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INVESTIGATION OF EFFICIENCY IMPROVEMENTS DURING CO_2 INJECTION IN HYDRAULICALLY AND NATURALLY FRACTURED RESERVOIRS

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ABSTRACT

This report describes the final work of the project, “Investigating of Efficiency Improvements during CO_2 Injection in Hydraulically and Naturally Fractured Reservoirs.” The objective of this project is to perform unique laboratory experiments with artificial fractured cores (AFCs) and X-ray CT to examine the physical mechanisms of bypassing in HFR and NFR that eventually result in more efficient CO_2 flooding in heterogeneous or fracture-dominated reservoirs. To achieve this objective, we divided the report into two chapters. The first chapter was to image and perform experimental investigation of transfer mechanisms during CO_2 flooding in NFR and HFR using X-ray CT scanner. In this chapter, we emphasized our work on understanding the connection between fracture properties and fundamentals of transfer mechanism from matrix to fractures and fluid flow through fracture systems. We started our work by investigating the effect of different overburden pressures and stress-state conditions on rock properties and fluid flow. Since the fracture aperture is one of important parameter that governs the fluid flow through the fracture systems, the average fracture aperture from the fluid flow experiments and fracture aperture distribution derived from X-ray CT scan were estimated for our modeling purposes. The fracture properties and fluid flow have significant changes in response to different overburden pressures and stress-state conditions. The fracture aperture distribution follows lognormal distribution even at elevated stress conditions. Later, we also investigated the fluid transfers between matrix and fracture that control imbibition process. We evaluated dimensionless time for validating the scheme of upscaling laboratory experiments to field dimensions.

In CO_2 injection experiments, the use of X-ray CT has allowed us to understand the mechanisms of CO_2 flooding process in fractured system and to take important steps in reducing oil bypassed. When CO_2 flooding experiments were performed on a short core with a fracture at the center of the core, the gravity plays an important role in the recovery of oil even in a short matrix block. This results are contrary with the previous believes that gravity drainage has always been associated with tall matrix blocks.

In order to reduce oil bypassed, we injected water that has been viscosified with a polymer into the fracture to divert CO_2 flow into matrix and delay CO_2 breakthrough. Although the breakthrough time reduced considerably, water “leak off” into the matrix was very high. A cross-linked gel was used in the fracture to avoid this problem. The gel was found to overcome “leak off” problems and effectively divert CO_2 flow into the matrix.

As part of our technology transfer activity, we investigated the natural fracture aperture distribution of Tensleep formation cores. We found that the measured apertures distributions follow log normal distribution as expected.

The second chapter deals with analysis and modeling the laboratory experiments and fluid flow through fractured networks. We derived a new equation to determine the average fracture aperture and the amount of each flow through fracture and matrix system. The results of this study were used as the observed data and for validating the simulation model. The idea behind this study is to validate the use of a set of smooth parallel plates that is common in modeling fracture system. The results suggest that fracture apertures need to be distributed to accurately model the experimental results.

In order to study the imbibition process in details, we developed imbibition simulator. We validated our model with X-ray CT experimental data from different imbibition experiments. We found that the proper simulation model requires matching both weight gain and CT water saturation simultaneously as oppose to common practices in matching imbibition process with weight gain only because of lack information from CT scan. The work was continued by developing dual porosity simulation using empirical transfer function (ETF) derived from imbibition experiments. This allows reduction of uncertainty parameter in modeling transfer of fluids from matrix to the fracture. The application of ETF approach not only reduces the computation times but also shows similar results when compared to the results from existing dual porosity simulator.

During the development of our numerical modeling, we found that the grid orientation effect (GOE) is major problem plaguing reservoir simulators that employ finite difference schemes. The GOE is clearly seen when using conventional Cartesian grid blocks during CO_2 flooding or unfavorable mobility ratio presence in the simulation model. We developed hybrid grid block (HGB) to reduce this effect. Using this grid block, the simulation is able to reduce the GOE even for unfavorable mobility ratio.

The last chapter discusses a modeling approach to reduce oil bypassed in CO_2 flood pattern. A fully compositional simulation model was developed to optimize the flood pattern. The simulation model was validated and CO_2 injection rate, slug size, WAG ratio, flood pattern were optimized. In addition, the use of viscous water during the WAG process and placing the polymer in high permeability streak were investigaed. The results show applying viscous water and polymer could significantly increase oil recovery. More details of the abstracts can be found in the following sections that appear in this report.

