Visualisation of water flooding and subsequent supercritical CO₂ flooding in fractured porous media with permeability heterogeneity using MRI

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Abstract

Fractured reservoirs form a large percentage of the world’s hydrocarbon reserves. However, in spite of their wide occurrence and huge reserves, the oil recovery from most of these reservoirs is extremely low. CO₂ flooding has proven to be an efficient Enhanced Oil Recovery (EOR) method. This article addresses the use of MRI technique to follow the removal process of oil, water, supercritical CO₂ multiphase flow in fractured artificial consolidated sandstone core with permeability heterogeneity at a typical reservoir temperature and pressure condition. Fluid saturation development was monitored both in the matrix and in the fractures. 2D images at various times and quantitative saturation curves were obtained during all stages of the flooding process. The fronts and interfaces between displaced and displacing fluids were also dynamics monitored in situ during water and subsequent supercritical CO₂ flooding process. The results showed that the oil recovery rate can be determined by porosity, permeability and structure of the core, supercritical CO₂ flooding can enhance oil recovery evidently after the water flooding.

Keywords: CO₂ flooding; MRI; porous media; fractured; heterogeneity

1. Introduction

The growing concern about global warming and shortage of energy supply has increased the interest in combined geological CO₂ storage and CO₂ flooding to enhance oil recovery (EOR). CO₂ flooding has proven to be an efficient Enhanced Oil Recovery (EOR) method. Fractured reservoirs form a large percentage of the world’s hydrocarbon reserves. However, in spite of their wide occurrence and huge reserves, the oil recovery from most of these reservoirs is extremely low. Fractured reservoirs form a large percentage of the world’s hydrocarbon reserves. However, in spite of their wide occurrence and
huge reserves, the oil recovery from most of these reservoirs is extremely low. This can be attributed to their poor response to both secondary and tertiary recovery operations. Various methods are used to stimulate production by fracturing underground formations. So understanding and predicting the flow mechanisms of multiple fluid phases in fractured media is important for designing methods to recover petroleum reserves and for remediation of groundwater resources. The presence of fractures greatly complicates the dynamics of flow within porous media, particularly in situations for which multiple fluid phases are present. In a fractured system, the displacement process is dependent on the fracture-matrix geometry, size and interaction apart from other physical phenomena[1]. Uleberg and Hoier[2] suggest that the injection fluid tends to flow through the highly permeable fractures, often resulting in early breakthrough and poor sweep efficiency. But most models for multiphase flow in fractured media are based on simplified or idealized conceptual representations which generally have not yet been sufficiently validated with experimental data. Nuclear magnetic resonance imaging(MRI) provide unprecedented opportunity to characterize fractures and flow distributions in porous media. For example, the transfer and fluid flow behavior during water flooding in the fractured rock was experimentally investigated[3-5]. Brautaset et al.[6] have investigated fluid saturation distributions and monitored the fluid flow characteristics in-situ during waterflood and subsequent injection of either liquid or supercritical CO$_2$ in four Portland Chalk core samples at different wettabilities. The visualization of CO$_2$ flooding in immiscible and miscible displacements in a high-pressure condition was studied using a 400 MHz MRI system.[7]

In this study, in order to expand the understanding of the recovery mechanisms, during water flooding and subsequent supercritical CO$_2$ flooding in fractured porous media, the fracture/matrix transfer and fluid flow behaviour in fractured rock was experimentally investigated in a flooding experiments using MRI. The effects of reservoir heterogeneity was also taken into account, the cores used for the flooding experiment were the artificial consolidated sandstone core with two different layers, which were permeability heterogeneity in horizontal direction. The objective was to determine the impacts on fluid flow in fractured porous media with horizontal permeability heterogeneity.

2. Experimental apparatus and measurement techniques

2.1 Experimental Setup

A simplified schematic diagram of the experimental setup is shown in Fig 1. The system consists of the core sample, a core holder to maintain the sample at high-pressure and high-temperature, a high-pressure control system(overburden), inlet and outlet pumps, and the MRI to monitor the distribution of water, oil and CO$_2$. The experimental setup consisted of two circuits, namely, the displacement process line and the temperature and pressure control circulation line. In the displacement process line, oil, water and CO$_2$ was injected into the core holder by a ISCO syringe pump, respectively. The flow rate and back pressure were controlled by the pump and a back pressure regulator (MODEL BP-2080-M, JASCO). The back pressure regulator employ a patented flow-switching valve (FSV) mechanism that enables stable system pressure control even at the lowest volume limit possible.

In the temperature and pressure control circulation line, Fluorinert (FC-40) was used as both the confining fluid and the temperature control medium. Fluorinert is a fluorocarbon and contains no hydrogen atoms, thus it is not imaged, and its low dielectric properties minimize radio frequency (RF) losses. This fluid was maintained at the desired pressure while circulated through the heating system and cell by use of a recirculation pump.

