coefficient. CO2
solubility also is a function of pressure and increases with pressure. The shutdown at higher pressure will increase the chances of CO₂ contacting larger portion of oil.

The hydrocarbon distribution of the oil recovered for the Case 8 is shown in Figure 12. The samples collected at initial stage (stock tank oil used for saturation of the core), during continuous injection, during the first blowdown followed by quasi-equilibrium during first shutdown and during the last cycle of blowdown were analyzed using GC-MS for carbon distribution and are presented here. Maintaining near miscible condition and injecting at continuous rate, oil swelling and extraction capacity of CO₂ increased. Recovery is also governed by the extraction process during the development of miscibility. While in the shutdown period, as the pressure decreases, condensation due to loss of miscibility occurs. The heavier carbon components dissolve in the CO₂ rich phase inside the matrix. Thus, it creates a middle phase and recovery of heavier component increases. As shown in Figure 12, during this period, C14-C17 as well as C18-C22 recovery was increased almost 13% and C22+ recovery increased by ~9%. Interestingly, there were almost zero C10+ components in the production. This emphasizes the role of density and gravity during quasi-equilibrium. Until the pressure reduces to the stabilization point (quasi-equilibrium), condensation and diffusion are the major driving mechanisms. After that, oil recovery is due to mobilization of oil inside the fracture due to pressure reduction which is very low in percentage amount and also lighter in hydrocarbon enrichment compared to the one obtained during the quasi-equilibrium state. The carbon distribution found was similar to the initial stock tank oil but still somewhat higher in heavier hydrocarbons. Below 600 psi, CO₂ is in a gas phase and further decrease in pressure only results in gas production.

Matrix-fracture diffusion simulation
Fracture-matrix transfer process was modeled numerically and presented in the form of dimensionless groups to analyze the effects of different parameters quantitatively. The process experimentally analyzed in the previous section was simulated using finite element modeling with the governing advection-convection equations and the Darcy equation. Only parameters other than those unavailable from the laboratory scale experiments are the diffusion/dispersion coefficients and mass transfer coefficients in the matrix and fracture. These parameters were obtained through matching the numerical modeling results to their experimental equivalents and then they were correlated to fluid-rock properties and flow velocity.

Figure 1 presents the matrix-fracture system (length = L and radius = 2r) with inlet, outlet as well as the boundary conditions. The x-axis is the principle flow direction, while the y-axis is the direction perpendicular to the flow. The pore space of the matrix is initially filled with oil (C = 0) and is flooded with a CO₂ (C = 1) from one side x = 0 at the center, where fracture (half aperture = b) is located. The oil is assumed to be dispersed uniformly into the porous matrix. It is assumed that both fluids, displacing and displaced, are incompressible and complete mixing across the fracture width takes place at all times. Both media has uniform properties. In this analysis, we do not impose any restriction on the geometric shape of the fracture, except that the cross section of the fracture is invariant with the axial position. The displacing fluid (CO₂) flows/injected at constant rate through fracture at the inlet x = 0; there is no flow in the matrix surrounding fracture. Under these conditions, Equations governing the system are shown below with the appropriate initial and boundary conditions. Assuming the diffusive flux from fracture to matrix is acting perpendicular to the fracture, the coupling parameter between matrix and fracture are the continuity of fluxes and concentrations along the interface (Tang et al. 1981).

The dead volume of the oil in the injection and production line have been subtracted from the final experimental results and then used for simulation of flow and diffusion behavior only inside the porous media. During the closing and opening of BPR valve the pressure fluctuation in a range of +/- 20 psi occurs. This fluctuation has been neglected while the performing simulation and flow at the bottom exit at the fracture has assumed to be regulated by constant outlet pressure.