Chapter I-1 Effect of Overburden Pressure on Unfractured and Fractured Permeability Cores

The fracture aperture and fracture permeability are usually considered to remain the same during the producing life of the reservoir regardless of degree of depletion. Our experimental results show that the fracture aperture and fracture permeability have significant pressure-dependent changes in response to applying variable injection rates and overburden pressures. This paper addresses the laboratory experiments on the effect of fracture aperture and fracture permeability on the fluid flow under different overburden pressure. The equations to quantify the flow through the matrix and the fracture at different overburden pressures are provided. In addition the reservoir simulation was performed to model the laboratory experiments.

Chapter I-2 Investigating the Changes in Matrix and Fracture Properties and Fluid Flow under Different Stress-state Conditions

Laboratory experiments were performed on a Berea core to investigate the changes in rock properties and fluid flow under different stress-state conditions. A comparative study was done to analyze the effect of the various loading systems. The experimental results show that fracture permeability reduces significantly compared to matrix permeability as the stress increases. The hydrostatic and triaxial stresses have greater impacts on permeability reduction compared to the uniaxial stress condition. Flow in the fracture dominates when the applied stress is relatively low. However, the flow in the matrix increases as applied stress increases and dominates at high stress even though the fracture is not completely healed.

Chapter I-3 Investigating Fracture Aperture Distributions under Various Stress Conditions Using X-Ray CT Scanner

Fracture aperture is usually estimated by cubic law, which assumes flow between two smooth parallel plates. However, many researchers have proved that the fracture aperture is not a smooth surface but rather has tortuous paths and roughness and hence the flow behavior is different. Previous research showed that fracture aperture follows lognormal distribution. Nevertheless, there has not been any research conducted to validate the fracture aperture distribution with the change in stress conditions, which is common in fractured reservoirs. With the advent of X-ray CT scanner in the field of petroleum engineering, fracture apertures can be visualized and measured. Since there is no direct calculation for fracture aperture measurement from CT scanner data a calibration curve needs to be established. We developed a calibration curve based on existing calibration techniques, which involves area integration of the fracture region to obtain a correlation between integrated CT numbers and the calibrated fracture aperture. Using this calibration curve, we obtained distribution patterns for fracture apertures along the length of the core for various stress conditions, from about six thousand fracture aperture measurements for each stress condition. The results show that aperture distributions still follow lognormal distribution under various stress conditions.

Chapter I-4 Imbibition Assisted Oil Recovery

Imbibition describes the rate of mass transfer between the rock and the fractures. Therefore, understanding the imbibition process and the key parameters that control the imbibition process is crucial. Capillary imbibition experiments usually take a long time, especially when we need to vary some parameters to investigate their effects. Therefore, this research presented the numerical studies with the matrix block surrounded by the wetting phase for better understanding the characteristic of spontaneous imbibition, and also evaluated dimensionless time for validating the scheme of upscaling laboratory imbibition experiments to field dimensions.

Numerous parametric studies have been performed within the scope of this research. The results were analyzed in detail to investigate oil recovery during spontaneous imbibition with different types of boundary conditions. The results of these studies have been upscaled to the field dimensions. The validity of the new definition of characteristic length used in the modified scaling group has been evaluated. The new scaling group used to correlate simulation results has been compared to the early upscaling technique.

The research revealed the individual effects of various parameters on imbibition oil recovery. Also, the study showed that the characteristic length and the new scaling technique significantly improved upscaling correlations.

Chapter I-5 Application of X-Ray CT for Investigation of CO_2 and WAG Injection in Fractured Reservoirs

Fractured reservoirs have always been considered poor candidates for enhanced oil recovery. This is mainly due to the complexities involved in predicting performance in such reservoirs. A good understanding of multiphase flow in fractures is important to reduce oil bypass and increase recovery in these reservoirs. This paper presents CO_2 flooding experiments in homogeneous and fractured rocks with in-situ saturation and porosity measurements using an X-Ray CT scanner. We found that injection rates played an important role in the recovery process, more so in the presence of fractures. At high injection rates we observed faster CO_2 breakthrough and higher oil bypass than at low injection rates. But very low injection rates are not attractive from an economic point of view. Hence we injected viscosified water to reduce the mobility of CO_2, similar to the WAG process. Breakthrough time reduced significantly and a much higher recovery was obtained. Saturation measurements were made from the CT scans and were found to be in good agreement with those obtained from effluent data.

