MAGNETIC RESONANCE IMAGING OF OIL RECOVERY DURING SPONTANEOUS IMBIBITION FROM CORES WITH TWO-ENDS OPEN BOUNDARY CONDITION

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ABSTRACT

Spontaneous counter-current imbibition into cores with different boundary conditions progresses at significantly different rates. In order to compare experiments conducted using different boundary conditions, one needs to be able to scale results for boundary conditions. One approach is based on the characteristic length. The definition by Ma et al. in 1997 provided satisfactory scaling for strongly water-wet high permeability Berea sandstone. The boundary conditions used in previous experiments include All-Faces-Open (linear and radial, counter-current imbibition), One-End-Open (linear, counter-current imbibition), Two-Ends-Open (linear, counter- and/or co-current imbibition) and Two-Ends-Closed (radial, counter-current imbibition). The characteristic length for Two-Ends-Open (TEO) boundary condition was expected to scale as if the process consists of linear imbibition into two separate One-End-Open (OEO) cores with length equal to half that of the TEO core. However, as further data were accumulated, TEO data often exhibited inconsistencies in scaling, usually with dimensionless times being longer than expected. These observations triggered more detailed investigation. The TEO geometry is a special case because it allows the possibility of recording recovery by imbibition separately from each of the producing end faces, and can therefore be used to test the theory behind the characteristic length. Separate production from each end face revealed that oil production was often asymmetrical, with more than 85% of the oil recovery from one side in some cases. The pressure generated within the core during imbibition was also recorded. Also, spontaneous imbibition was imaged using Magnetic Resonance Imaging (MRI) to track the movement of water and oil within the core plug. Brine imbibition was usually symmetrical and oil production asymmetrical. In two tests, an imbibition brine front was developed almost entirely from one end face of the core and moved in a piston-like manner. In each test, the oil produced from each open end face was highly asymmetrical. In repeated tests with the core plug orientation inverted, the primary imbibition front was still established from the same end face, no matter whether gravity aids or opposes imbibition. This demonstrated that both co-current and counter-current flows occur during imbibition. The TEO imbibition results present a special case that is amenable to detailed investigation.

INTRODUCTION

Counter-current flow due to spontaneous imbibition is considered to be an important mechanism of oil recovery in fractured reservoirs (Morrow and Mason, 2001). Laboratory imbibition experiments generally provide an oil production curve of oil recovery versus imbibition time. The imbibition production rate can be used to assess wettability and the final oil recovery determines the microscopic displacement efficiency. Imbibition experiments are used to investigate the effects of rock type, oil, brine, interfacial tension, viscosity ratio, permeability, and wettability on the production of oil by encroaching water. Other measurements that have been made during imbibition experiments include pressure in the oil phase in the uninvaded end of the core (Li et al., 2009). In the present study, magnetic resonance imaging is used to provide details of initiation of imbibition, frontal movement, and saturation profiles that will aid in developing an improved understanding of the imbibition oil recovery mechanism.

Understanding mechanisms of spontaneous imbibition is crucial for modeling fractured reservoirs (Kazemi et al., 1992; Behbahani et al., 2006). While correlation of spontaneous imbibition results has been studied extensively (Mattax and Kyte, 1962; Reis and Cil, 1993; Ma et al., 1997; Wang, 1999; Zhou et al., 2002; Ruth et al., 2004; Li and Horne, 2006; Fischer et al., 2008; Standnes, 2009; Mason et al., 2010b), much remains to be understood about the conditions under which characteristic lengths can compensate for different boundary conditions. One of the widely used methods to calculate characteristic core length for different boundary conditions (Rangel-German and Kovscek, 2005; Yildiz et al., 2006; Fischer et al., 2006; Hatiboglu and Babadagli, 2007; Fischer et al., 2008) was proposed by Kazemi et al. (1992) and modified by Ma et al. (1997).

Ma et al. (1997) tested the block shape factor introduced by Kazemi et al. (1992) against experimental data and showed that improved correlation was obtained by defining L_c as

$$L_c = \sqrt{\frac{V_b}{\sum_{i=1}^{n} \frac{A_i}{l_{Ai}}}}$$

where the definitions of V_b and A_i are the same as that of the block shape factor defined by Kazemi et al. (1992), but l_{Ai} is the distance from any particular open surface to its no-flow boundary rather than for the center of the block.