Domain 1 – Fracture
\[
\frac{\partial CF_1}{\partial t} - D_L \frac{\partial^2 CF_1}{\partial x^2} - D_L \frac{\partial^2 CF_1}{\partial y^2} = -u_f \frac{\partial CF_1}{\partial x}
\]

Domain 2 – Matrix
\[
\frac{\partial CM_1}{\partial t} - D_e \frac{\partial^2 CM_1}{\partial x^2} - D_e \frac{\partial^2 CM_1}{\partial y^2} = 0
\]
\[
\frac{\partial CM_2}{\partial t} - D_e \frac{\partial^2 CM_2}{\partial x^2} - D_e \frac{\partial^2 CM_2}{\partial y^2} = 0
\]
Initial conditions:

\[ CF_1(x, y, 0) = 0; \quad CM_1(x, y, 0) = 0; \quad CF_2(x, y, 0) = 1; \quad CM_2(x, y, 0) = 1; \quad CF_1(0, t) = CF_0 \]  

(5)

Boundary conditions:

\[ \frac{\partial CM_1}{\partial y} \bigg|_{(x,r)} = 0 \quad \frac{\partial CM_2}{\partial y} \bigg|_{(x,r)} = 0 \]  

(6)

\[ \frac{\partial CF_1}{\partial x} \bigg|_{(x,r)} = 0 \quad \frac{\partial CF_2}{\partial x} \bigg|_{(x,r)} = 0 \]  

(7)

\[ D_L \frac{\partial CF_1}{\partial y} = -D_e \frac{\partial CM_1}{\partial y}; \]  

(8)

\[ D_L \frac{\partial CF_2}{\partial y} = -D_e \frac{\partial CM_2}{\partial y} \quad \text{at} \quad t = t \quad \forall x, b \]

The simulation results were compared with the results of experimental performed earlier. Through matching the experimental results with the numerical ones, the values of \( D_L \) and \( D_e \) were obtained.

**Correlation for CO₂ sequestration and oil production**

In previous attempts, different studies derived dimensionless groups to represent the efficiency of the immiscible or miscible EOR processes. Mostly all of them were for homogeneous systems and only a few focused on heterogeneous reservoirs. Gharbi et al. (1998) and Gharbi (2002) used inspection analysis to investigate the miscible displacement in homogeneous porous media. Grattoni et al. (2001) defined a new dimensionless group combining the effects of gravity; viscous and capillary forces which showed a linear relationship with the total recovery. For the application of the dimensionless groups, Kulkarni and Rao (2006) presented the effect of major dimensionless groups on the final recovery based on various miscible and immiscible gas assisted gravity drainage field data and laboratory experimental data. In another study (Wood et al. 2006) dimensionless groups were derived for tertiary enhanced oil recovery (EOR) using CO₂ flooding in waterflooded reservoirs and presented a screening model for EOR and storage in Gulf Coast reservoirs. For transfer in fractured porous media a dimensionless group, FDI (Fracture Diffusion Index), was proposed (Trivedi and Babadagli, 2006) as a ratio of viscous forces in the fracture and diffusion forces in the matrix using the analogy to capillary imbibition controlled immiscible displacement in fractured porous medium. In a recent attempt, Trivedi and Babadagli 2008b derived a new dimensionless group with its physical significance towards the efficiency of miscible recovery process into fractured porous media. In the present analysis, we used the same group – Matrix-Fracture Diffusion group (\( N_{M-FD} \)) – for our experimental results to analyze the efficiency. (\( N_{M-FD} \)) is defined as follows:

\[
(N_{M-FD}) = \left( \frac{\mu_0 a b}{k_f \Delta \rho g D_m} \right) \left( \frac{L}{\phi_m r} \right) = \frac{Pe * Ar_M}{N_g}
\]

where,

\[ Pe = \frac{u_T * b}{D_m}; \quad N_g = \left( \frac{k_f \Delta \rho g}{\mu_0 u_T} \right); \quad Ar_M = \left( \frac{L}{\phi_m r} \right) \]