Chapter I-6 Analysis of Gravity Drainage Mechanism in a Short Vertically Fractured Core

Gravity drainage is an important oil recovery mechanism in naturally fractured reservoirs. In some cases it is the only mechanism that allows oil recovery and production of oil from the matrix blocks. Oil recovery by gravity drainage strongly depends on the height of the capillary continuity. Hence gravity drainage has always been associated with tall matrix blocks. Our experimental results show that gravity drainage can be an important recovery mechanism even in short matrix blocks. CO_2 flooding experiments were performed on cores with a diameter of 1 inch with a fracture at the center of the core, aligned vertically. A fourth generation CT scanner was used to obtain cross-sectional scans and determine saturations at different points of time. Saturation images indicate that gravity plays an important role in the recovery of oil by CO_2 even in a 1 inch fracture.

Chapter I-7 Investigation of Natural Fracture Aperture Distribution of Tensleep Formation Cores using X-Ray CT Scanner

The Tensleep Formation in Teapot Dome is an intensely fractured rock and considered as a CO_2 sequestration candidate. Fractured reservoirs are ideal candidates for sequestration due to the large volume of CO_2 that can be injected in a short period of time however this is an unproven and risky technology as a result of the high conductivity channels that fractures provide. The ultimate oil recovery in most NFR is very low compared to conventional oil reservoirs thus a significant fraction of the resources are left behind after abandonment. The low recovery inherent in NFR makes such reservoirs ideal candidates for sequestration/EOR carbon cycle projects since the improved cash flow will nurture the desire to apply expensive sequestration technology. However, it has not been clear how the CO_2 would flow through highly conductive fracture network. Therefore, it is critical to know the characteristics of fracture media for the success of the project.

Two cores from the RMOTC 48X28 well, Teapot Dome, were analyzed. One is retrieved from 5565 ft depth (Core-A) and the other one is from 5566 ft depth (Core-B). Both cores contain mineralized fractures and open fractures. The mineralized fractures are filled with high dense mineral such as crystalline dolomite. Some fractures exit the cores and terminations of such fractures cannot be observed.

We applied 4th generation CT scanner to get information on fracture properties such as aperture, mineralization, aperture distribution and permeability distribution without damaging cores. The CT scanner provides CT images, which show the difference between material densities. These images are not the actual physical property of fracture. Thus, it is required to provide a unique calibration curve for the Tensleep rock from these images to obtain aperture size. We found that the measured aperture distributions follow log-normal distribution by comparing measured data with generated data using log-normal probability density function. Aperture of the open fracture of Core-B is wider and distributes more widely than that of Core-A. Aperture data were converted into permeability values with the assumption of parallel plate model.

Chapter II-1 Experimental and Simulation Analysis of Fractured Reservoir Experiencing Different Stress Conditions

Flow through the fracture is usually estimated by cubic law, which assumes flow to occur between two parallel plates. The cubic law is valid to represent the flow through the fracture system if the matrix permeability is very low to provide any significant flow contribution. However, in high permeability rocks, the flow occurs through both fracture and matrix systems. Flow through matrix may sometimes exceed that through the fractures under increased stress acting on the reservoirs. Under these circumstances, the cubic law should be modified by combining the weighted average of the permeabilities in order to account for flow through matrix. In this paper we present the amount of flow through fracture and matrix system based on modified cubic law equations by conducting a series of laboratory experiments on fractured cores under different stress conditions. The flow rate through fracture and matrix system and the pressure drop were matched using simulation. X-ray CT was used to determine the fracture aperture and saturation distributions. In addition, the saturation distributions from simulation results were compared to X-ray CT Scan results.

Chapter II-2 Modeling Fluid Flow through a Single Fracture using Experimental, Stochastic and Simulation Approaches

In this chapter, sensitivity of fracture modeling, error involved in the experiments and saturation match of fracture imbibition experiments using X-ray CT Scanner are established.

A fracture is usually assumed as a set of smooth parallel plates separated by a constant width. However, the flow characteristics of an actual fracture surface are quite different, affected by tortuosity and the impact of surface roughness. Though several researchers have discussed the effect of friction on flow reduction, their efforts lack corroboration from experimental data and have not converged to form a unified methodology for studying flow on a rough fracture surface. The goal of this research is to examine the effect of surface roughness for flow through fractures and to effectively incorporate them into simulations with the aid of geostatistics.

In this study, we have shown an integrated methodology, involving experiments, stochastics and numerical simulations that incorporate the fracture roughness and the friction factor, to describe flow on a rough fracture surface. Laboratory experiments were performed to support the study in quantifying the flow contributions from the matrix and the fracture under varying confining pressures. The results were used to modify the cubic law through reservoir simulations. Observations suggest that the fracture apertures need to be distributed to accurately model the experimental results.