For the TEO open condition the Kazemi and Ma characteristic lengths are identical. However, correlation of TEO data was comparatively poor (Johannesen, 2008). Mason et al. (2010a) reported that oil recovery from the two end faces of a Very Strongly Water Wet (VSWW) TEO core could range from almost symmetric to highly asymmetric for essentially duplicate experiments. Nuclear tracer studies showed that, while the production of oil could be highly asymmetric, the invasion of brine was always close to symmetric.

The TEO boundary condition has been investigated using MRI. Oil production from the two end faces and observations by MRI of the distance of advance of the imbibition front with time has provided further details, including the effect of gravity on mechanism of imbibition.

EXPERIMENTAL METHODS

Rock Types

Chalk

Chalk core samples were obtained from the Rørdal outcrop at the Portland cement factory in Ålborg, Denmark. The rock formation is of Maastrichtian age and consists mainly of coccolith deposits, and the composition is mainly calcite (99%) with some quartz (1%).

Whitestone Upper Zone (UZ) Limestone

Whitestone UZ is a quarried oolitic limestone also known as Texas Crème. Porosity is associated with fossil shells that are filled with varying amounts of calcite cement. Heterogeneity was indicated by variation in gas permeability and porosity even for cores cut from a single core block. Imbibition studies for recovery of mineral oil indicated that this limestone, as received, gives VSWW conditions.

Oil

Mineral oil (μ = 1.4 cP, ρ = 0.78 g/cm^3) was used for the imbibition experiments on chalk. n-Decane (μ = 0.92 cP, ρ = 0.73 g/cm^3) was used as the oil in the experiments with limestone on imaging. The oil was placed under vacuum to remove any dissolved air before saturating the cores.

Brine

A synthetic seawater was prepared with D_2O (μ = 1.4 cP, ρ = 1.13 g/cm^3) as the aqueous phase for the MRI experiments. The brine was prepared with D_2O to provide the contrast needed for detection of the n-Decane saturation.

Spontaneous Imbibition Experimental Setup and Procedures

Initial tests used the experimental setup shown in Figure 1 to measure produced oil from each end of a TEO arrangement in a series of chalk cores. The cylindrical surface of the cores was coated with epoxy resin to create the TEO boundary geometry. Some samples were saturated with mineral oil under vacuum without initial water, whereas others were saturated with brine and then oil flooded with a constant differential pressure to low initial water saturation. Oil was injected in both directions to aid in establishing a uniform distribution of initial water. Cores were submerged in brine and production was recorded from each open end face as a function of time (Figure 1).

Magnetic Resonance Imaging Experimental Setup and Procedures

MRI 2-D and 3-D images were acquired with a Varian 2.0T Anova imager setup (Figure 2) using standard spin-echo pulse sequences. This MRI operated at about 2 Tesla resonance frequency with a spatial resolution of about 0.8 mm^3. Suitable images were collected every 4 or 8 minutes during the imbibition tests to obtain the desired signal-to-noise with this equipment. These vertical images have a Field Of View (FOV) of 100 mm x 125 mm.

After measurement of basic core properties, the outer surface of the core was coated with epoxy. The core was then saturated with n-Decane (no initial water saturation) under vacuum and then pressured at 1000 psi pressure to ensure complete saturation. The cores were immersed in synthetic seawater prepared with D_2O. 3D images were obtained for the fully n-Decane saturated core and the core at residual oil saturation at the end of the experiment, because these stable saturation conditions allow long scanning times. 2D images of much lesser volume than the whole core plug were obtained continuously throughout the experiment for a 2 cm wide slice along the middle of the core. The distance of advance of the imbibition front was measured from the images and plotted against the square root of time. 2D images and saturation profiles were used to obtain an estimate of oil production. The MRI 3D image intensities at the beginning and end of the experiments were used to verify the residual oil saturation. Production determined from imaging was checked against volumetric material balance at each step of an experiment.

One TEO core was immersed in brine vertically while a second TEO core was immersed in brine horizontally to investigate possible differences in oil production rates which could result from differences in orientation. At the end of the vertical TEO experiment, the core was cleaned with Toluene and Methanol and placed in a vacuum oven to dry. The core was re-saturated completely with n-Decane. The core was then inverted with respect to the previous vertical TEO experiment and immersed in brine to investigate whether the oil production is affected by the density differences between the brine and the oil.