The TOP/TSI (total oil produced / total solvent injected) ratio is of particular interest when it comes to optimization and the critical rate determination. In previous attempts, dimensionless numbers (empirical and derived) were correlated to TOP/TSI and also with TSS/TSI using the experimental results for solvent injection (Babadagli and Trivedi, 2006 and 2008a). They used the first contact miscible solvent to mimic the CO₂ injection process whereas we used the results of CO₂/oil experiments performed in this study for the same type of analyses. Well known dimensionless numbers, Peclet number (\( Pe \)), gravity number (\( N_g \)) and matrix-fracture diffusion group (\( N_{M-FD} \)) for different experiments conducted in this study, are shown in Table 3. We also included the results from Trivedi and Babadagli (2008a) (Cases 8, 9, and 10) and Firoozabadi and Markeset (1994) (Cases 11, 12, and 13) which were performed under similar experimental conditions but
different solvent/solute pairs. As presented in Figure 13, $N_{MF-D}$ shows a power law relation with high accuracy with the TOP/TSI values for all experiments. In many enhanced oil recovery processes the time to reach the ultimate recovery could be more critical compared to the amount of solvent injected while sometimes the compression cost associated with the amount of CO$_2$ injected could be important considering overall economics of the project. Higher $N_{MF-D}$ indicates a faster recovery with more solvent injection. On the other hand, a low value of the $N_{MF-D}$ is an indication of slow but higher normalized recovery due to less amount of total solvent injected. The process having too low $N_{MF-D}$ also cannot be considered as the best scenario because of extremely slow nature of the process. The optimal/critical value of $N_{MF-D}$ group would be the one which is time effective as well as effective in terms of amount of solvent injected or produced minimization and define the critical rate. The critical $N_{MF-D}$ value found here is between $3.5 \times 10^3$ to $1 \times 10^4$.

Conclusions
The heavier hydrocarbon components recovery is increased by a large fraction during shutdown after continuous injection of CO$_2$. The shutdown after slower rate injection for a longer period of time yielded higher diffusion and higher amount of oil recovered during first blowdown compared to faster injection rate case for a shorter period of time. The pressure decay during this shutdown period gives a measure of diffusion as well as recovery enhancement phenomenon in fractured porous media. During the project life blowing down reservoir for an economic benefit of oil recovery is not viable after a particular pressure stage and that pressure was found to be around 600-700 psi for Berea sandstone and 400 psi for Midale carbonate cores. Similarly, while considering greenhouse gas sequestration same pressure was proved to be the bottom limit to exceed for viable range.

Understanding of diffusion/dispersion phenomenon into the matrix-fracture system and its quantification were achieved using successful simulation match of very slow rate CO$_2$ injection into oil saturated fractured porous media experimental results. Efficiency of the miscible gravity drainage process in the fractured porous media can be generalized using a dimensionless group $N_{MF-D}$. The critical value of dimensionless matrix-fracture diffusion group was found to be in a range of $3.5 \times 10^3$ to $1 \times 10^4$.

Acknowledgements
This research was funded by NSERC (Strategic Grant No: G121990070) and Apache Canada Ltd. The funds for the equipment used in the experiments were obtained from the Canadian Foundation for Innovation (CFI, Project #7566) and the University of Alberta. We are also thankful to Apache Canada Ltd for providing field and well data, and permission to use them in this research. We, finally, would like to extend our gratitude to Mr. Rob Lavoie (CalPetra) for his invaluable assistance during data collection, trip to the Midale field and for sharing his experience on the operations done in the field over the last three decades.