The methodology successfully modeled fractured core experiments, which were earlier not possible through parallel plate approach. A gravity drainage experiment using an X-ray CT scan of a fractured core has also validated the methodology.

Chapter II-3 Simulation of Fluid Flow through Rough Fractures

Flow through a fracture is usually assumed to take place between two smooth parallel plates. However, it is widely accepted that the fracture has tortuous paths as a result of surface roughness and hence the flow behavior in these paths compared to that in parallel plates is different. Although previous studies have shown that the fracture aperture follows lognormal distribution, studies have not been conducted to determine the distribution of fracture aperture with changes in stress conditions. In this paper, we present fracture aperture measurements under different stress conditions using an X-Ray CT scanner. We developed a calibration curve to obtain a correlation between CT numbers and fracture aperture since there is no direct calculation of aperture from CT scanner data. Aperture distribution patterns from about six thousand aperture measurements were obtained for each stress condition evaluated. The results of this study show that the apertures follow lognormal distribution even at elevated stress conditions. We then performed waterflood experiments as a precursor to CO_2 injection to validate the use of distributed apertures in simulators. A sensitivity analysis was also performed to analyze the effect of injection rates and fracture roughness on oil recovery.

Chapter II-4 X-Ray Tomography Results Validate Numerical Modeling of Flow in Fractures

Spontaneous imbibition plays a very important role in the displacement mechanism of non-wetting fluid in naturally fractured reservoirs. To quantify this spontaneous imbibition process, we developed a 2D two-phase numerical model. This numerical model was developed because an available commercial simulator cannot be used to model small-scale experiments with different boundary conditions. In building the numerical model, we started with the basic equation of fluid flow and developed a numerical approach of solving the non-linear diffusion saturation equation. We compared our numerical model with the analytical solution of this equation to ascertain the limitations of the assumptions used to arrive at that solution. The unique aspect of this paper is that we validated our model with X-ray computerized tomography (CT) experimental data from a different spontaneous imbibition experiment, where two simultaneously varying parameters of weight gain and CT water saturation were used. This requires us to undertake extensive sensitivity studies on key parameters before a successful match could be obtained. We also successfully captured our own X-ray computerized tomography (CT) laboratory experiment on a fractured core.

Chapter II-5 Simulation of Naturally Fractured Reservoirs Using Empirically Derived Transfer Function

This research utilizes the imbibition experiments and X-Ray Tomography results for modeling fluid flow in naturally fractured reservoirs. Conventional dual porosity simulation requires large number of runs to quantify transfer function parameters for history matching purposes. In this study empirical transfer functions (ETF) are derived from imbibition experiments and this allows reduction in the uncertainty in modeling of transfer of fluids from the matrix to the fracture.

The application of ETF approach is applied in two phases. In the first phase, imbibition experiments are numerically solved using the diffusivity equation with different boundary conditions. Usually only the oil recovery in imbibition experiments is matched, however, with the advent of X-Ray CT the spatial variation of the saturation can also be computed. The matching of this variation can lead to accurate reservoir characterization. In the second phase, the imbibition derived empirical transfer functions are used in developing a dual porosity reservoir simulator. The results from this study are compared with published results. The study reveals the impact of uncertainty in the transfer function parameters on the flow performance and reduces the computations to obtain transfer function required for dual porosity simulation.

Chapter II-6 A Unique Grid-Block System for Improved Grid Orientation

The grid orientation effect is a long-standing problem plaguing reservoir simulators that employ finite difference schemes. This study develops a unique grid-block assignment where rectangular grid blocks are interspersed with octagonal grid blocks. This grid block system is called the Hybrid Grid Block (HGB) system. The objective of this study is to evaluate the grid orientation effect of the HGB grid to see whether it is an improvement over the conventional Cartesian grid system. In HGB, flow can progress in four directions in the octagonal grid blocks and two in the square grid blocks. The increase in the number of flow directions in the octagonal grid blocks is expected to reduce the grid orientation effect in the model. This study also evaluates the grid orientation effect of the HGB and compares it with the Cartesian grid system.

HGB grid is able to reduce the grid orientation effect even for unfavorable mobility ratio displacement problems (up to M = 50.0), with maximum relative difference in pore volume recovered of 6% between parallel and diagonal HGB grid models for all the cases run in this study. Comparisons between the conventional Cartesian and HGB grid show that the HGB grid is more effective in reducing the grid orientation effect than the Cartesian grid. The HGB grid performs better by consistently giving a smaller relative difference between HGB parallel grid and HGB diagonal grid in pore volume recovered compared to the relative difference between Cartesian parallel grid and Cartesian diagonal grid in pore volume recovered at similar averaged area per grid block for all the four comparison cases studied.