RESULTS AND DISCUSSION

For 13 chalk cores (C1-C13) the produced oil (% OOIP) was collected separately from each open end face and recorded versus time (minutes) (Figure 3). The degree of asymmetric production varied from core to core. Asymmetric production was not sensitive to the presence of water as indicated by equal asymmetry, for cores C1 and C6 which were with and without initial water, respectively. The total rate of production from both end faces was not correlated to the degree of asymmetry observed when measuring the production from each open end face separately (Table 1). For example, similar total recovery curves were observed for cores C1 and C7, but production was almost symmetric for core C1 and highly asymmetric for core C7. Three cores (C7, C8 and C11) gave more than 80% of total oil production from one side. For ten of the 13 cores (C2, C3, C6 and C7 through C13), production started at the end face that ended up with the lowest total production. For the other three cores (C1, C4 and C5), the production from the starting end face remained highest throughout the test. MRI spontaneous imbibition experiments were performed to further investigate the asymmetry in oil recovery from the two open end faces.

Almost all of the MRI images showed the development of sharp piston-like fronts in the VSWW experiments. These images support modeling of imbibition at VSWW conditions as piston-like displacement with due allowance for counter flow of the non-wetting (oil) phase. The TEO experiments on a core set vertically demonstrated that the imbibition front was established at the same end face of the core regardless of the core orientation (Figures 4 and 6). This result is definitive support for the conclusion (Mason et al. 2010) that the detailed pore structure of individual cores plays a significant role in determining the end of the core at which imbibition begins. So it is important to keep track of the direction in which cores are drilled and also to track how this relates to porosity and initial water distributions before imbibition tests are performed. Any noticeable saturation gradients along the core might provide indication as to the end face from which the imbibition front first becomes established. It was observed through NMR measurements that most of the Whitestone UZ limestone cores had a saturation gradient along the cores probably due to heterogeneity in pore structure. Vugs observed in new core blocks of Whitestone UZ limestone could further contribute to variations in saturation and porosity. At the beginning of imbibition, counter-current flow appeared to be dominant. However, as the imbibition experiment progressed, the oil recovery was observed mostly from the opposite end face of the core, so the flow of oil was to some degree co-current with respect to influx of brine from one of the end faces.

Imaging techniques allow investigation of relationships between imbibition fronts, oil recoveries, and imbibition rates. In the current study, all of the obtained oil recovery and average frontal distance data exhibited linear relationships with respect to square root of time (Figures 5 (a) and 7 (a)). The average frontal distance squared versus imbibition time plots, as provided, exclude small induction times at the beginning of experiments (Figure 5 (b) and 7 (b)). Even though oil production and imaging began once the experiment was set up, the first image was not obtained until a few minutes had passed. An adequate number of scans have to be run to obtain a good quality image and therefore, details of the saturation profiles and fronts were not obtained for the very beginning of the experiment. Oil recovery data could not be estimated for the TEO imbibition experiment with the horizontal orientation because the saturation profiles were too noisy.

Comparison of average frontal distance relationships for the different boundary conditions showed that the fastest imbibition was observed for the TEO experiments with vertical orientation where the imbibition front was established from the top end face of the core, even though the density difference between brine and oil opposed imbibition. The TEO experiment with the horizontal orientation showed imbibition fronts in between the two vertical TEO experiments. However, towards the end of the experiment, horizontal imbibition was similar to that of the vertical TEO case where the imbibition front was established at the bottom end of the core. Even though there were differences in imbibition rates, the oil production ratios from the two end faces in the vertical experiments with the same core were almost identical; 84.4% at the top end and 15.6% at the bottom end for the TEO vertical orientation and 16% at the top end and 84% at the bottom end for the TEO vertical – reverse orientation.

Magnetic resonance imaging could be further used to monitor spontaneous imbibition of D_2O into cores containing low initial water saturations and varied degrees of water wetness to determine the nature of displacement fronts for a wider range of conditions.

CONCLUSIONS

VSWW, TEO imbibition resolved into a sharp piston-like (frontal) displacement. The imbibition fronts of the VSWW, TEO vertical experiments always initiated from the same end face of the core despite the orientation of the core. The VSWW, TEO horizontal experiment also showed initiation of the imbibition front from one end face of the core. This behavior implies that subtle differences in the rock properties at each end of the core can have a greater effect than gravity on determining the relative amounts of oil production from each face. The dominant property involved is most likely the capillary back pressure required to produce oil from a surface immersed in wetting phase. The oil in the core is under a positive pressure (generated by the imbibing interfaces) and escapes from one end of the core before the other, if the capillary back pressure for onset of oil production is lower for one end face than the other. Oil recovery and average frontal distance of advance were relatively linear with respect to the square root of time.