Nomenclature

\[ b = \text{Fracture width m}, \]
\[ D_f = \text{Effective dispersion coefficient in fracture m}^2/\text{s}, \]
\[ D_e = \text{Effective diffusion coefficient in matrix for matrix-fracture system m}^2/\text{s}, \]
\[ g = \text{Gravity force m/s}, \]
\[ k_f = \text{Fracture permeability m}^2, \]
\[ k_m = \text{Matrix permeability m}^2, \]
\[ L = \text{Length of Fracture m}, \]
\[ L_x = \text{Matrix size in x direction m}, \]
\[ L_y = \text{Matrix size in y direction m}, \]
\[ r = \text{Matrix width m}, \]
\[ u_T = \text{Flow velocity m/s}, \]

Symbols

\[ \rho_i = \text{Density of injected (solvent) phase, kg/m}^3, \]
\[ \rho_o = \text{Density of displaced (oil) phase, kg/m}^3, \]
\[ \phi_F = \text{Porosity (Fracture)} \]
\[ \phi_M = \text{Porosity (matrix)} \]
\[ \mu_s = \text{Solvent viscosity, kg/m.s}, \]
\[ \mu_o = \text{Solute viscosity, kg/m.s}, \]
\[ \Delta \mu = \text{Viscosity difference, kg/m.s}, \]
\[ \Delta \rho = \text{Density difference, kg/m}^3 \]
References


Table 1: Experiments details.

<table>
<thead>
<tr>
<th>Case No</th>
<th>Core type</th>
<th>Flow rate (cc/hr)</th>
<th>Length (inches)</th>
<th>Oil type</th>
<th>Pressure (psi)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Berea Sandstone</td>
<td>5</td>
<td>6</td>
<td>decane</td>
<td>950</td>
<td>20-22</td>
</tr>
<tr>
<td>2</td>
<td>Berea Sandstone</td>
<td>5</td>
<td>6</td>
<td>decane</td>
<td>1200</td>
<td>20-22</td>
</tr>
<tr>
<td>3</td>
<td>Berea Sandstone</td>
<td>10</td>
<td>6</td>
<td>decane</td>
<td>1400</td>
<td>20-22</td>
</tr>
<tr>
<td>4</td>
<td>Berea Sandstone</td>
<td>5-10</td>
<td>6</td>
<td>decane</td>
<td>1250</td>
<td>20-22</td>
</tr>
<tr>
<td>5</td>
<td>Berea Sandstone</td>
<td>10</td>
<td>6</td>
<td>decane</td>
<td>1000</td>
<td>20-22</td>
</tr>
<tr>
<td>6</td>
<td>Berea Sandstone</td>
<td>20</td>
<td>6</td>
<td>decane</td>
<td>1250</td>
<td>20-22</td>
</tr>
<tr>
<td>7</td>
<td>Midale core (Marly zone)</td>
<td>10</td>
<td>6</td>
<td>Midale crude oil (dead)</td>
<td>950</td>
<td>27-31</td>
</tr>
<tr>
<td>8</td>
<td>Midale core (Marly zone)</td>
<td>10</td>
<td>6</td>
<td>Midale crude oil (dead)</td>
<td>1700</td>
<td>27-31</td>
</tr>
</tbody>
</table>

Table 2: Hyperbolic behavior for oil recovery during production life.

<table>
<thead>
<tr>
<th>Case No</th>
<th>y₀</th>
<th>a</th>
<th>b</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61.99</td>
<td>4.99</td>
<td>-1059</td>
<td>0.9985</td>
</tr>
<tr>
<td>2</td>
<td>41.68</td>
<td>3.488</td>
<td>-1357</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
<td>12.66</td>
<td>-1989</td>
<td>0.9832</td>
</tr>
<tr>
<td>4</td>
<td>85.98</td>
<td>13.89</td>
<td>-1989</td>
<td>0.9949</td>
</tr>
<tr>
<td>5</td>
<td>90.74</td>
<td>10.45</td>
<td>-1997</td>
<td>0.9729</td>
</tr>
<tr>
<td>6</td>
<td>44.32</td>
<td>7.748</td>
<td>-1849</td>
<td>0.9989</td>
</tr>
<tr>
<td>7</td>
<td>48.13</td>
<td>10.53</td>
<td>-1379</td>
<td>0.9316</td>
</tr>
<tr>
<td>8</td>
<td>52.28</td>
<td>17.23</td>
<td>-2420</td>
<td>0.8361</td>
</tr>
</tbody>
</table>

Table 3: Dimensionless numbers and TOP/TSI predicted values using Nₐ-FD.