Chapter II-7 Reduced CO_2 Bypassing and Optimized CO_2 Flood Design

This research utilized a modeling approach to reduce oil bypassed in CO_2 flood pattern. A fully compositional simulation model with detailed geological characterization was developed to optimize the flood pattern. The simulation model is a quarter of an inverted nine-spot and covers 20 acres area. The Peng-Robinson equation of state (EOS) was used to describe the phase behavior during CO_2 flooding. Simulation layers represent actual flow units and resemble large variation of reservoir properties. A-34 year production and injection history was matched to validate the model. Then, several sensitivities run including CO_2 injection rate, slug size, WAG ratio, pattern reconfiguration and conformance control were conducted to improve CO_2 sweep efficiency and increase oil recovery.

We found that the optimum CO_2 injection rate is approximately 300 rb (762 MSCF/D). The optimum water-alternating-gas (WAG) ratio is 1:1. This ratio allows an incremental oil recovery up to 18% with an ultimate CO_2 slug of 100% hydrocarbon pore volume (HCPV). If a polymer is placed in high permeability streak during the course of 1:1 WAG ratio, an additional recovery could increase up to 34%. The simulation results also reveal that a pattern reconfiguration change from inverted nine spot to staggered line drive could significantly increase oil recovery.

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EXECUTIVE SUMMARY

This report describes the work performed during the second year of the project, "Investigating of Efficiency Improvements during CO_2 Injection in Hydraulically and Naturally Fractured Reservoirs." The objective of this project is to perform unique laboratory experiments with artificial fractured cores (AFCs) and X-ray CT to examine the physical mechanisms of bypassing in HFR and NFR that eventually result in less efficient CO_2 flooding in heterogeneous or fracture-dominated reservoirs.

We are on the verge of an important step in the global understanding of the connection between fracture characterization and fundamentals of fluid flow in fractured systems. The combination of X-Ray CT scanning and basic fluid flow experiments in tandem with numerical simulation has allowed us to take the first steps in making the connection between field observations, simulation and small-scale experiments commonly performed in laboratories. The applications of this research are wide ranging and include the use of X-Ray CT scanning, open hole logs, well test analysis and simulation in order to input realistic fracture networks into reservoir simulators. The profound impact this research has on future engineering applications in naturally and hydraulically fractured reservoirs is immense. Until now, there has been a large disconnect between field performance, interpretation of data collected to characterize fracture networks and the techniques used to simulate and predict fluid flow in fractured systems. We believe this research will eventually provide basic tools that will allow the long-missing connection between laboratory work and theory and actual field performance.

This report provides results of the final report that consists of experiment, numerical modeling, reservoir simulation and field application. We are researching basic fluid flow in single, rough fractures and investigating different levels of stress on fluid flow behavior in the fracture. We have become adept at performing numerical simulations on this type of experiment and closely matching the observed results. An important point is we are no longer relying simply on pressure matches but also saturation distributions in the rock as determined by X-Ray CT scanning and matched with reservoir simulators. This important advancement has provided a plethora of methodologies that will eventually provide the connection between the abundant theoretical work and the numerous observations of fluid flow in naturally and hydraulically fractured reservoirs. The following headings and subsequent findings outline the work that appears in this report.

Chapter I-1 Effect of Overburden Pressure on Unfractured and Fractured Permeability Cores

We performed laboratory experiments to investigate the changes in fracture aperture and fracture permeability in response to applying variable injection rates and overburden pressures. We provided the equation to quantify the flow through matrix and fracture at different overburden pressures. The laboratory results show that the fracture aperture and fracture permeability have significant pressure-dependent changes in response to applying variable injection rates and overburden pressures as expected.

The change in matrix permeability with different injection rates under variable overburden pressures is not significant in contrast with that effect on fracture aperture and fracture permeability. At high overburden pressure the influence of existing fracture permeability on fluid flow contributor in permeable rocks (> 200 md) is not too significant.

Chapter I-2 Investigating the Changes in Matrix and Fracture Properties and Fluid Flow under Different Stress-state Conditions

In this chapter, the laboratory experiments were extended to investigate the changes in rock properties and fluid flow under different stress-state conditions. A comparative study of different stress conditions was conducted to analyze the effect of various loading systems. The experimental results show that as the stress increases, fracture permeability reduces significantly compared to matrix permeability. The hydrostatic and triaxial stresses have greater impacts on permeability reduction compared to applying stress in the uniaxial stress condition. Fluid flow through fracture dominates when applied stress is less. However, the flow through matrix increases as applied stress increases and dominates at high stress even though the fracture still does not heal completely.