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Table 1 Ratio of oil production from each open end face during asymmetric oil recovery

Core	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Total R_f [%OOIP]	0.49	0.57	0.62	0.58	0.60	0.62	0.63	0.55	0.50	0.58	0.58	0.63	0.60
Low prod [%]	44%	38%	38%	28%	32%	42%	15%	20%	48%	28%	19%	28%	47%
High prod [%]	56%	62%	62%	72%	68%	58%	85%	80%	52%	72%	81%	72%	53%

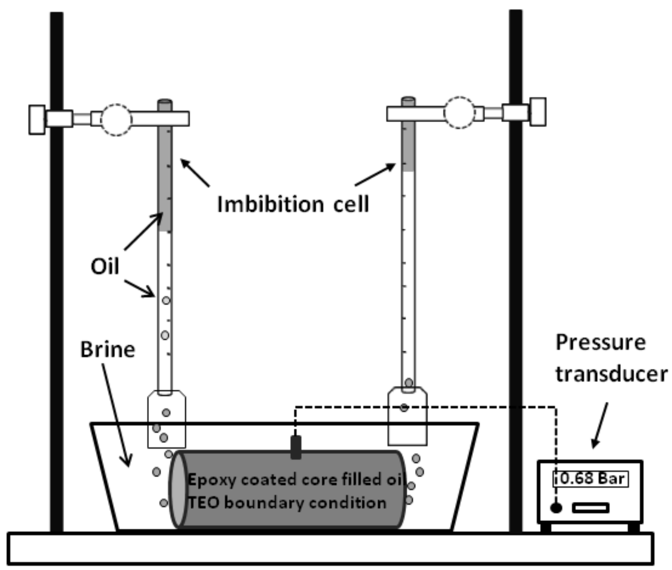


Figure 1 Experimental setup for collecting produced oil separately from each of the open end faces in oil saturated Chalk cores with TEO boundary condition.

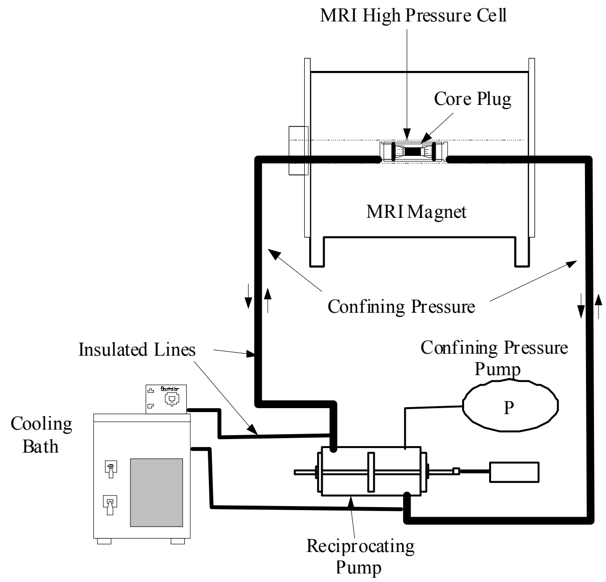


Figure 2 Schematic diagram of the MRI setup for spontaneous imbibition experiments of Whitestone UZ limestone cores with TEO boundary condition.