In this study, for the visualization of the process of CO$_2$ injected into the core at a high pressure and a high temperature, a high-pressure core holder was designed and constructed for the Varian NMR Systems with a 40mm inner diameter RF probe. The high-pressure core holder are shown in Fig 2. The holder was designed and constructed for MRI measurements, which was inserted vertically into the MRI system.
according to Fig 1. The maximum working pressure is 15MPa and the maximum working temperature is 70°C. This high-pressure core holder is constructed from materials that are compatible with the strong magnetic and RF fields generated by the MRI. The housing is made with polyimide. This housing is strong enough to handle the pressure of the experiments, The end caps are made from titanium and are held in place by non magnetic cobalt screws that threads through the housing into the end cap. The end caps contains two holes acting as system line pass-through, these are sealed around the system lines using o-rings.

The confining fluid is connected to two lines on one of the end caps. One of the confining lines passes through to the other side of the confining volume and allows the fluid to circulate. The end pieces directly connected to the core are constructed from polyimide. They are assembled with the core using two polyimide end spacers on the core ends and two layers of Teflon® shrink tubing around the core. The seal is provided by an o-ring milled into the end piece. The pass through on the cell end caps stabilizes the end piece and helps to hold the core and shrink tubing in place. Temperatures at the inlet and outlet of the core holder were measured using thermocouples.
2.2 Experimental material and measurement method

The artificial consolidated sandstone core with 15mm in diameter and 40mm in length were used in the experiments, showed in Fig 3. The sandstone layers were oriented such that the normal to each layer surface was parallel to the cylinder axis. The critical point of CO₂ is at 31.1°C and 7398kPa. Minimum Miscible Pressure (MMP) for the n-Decane/CO₂ system has been determined at 35°C and 7329kPa[8] and at 37.8°C and 7894kPa[9]. In this study, temperature of 40°C and pressure of 8.5MPa were selected to ensure the supercritical properties for the supercritical CO₂ miscible displacement test. These conditions corresponded to conditions in the reservoir at a depth of about 850m.

CO₂ with 99% purity was used as the gaseous phase, and n-Decane was used as the oleic phase in the experiments. The density of CO₂ is 0.354g/cm³ and the viscosity is 0.026cP, the density of n-Decane is 0.721g/cm³ and the viscosity is 0.749cP at 40°C and 8.5MPa. The absolute permeability to air of the left part is 506mD, the right part is 252mD. The porosity of the left part was 26.7%, the right part is 26.5%, which was calculated from the traditional gravimetric measurements method.

All MRI measurements were performed on Varian NMR systems with 9.4Tesla, wide-bore (89mm in diameter) and vertical superconducting magnet. A ¹H 40mm Millipede vertical micro-imaging probe was used and the gradient coils provided a maximum gradient strength of 50G/cm. The spatial resolution used is in the sub-millimeter scale. All the images were acquired with standard spin-echo multi-slice pulse sequence (SEMS). Because the water and oil wetted the pore surface and interacted with the mineral surface, the T₂* relaxation was short. To obtain reasonable signal intensity from the 2D spin-echo images the echo time was set to be short. The MRI was conducted during flooding by using the following experimental parameters: echo time (TE) is 1.31ms, repetition time (TR) is 2s, image data matrix is 96×96, field of view (FOV) is 40mm×40mm with 2mm or 16mm thickness, number of images for averaging is 1, acquisition time is 3 minutes 12 seconds. Water/oil contained in the core was visualized in longitudinal planes along the flow direction.

2.3 Experimental Procedure

A general outline of the experimental procedure is given below:
1. For a fractured core experiment, the core is first heated at about 90°C for a sufficient period to remove all residual water saturation, then the core are assembled in the core holder, placed in the MRI superconducting magnet and evacuated using a vacuum pump.
2. The core is saturated with deionized water at the desired temperature and pressure, and then carefully tuned shimming and set the pulse parameters, scan the core to obtain the image at 100% water saturation and determine the porosity.
3. The backpressure regulator at the outlet is fully closed and the pressure in the core holder is allowed to build up. Care is taken that the overburden pressure is always at least 2MPa higher than the pressure
inside the sleeve. Once the desired pressure is reached, Fluorinert was maintained at the desired 
temperature and pressure while circulated through the heating system and cell by use of a recirculation 
pump.

4. MnCl₂ aqueous solution (of Mn²⁺ ion concentration of 5000mg/L) flooding deionized water, until 
100% deionized water is displaced by MnCl₂ aqueous solution (¹H image signal cannot be detected 
completely), then oil is injected to flood MnCl₂ aqueous solution, establish irreducible water, until the 
content of oil is reached 98% or more at the outlet, oil injection is stopped. The oil-saturated core is 
imaged again to obtain oil saturation distribution and determine the initial oil saturation.

5. For a water flooding and subsequent supercritical CO₂ flooding experiment, water and following CO₂ 
is injected when desired and the core is imaged at various times to visualize fluid flow and determine 
saturations at various times during the injection process.