Chapter I-3 Investigating Fracture Aperture Distributions under Various Stress Conditions Using X-Ray CT Scanner

This research uses X-ray CT scanner to image the fracture aperture under various overburden pressures. CT scan provides only the density differences between matrix and fracture systems but not a direct fracture aperture description. In order to determine fracture aperture, a calibration curve was developed from known fracture aperture. After the curve was established, the fracture apertures were measured at various points along the length of the core to generate sufficient data for characterizing the distributions of fracture apertures.

Our experimental results show that parallel plate approach of the fractures is no longer valid when the fracture aperture is small due to significant applied overburden pressure. The result of this study confirms the previous studies that fracture aperture distribution is lognormal distribution without overburden pressure. Upon applied overburden pressure, the distribution still follows the common lognormal distribution. The result of this study confirms the previous studies that fracture aperture distribution is lognormal distribution at no overburden pressure. Upon applied overburden pressure, the distribution still follows the common lognormal distribution.

Chapter I-4 Imbibition Assisted Oil Recovery

Different critical aspects of the capillary imbibition process have received a limited treatment in the petroleum literature. None of the recent papers devoted to capillary imbibition studies investigated the numerical scale-up of the process. The objectives of our study were to conduct numerical studies with the matrix block surrounded by the wetting phase for better understanding the characteristic of spontaneous imbibition, and also to evaluate dimensionless time for validating the scheme of upscaling laboratory imbibition experiments to field dimensions. To achieve these objectives, we performed numerous parametric studies to investigate oil recovery during spontaneous imbibition with different types of boundary conditions. These studies included the effect of varying mobility ratio, different fracture spacing, different capillary pressure, different relative permeabilities, and varying permeability profiles along the core.The results of these studies were upscaled to the field dimensions. The validity of the new definition of characteristic length used in the modified scaling group was evaluated based on our model. The new scaling group used to correlate simulation results was compared to early upscaling technique. We found that (1) the comparative study for different types of boundary conditions revealed the fact that the time required for capillary imbibition until residual oil saturation increases exponentially, as the number of open faces available for imbibition decreases. (2) The comparison of all four types of boundary conditions showed that oil recovery for the All Faces Open type of a model is most efficient and fast, as compared to other cases. (3) The effect of varying permeability profiles along the core on oil recovery showed that when water imbibes in the direction of decreasing permeability, oil recovery is higher than when water imbibes in the direction of increasing permeability. (4) The study of the effect of different water-oil viscosity ratios, at which water imbibed into the core, shows that the lower oil viscosity, the greater the volumes of oil produced from the core as a function of time. (5) As capillary pressure increases the imbibition recovery increases. Oil recovery by imbibition was sensitive to oil relative permeability curves, while no significant effect was observed in changing the water relative permeability curves. (6) The characteristic length described by Ma *et al*. in the equation of dimensionless time improved a correlation between data points for the models with different boundary conditions. (7) The spontaneous imbibition results of this study have been upscaled to the field dimensions. The validity of a new definition of characteristic length used in the modified scaling group has been evaluated. The new scaling group used to correlate simulation results has been compared to the early upscaling techniques. (8) The new technique used for upscaling, significantly improves correlations by taking end-point fluid phase mobilities and the mobility ratios into account. (9) The comparison between the new and the previous dimensionless times proves that even if non-wetting fluid viscosity varies by 3 orders of magnitude, the data could be reduced to a single curve, if we use new dimensionless time definition.

Chapter I-5 Application of X-Ray CT for Investigation of CO_2 and WAG Injection in Fractured Reservoirs

In this chapter, we investigated the displacement of oil by CO_2 using X-ray CT scanner in homogeneous and fractured cores. We conducted the experiments at various injection rates. We quantified the amount of oil bypass due to the effect of different injection rates. We also investigated the fluid transfer between matrix and fracture media. We investigated CO_2 flow in fractures, in the present of water as a mobility control agent. We also performed the experiment with adding a cross-linker to the solution to form a gel. We scanned the entire length of the core in order to obtain saturation distributions at various stages during the course of the experiments, which are important to study fluid transport in the matrix and the fracture. Important conclusions can be drawn from the work include:

1. Injection rate plays an important role in affecting oil recovery and breakthrough.
2. Early breakthrough and higher oil bypass are observed at high injection rates.