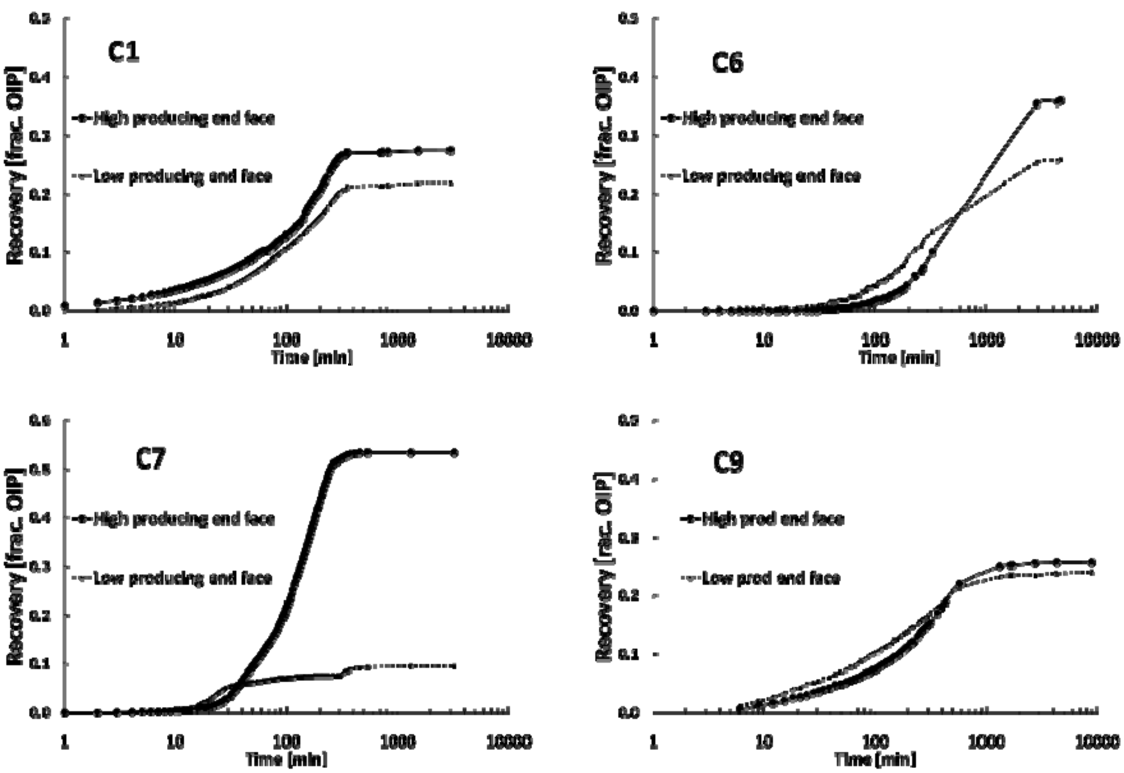


Figure 3 Production measured separately from each open end face during spontaneous imbibition in four of the strongly water-wet chalk samples with the TEO boundary geometry. Production was asymmetric in all cases, with different volumes of oil produced from each end face.