<table>
<thead>
<tr>
<th>No</th>
<th>q, (ml/hr)</th>
<th>Pressure (psi)</th>
<th>Pe</th>
<th>Nₐ</th>
<th>Nₐ-FD</th>
<th>TOP/TSI (predicted)</th>
<th>TOP/TSI (Experimental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>1250</td>
<td>300</td>
<td>3.9636</td>
<td>2149.6187</td>
<td>0.55</td>
<td>0.5825</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1250</td>
<td>600</td>
<td>1.7341</td>
<td>9826.8282</td>
<td>0.3707</td>
<td>0.3656</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1250</td>
<td>1200</td>
<td>0.9909</td>
<td>34393.899</td>
<td>0.2676</td>
<td>0.2842</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>950</td>
<td>1714.286</td>
<td>0.6606</td>
<td>73701.212</td>
<td>0.219</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>1350</td>
<td>150</td>
<td>0.4955</td>
<td>8598.4747</td>
<td>0.384</td>
<td>0.3645</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>1200</td>
<td>800</td>
<td>0.6606</td>
<td>34393.899</td>
<td>0.268</td>
<td>0.314</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1700</td>
<td>240</td>
<td>1.6515</td>
<td>3852.1167</td>
<td>0.47</td>
<td>0.39</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>15</td>
<td>62.1055</td>
<td>1.6765</td>
<td>1068.912</td>
<td>0.659</td>
<td>0.62</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>15</td>
<td>186.3165</td>
<td>0.5588</td>
<td>9620.206</td>
<td>0.372</td>
<td>0.334</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>15</td>
<td>372.6329</td>
<td>0.2794</td>
<td>38480.82</td>
<td>0.259</td>
<td>0.23</td>
</tr>
<tr>
<td>11</td>
<td>0.0026087 (velocity)</td>
<td>15</td>
<td>80.8697</td>
<td>2.3891</td>
<td>418.542</td>
<td>0.842</td>
<td>0.98</td>
</tr>
<tr>
<td>12</td>
<td>0.01435 (velocity)</td>
<td>15</td>
<td>81.7739</td>
<td>0.4343</td>
<td>2328.069</td>
<td>0.539</td>
<td>0.51</td>
</tr>
<tr>
<td>13</td>
<td>0.04348 (velocity)</td>
<td>15</td>
<td>82.184</td>
<td>0.1433</td>
<td>7089.021</td>
<td>0.403</td>
<td>0.383</td>
</tr>
</tbody>
</table>
Figure 1: Core Preparation.

Place into the Core holder

Saturation under vacuum
Porosity, permeability test

Figure 2: Experimental Setup.
Figure 3: Oil recovery with the pressure blowdown for Berea sandstone.

Figure 4: Oil recovery with the pressure blowdown for Midale carbonate.
Figure 5: CO₂ production with the pressure blowdown for Berea sandstone.

Figure 6: CO₂ production with the pressure blowdown for Midale carbonate.
Figure 7: CO$_2$ storage with the pressure blowdown for Berea sandstone.

Figure 8: CO$_2$ storage with the pressure blowdown for Midale carbonate.
Figure 9: Normalized recovery factor with the CO₂ PV injected for Berea sandstone.

Figure 10: Normalized recovery factor with the CO₂ PV injected for Midale carbonate.
Figure 11: Pressure decay and attainment of quasi-equilibrium behavior.

Figure 12: Hydrocarbon recovery distribution for the Case-8 at different stages of the production life.
Figure 13: (TOP/TSI) with matrix-fracture diffusion group ($N_{MF}$).

Equation:

\[ y = 4.046x^{0.26} \]

\[ R^2 = 0.938 \]