3. Low injection rate gives better sweep and higher recovery, but this is not attractive as the recovery is too slow
4. In a fractured system, fluid flow occurs mainly through the fractures and a considerable amount of time is required for the injection fluid to penetrate the matrix.
5. An alternative method like WAG is necessary to reduce the mobility of CO_2 in the fractured system.
6. Coreflood experiments using viscosified water confirmed that WAG can delay CO_2 breakthrough and improve recovery. However, leakoff into the porous rock is very high. This leakoff might be much lower in an oil-wet rock but more work is required to establish this.
7. Formation of gel can eliminate the problem of liquid leakoff into the matrix.
8. Using gel for conformance control results in better sweep and higher recoveries. The type and composition of gel to be used in the presence of CO_2 needs more investigation.

Chapter I-6 Analysis of Gravity Drainage Mechanism in a Short Vertically Fractured Core

We continued our CO_2 experiments to investigate the important mechanisms on oil recovery in a short core. We performed CO_2 experiments on cores with a diameter of 1 inch with a continuous horizontal fracture at the center of the core. CO_2 was injected into the oil saturated core at a low injection rate of about 0.1cc/min to eliminate the effect of viscous forces. A fourth generation CT scanner was used to obtain cross-sectional scans and determine saturations at different points of time. We found that gravity drainage is the main recovery mechanism in this short matrix blocks contrary with previous widely believed that the gravity drainage had always been associated with tall matrix blocks.

Chapter I-7 Investigation of Natural Fracture Aperture Distribution of Tensleep Formation Cores using X-Ray CT Scanner

As part of our technology transfer activity, we collaborated with DOE-RMOTC to implement CO_2 sequestration in Tensleep formation of Teapot Dome. With our expertise in X-Ray CT scanning, we investigated the fracture properties of Tensleep fractured cores. We conducted similar experiments as we did for Berea cores. We found that the Tensleep cores have the following properties:

(1) The cores have open and mineralized fractures, (2) the open and mineralized fractures have totally different fracture aperture sizes, (3) and the open fracture has wider aperture size and more widely distributed apertures than the mineralized fracture. The results of this study will be included in our current effort in modeling and simulating the sequestration process in Teapot Dome.

Chapter II-1 Experimental and Simulation Analysis of Fractured Reservoir Experiencing Different Stress Conditions

In the last topic, the modeling of fluid flow through a single fracture incorporating the effect of surface roughness is conducted. Fracture permeability is usually estimated by a cubic law that is based on the theory of hydrodynamics for the laminar flow between flat plates. However, the cubic law is too simple to estimate the fracture permeability correctly, because the surface of real fracture is much more complicated and rougher than the surface of flat plate. Several researchers have shown that the flow characteristics of an actual fracture surface would be quite different due to the effect of tortuosity, impact of surface roughness and contact areas. Nonetheless, to date, these efforts have not converged to form a unified definition on the fracture aperture needed in the cubic law. In this study, therefore, we show that the cubic law could still be used to model small-scale and field-scale data as long as it is modeled effectively, accounting for the effect of surface roughness associated with the fracture surface. The goal of this research is to examine the effect of surface roughness for flow through fractures and to effectively incorporate them into simulations with the aid of geostatistics. Since the research has been supported with experimental results, the consistency of the results enabled us to define a methodology for single fracture simulation. This methodology successfully modeled the flow rate and pressure drop from fractured core experiments, which were earlier not possible through parallel plate approach. Observations suggest that the fracture aperture needs to be distributed to accurately model the experimental results. The effect of friction and tortuosity due to surface roughness needs to be taken into account while modeling.

Chapter II-2 Modeling Fluid Flow through a Single Fracture using Experimental, Stochastic and Simulation Approaches

X-ray CT scan reveal that the parallel plate assumption in modeling fluid flow in fracture media seldom reflects the nature of flow through fractures. In this chapter, sensitivity of fracture modeling, error involved in the experiments and saturation match of fracture imbibition experiment using X-ray CT Scanner are established. Important conclusions can be drawn from the work include:

1. The fracture aperture needs to be distributed to accurately model the experimental results.
2. The effect of friction factor due to surface roughness should be considered in modeling fluid flow through rough fracture surface.
3. Fluid flow increases as the variance of the aperture distribution increases. This reiterates the fact that tortuosity in fluid flow is a significant factor.
4. The effective hydraulic aperture is reduced with increased variance of the aperture distribution.
5. Beyond an aperture size of approximately 60 microns, the effect of roughness or tortuosity is found to be insignificant.