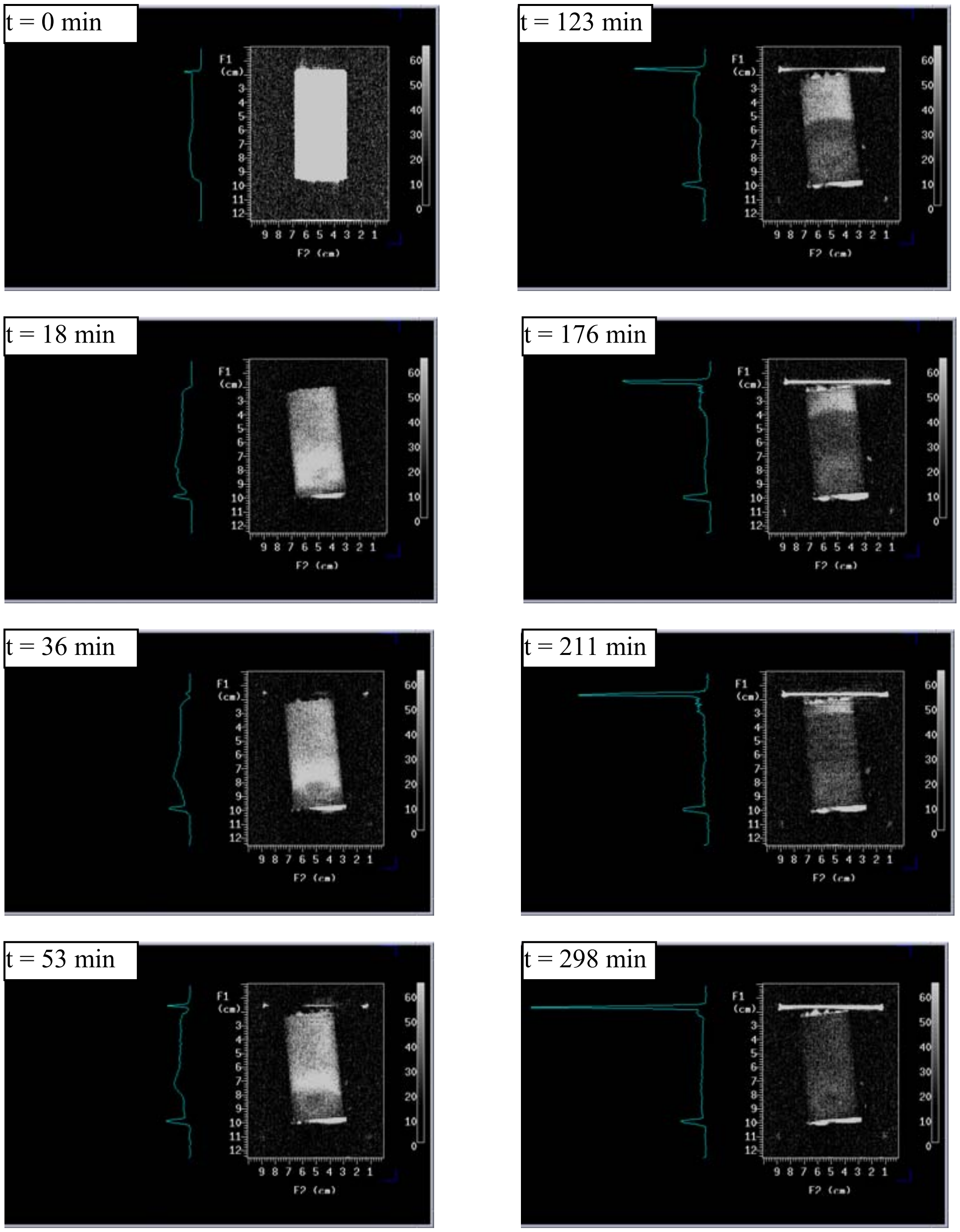
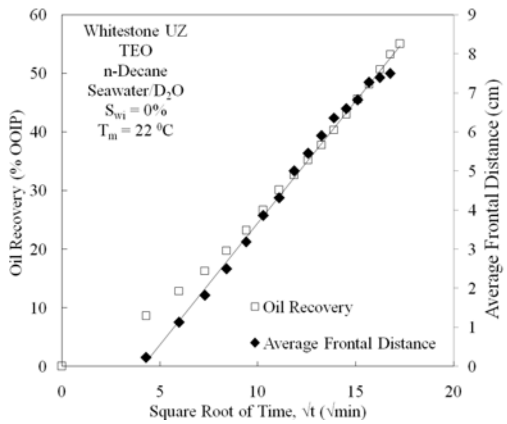
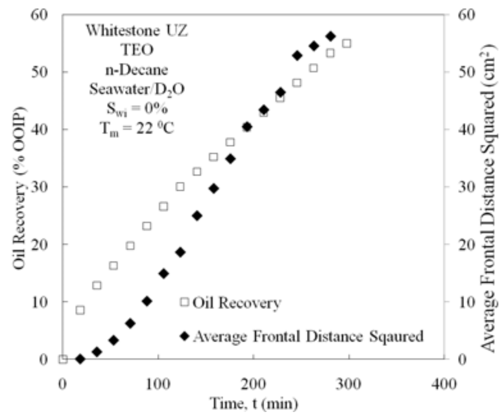


Figure 4 MRI images for oil recovery by spontaneous imbibition of a TEO vertical Whitestone UZ limestone core. The imbibition front was formed from one end face of the core.



(a) Oil recovery & average frontal distance versus square root of time



(b) Oil recovery & average frontal distance squared versus time

Figure 5 Oil recovery & average frontal distance relationships for the TEO vertical Whitestone UZ limestone core.