3. Results and Discussion

3.1 MnCl₂ aqueous solution injection

Fig 4 shows a series of NMR images during the process of the aqueous paramagnetic ion solution 
(5000mg/L of MnCl₂) flooding water at constant injected rate of 0.05ml/min, which illustrate oil 
saturation at different injected time of 0, 8, 16, 24, 32, 40, 48 and 56min, respectively. The bright regions 
(red) indicate the high NMR signal intensities corresponding to high water saturation, while the dark 
regions (blue) indicate the lower water saturation. The permeability of a fracture is typically about 10³ to 
10⁶ times greater than the permeability of the porous rock. In a fractured system, when the aqueous 
paramagnetic ion solution (5000mg/L of MnCl₂) was injected, the tendency of the fluid would be to flow 
through the high permeability fracture which leads to early breakthroughs. MnCl₂ aqueous solution in the 
left part of the core moved upward rapidly than in the left part of the core because the permeability of the 
left part is higher than the right part. Fig 5 shows the evolution of MRI signal intensity curves during 
MnCl₂ aqueous solution injection.

![Fig. 4 Distribution of MRI signal intensity in the core during MnCl₂ aqueous solution injection rate of 0.05mL/min](image-url)
Fig. 5  MRI signal intensity curves vs. time during MnCl₂ aqueous solution injection

3.2 Water and subsequent supercritical CO₂ injection

Fig. 6  Distribution of MRI signal intensity in the core during water injection and subsequent supercritical CO₂ injection rate of 0.05mL/min
The NMR signal intensity on the spin density images from any local position is proportional to the oil content in the porous media. This means that the measured NMR signal intensity reflects the local oil saturation in the porous media. In the flooding experiments with CO\textsubscript{2} injection, the initial NMR signal intensity distributions in the porous media saturated with oil is obtained. Then, the CO\textsubscript{2} is injected into the porous media with time-series acquisition of NMR images. The injected CO\textsubscript{2} would displace some oil in the porous media thus decreasing the NMR signal intensity. The oil saturation in each pixel is calculated as the ratio of the NMR signal with and without the CO\textsubscript{2} \((t = 0)\). The oil saturation profile of total core versus volume of CO\textsubscript{2} injection is obtained and the results were shown in Fig 6.

Fig 6 shows a series of NMR images at constant CO\textsubscript{2} injected rate of 0.05 ml/min, which illustrate oil saturation at different CO\textsubscript{2} injected time of 0, 16, 36.8, 57.6, 78.4, 100.8, 108.8, 120, 140.8, 161.6, 182.4 and 196.8 min, respectively. The bright regions (red) indicate the high NMR signal intensities corresponding to high oil saturation, while the dark regions (blue) indicate the lower oil saturation. For instance, the first image shows the initial oil distribution in porous media. Fluid saturation development was monitored both in the matrix and in the fractures. 2D images at various times (Fig 6) and quantitative saturation curves (Fig 7) were obtained during all stages of the flooding process. The injection of water was stopped after 100.8 min and CO\textsubscript{2} injection started. The fronts and interfaces between displaced and displacing fluids were also dynamics monitored in situ during water and subsequent supercritical CO\textsubscript{2} flooding process. In a fractured system, when the water and following CO\textsubscript{2} were injected, the fluid early breakthrough the high permeability fracture, and the fluid in the left part of the core moved upward rapidly than in the left part of the core because the permeability of the left part is higher than the right part. The results showed that the oil recovery rate can be determined by porosity, permeability and structure of the core, CO\textsubscript{2} flooding can enhance oil recovery evidently after the water flooding. The initial oil saturation is 78%, the oil recovery rate is 27.5% after water flooding and 66% after CO\textsubscript{2} flooding in the left part of core. The initial oil saturation is 75%, the oil recovery rate is 23.6% after water flooding and 57.1% after CO\textsubscript{2} flooding in the right part of core. The total mean oil recovery rate is 25.4% after water flooding and 61.4% after CO\textsubscript{2} flooding.

Conclusions

The following conclusions can be derived from the core flooding experiments performed in the laboratory.
1. In a fractured system, the high permeability fracture serves as the preferred path for the injected fluid. This leads to early breakthrough and higher oil bypass. Oil recovery rate can be determined by porosity, permeability and structure of the core, CO2 flooding can enhance oil recovery evidently after the water flooding.

2. MRI is a powerful non-destructive analytical tool in studies of multiphase flow in fractured porous media with permeability heterogeneity, 2D images at various times and quantitative saturation curves were obtained during all stages of the flooding process. The fronts and interfaces between displaced and displacing fluids were also dynamics monitored in situ during water and subsequent supercritical CO2 flooding process. provides excellent dynamic information of the displacement process, and evaluates the swept efficiency of enhanced oil recovery efforts.

Acknowledgements

The authors acknowledge the funding of the National Natural Science Foundation of China (Key Program, Grant No. 51106019), the National High Technology Research and Development Program of China (863 Program, Grant No. 2009AA063402), the National Basic Research Program of China (973 Program, Grant No. 2011CB707304), the National Natural Science Foundation of China (Grant Nos. 51106019, 51206018), and the Fundamental Research Funds for the Central Universities (Grant No. DUT11RC(3)65).

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