Chapter II-3 Simulation of Fluid Flow through Rough Fractures

In this chapter, we investigated waterflooding displacement mechanisms in fractured cores using X-ray CT scanner. We conducted the experiments at various injection rates and scanned the core being flooded at certain times. We recorded oil and water rates at the outlet point. We developed two simulation models where one model describes fracture as parallel plate model and the other model describes it as distributed fracture aperture model. Both results were compared to the experimental data. Once we achieve satisfactory matches, we performed sensitivity studies to analyze the effect of injection rates on oil recovery and breakthrough time. Important conclusions can be drawn from the work include:

1. Simulation results indicate that the parallel plate model fails to duplicate laboratory experiment performance hence this model does not adequately represent a fractured model.
2. On the other hand, satisfactory matches between simulation and experimental data using distributed aperture model shows this model provides an accurate description of a fractured model.
3. The water breakthrough time increases as fracture aperture and injection rate increase.
4. As the injection rate increases the difference in the oil recoveries predicted by the two models increases.
5. At large aperture sizes, the performance of the parallel plate model becomes closer to that of the distributed aperture model. This indicates that there is a certain critical fracture aperture where both models would give similar results.

Chapter II-4 X-Ray Tomography Results Validate Numerical Modeling of Flow in Fractures

This chapter emphasis on modeling spontaneous imbibition experiments in order to understand the spontaneous imbibition process. As a tool to verify this numerical model, the results from X-Ray CT were utilized. We started our modeling development from basic equation and came up with a robust two-dimensional two-phase numerical model that could faithfully reproduce laboratory experiments. This model was rigorously verified with experimental data.

Chapter II-5 Simulation of Naturally Fractured Reservoirs Using Empirically Derived Transfer Function

In previous chapter, we have shown that we are able to model the spontaneous imbibition experiment utilizing the X-Ray CT scan results. We continued our effort by including the imbibition modeling into dual porosity simulation by changing the fluid transfer term. A detail explanation about different transfer functions, derivation of mathematical modeling and dual porosity simulator development using empirical derived transfer function (EDTF) are presented in this report. The results show that dual porosity simulation with EDTF is inherently faster because the number of unknowns per grid block is reduced to two from four. However, "Material Balance" is not conserved to the extent of conventional dual porosity formulations.

Chapter II-6 A Unique Grid-Block System for Improved Grid Orientation

The second chapter is part of our paper that will appear at the SPE Asia Pacific Oil and Gas Conference and Exhibition held in Perth, Australia, 18–20 October 2004. In this chapter, we developed a finite difference IMPES-formulated two dimensional black oil simulator using both Cartesian grid block system and a unique grid block system called Hybrid Grid Model (HGB). We compared the viability of this simulator using Cartesian grid block system with a commercial simulator Eclipse™. We examined the grid orientation in conventional grid block system and then we ran simulation cases using the HGB grid system. Important conclusions can be drawn from the work include: (1) The grid orientation effect was observed in rectangular Cartesian grid models even with isotropic and homogeneous reservoirs with favorable mobility ratio. (2) Grid refinement can help to minimize the grid orientation effect in rectangular Cartesian grid models when there are favorable mobiliy ratios, ie. M=1.0 or less. However, at an unfavorable mobility ratio, neither the parallel, diagonal grid orientation, nor grid refinement is effective in reducing the grid orientation effect. (3) HGB grid is able to minimize the grid orientation effect even for unfavorable mobility ratio displacement problems, with relative difference of about 6% for all the cases run.

Chapter II-7 Reduced CO_2 Bypassing and Optimized CO_2 Flood Design

All the previous CO_2 flooding studies were conducted in the laboratory scale. As part of our technology transfer activity, in this chapter we focused on investigating CO_2 performance in the field scale dimensions. The effect of heterogeneity in the prominent Wasson Field CO_2 flood in West Texas on the overall sweep efficiency was investigated. A compositional simulation model was developed and then used to optimize CO_2 injection rate, flood patterns, slug sizes, and WAG ratio. The use of a viscous agent in WAG application and polymer injection in conformance control were explored to improve oil recovery. The results show that (1) recovery from a WAG process is a function of the injection rate as well as WAG ratio and the percentage of CO_2 slug size. (2) WAG injection is effective in increasing the sweep efficiency of the CO_2 injection. (3) Increasing viscosity of water injection and placing polymer in high permeability streak result in a positive production response and (4) a pattern reconfiguration change from inverted nine spot to staggered line drive could significantly increase oil recovery.

Project Fact Sheet

Progress work efforts at Project Fact Sheet are listed in the Appendix.