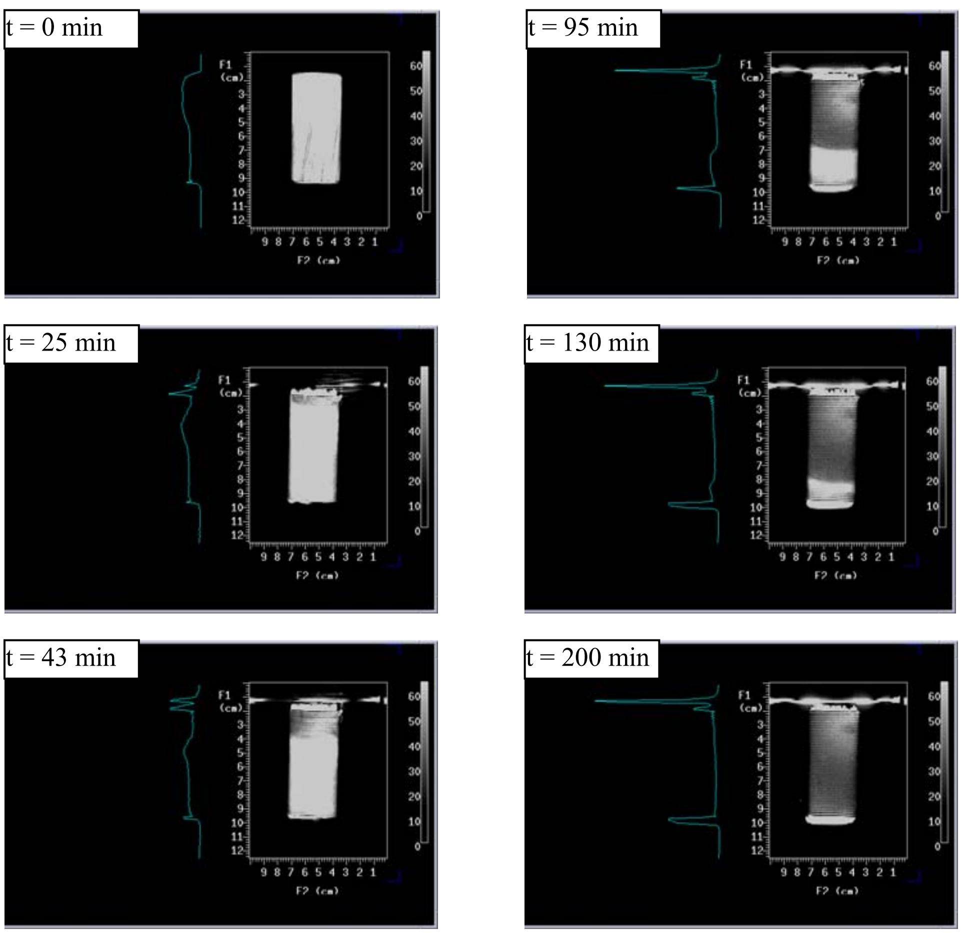
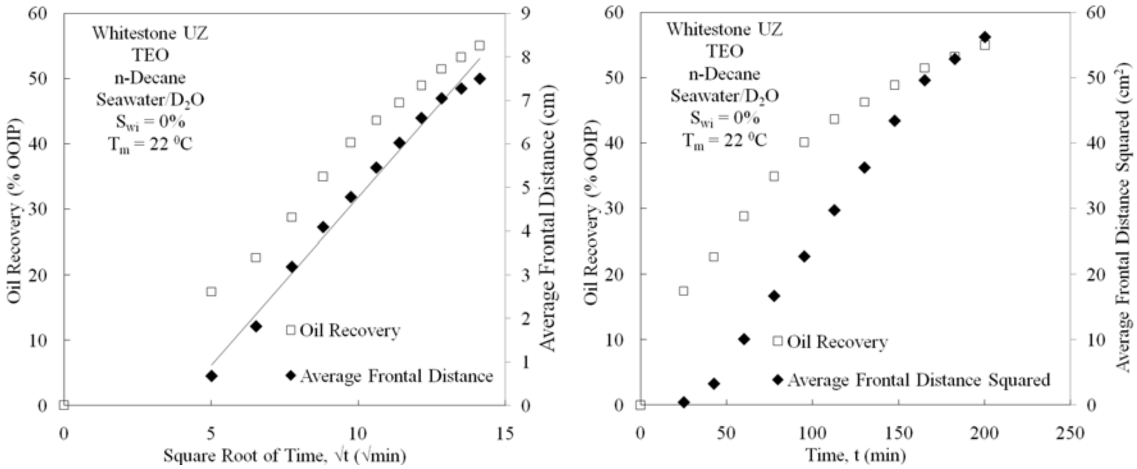


Figure 6 MRI images for oil recovery by spontaneous imbibition of the TEO vertical – reverse Whitestone UZ limestone core**.** The imbibition front was formed from the same end face of the core when the core orientation was reversed.



(a) Oil recovery & average frontal distance versus square root of time

(b) Oil recovery & average frontal distance squared versus time

Figure 7 Oil recovery & average frontal distance relationships for the TEO vertical – reverse Whitestone UZ limestone core.