Positive Capillary Forces: The Key for Optimized Oil Recovery in Low-Permeable Cores

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Abstract. In recent years, Smart Water injection has gained attention as a promising Enhanced Oil Recovery (EOR) technique for both sandstone and carbonate reservoirs. Laboratory studies have shown that Smart Water can significantly improve oil recovery by altering the pore surface wettability in cores towards more water wet conditions. The wettability alteration creates increased positive capillary forces which improves the microscopic sweep efficiency leading to higher ultimate oil recoveries.

The flow of water and oil in reservoirs is controlled by viscous, gravity, and capillary forces. Spontaneous imbibition experiments conducted on restored cores gives a direct measurement of capillary forces. When formation water (FW) as the imbibing brine spontaneously infiltrates the porous system and displaces oil, capillary forces contribute to the oil mobilization. If we observe a gradually and significant increase in oil mobilization when FW is substituted with an injection brine with different ion compositions, this confirms increased positive capillary forces and that the injection brine behaves as a Smart Water.

Numerical models in reservoir simulation primarily focus on viscous forces and often neglect the direct influence of capillary forces on oil mobilization. Despite the availability of capillary pressure (Pc) modelling capabilities which represents capillary forces, the impact or sensitivity of Pc is very low in numerical studies on field scale. To demonstrate the importance of capillary forces in the oil displacement process, a series of oil recovery tests have been performed on low-permeability heterogeneous carbonate chalk cores restored to different initial wetting states. The tests include viscous flooding (VF) and spontaneous imbibition (SI) oil recovery experiments. The results shows that capillary forces play a crucial role in the oil recovery process. Highest ultimate oil recoveries from cores with highest positive capillary forces and oil recovery declines as the capillary forces decreases. Only minor changes in capillary forces have a significant impact on ultimate oil recoveries. The results are in line with Smart Water EOR observations in both Carbonate and Sandstones, where increased positive capillary forces significantly improve the ultimate oil recovery compared to FW.

This study provides valuable insight into the underlying mechanisms of Smart Water EOR and highlights the importance of positive capillary forces in oil recovery processes from heterogeneous systems. It also highlights the importance of core restoration in front of SCAL analyses. It also highlights that capillary forces need to be included when results from laboratory experiments are discussed, and in numerical models to correctly describe the fluid flow in reservoir systems.

1 Introduction

The mobilization of oil from porous rock systems is driven by viscous, gravity, and capillary forces. The ultimate recovery of oil in COBR (Crude oil, Brine, Rock) systems during water injection on a core scale is influenced by various factors such as pore size distribution, oil and water interactions with mineral surfaces, interfacial tensions, fluid viscosities, and applied forces. These factors are crucial in determining the effectiveness of individual drive mechanisms for oil mobilization. The significance of capillary forces and flooding rates in oil recovery has been extensively studied by several authors in since last century, including Hassker et al. (1944), F.M. Perkins (1957), de Haan (1959), Constantinides and Payatakes (2002), Tie and Morrow (2005), Ortiz-Arango and Kantzas (2009), Okoro (2018), Arab et al. (2020), Aslanidis et al. (2021). Their research has shed light on the importance of understanding the role of capillary forces and optimizing flooding rates to enhance oil recovery in carbonate reservoirs.

Reservoir simulation models typically focus on the effects of viscous and gravitational displacement forces and to a large extent neglecting contribution from capillary forces. However, capillary forces can be included in the model through Pc. Numerical simulators commonly incorporate capillary pressure (Pc) in various forms, although the specific modelling approach can vary. However, it is worth noting that many field-scale numerical studies show limited sensitivity or impact of Pc on simulated recoveries.

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In three-dimensional heterogeneous pore networks, the injection brine tends to follow preferential pathways through highly permeable pores with less restrictions. As a result, the displacement of oil from less accessible and low permeable pores heavily relies on the presence of positive capillary forces and spontaneous imbibition (SI).
During water injection in reservoirs with radial flow geometry, low laminar flow rates are expected in the central part, away from the injection and production well. At these low flow rates, time-dependent wettability alteration processes could occur promoting increased capillary forces, endorsing water imbibition into unswept pores, thereby increasing the oil mobilization and overall oil recovery by improved sweep efficiency.

When the differential pressures in the reservoir are high, particularly near the injection and production wells, viscous forces play a significant role in displacing oil efficiently. However, it is hypothesized that at locations with low or negligible viscous forces, capillary forces become dominant in the oil displacement process. In this study, the importance of capillary forces in the oil recovery process from heterogeneous cores have been investigated by comparing oil recoveries through spontaneous imbibition (SI) and low-rate viscous flooding (VF). The experiments were conducted using restored outcrop chalk cores at elevated reservoir temperatures. To minimize variations in the presence of capillary forces, optimized core restauration procedures were implemented. Furthermore, the study aimed to compare the effect of capillary forces on displacement efficiency and ultimate oil recoveries at static conditions with FW, and during dynamic change in capillary forces using seawater (SW) which behaves as a Smart Water.

2 Experimental

2.1 Core Material

The chalk material used in this work was collected from the Stevns Klint (SK) quarry in Denmark. The chalk is very pure and consist of 98% biogenic CaCO3, similar to North Sea chalk reservoirs [10]. All cores were taken from the same block, drilled and shaped to 38 mm in diameter and 70 mm in length. Cores were visually inspected and had no visible fractures or heterogeneities.

Table 1 provides the physical core properties measured, which are consistent with previous published data [10-12].

Table 1. Physical properties of the SK cores.

Core #	Porosity (%)	Water Permeability k_w (mD)	Pore Volume (mL)	BET m^2/g
SK0	48.5	4.3	30.6	2.0
SK1	49.1	4.2	38.2	
SK2	49.2	3.8	38.6	
SK3	48.4	4.1	38.6	
SK4	48.6	4.7	39.1	
SK5	47.3	3.8	38.2	
SK6	49.5	3.9	40.9	
SK7	48.5	4.8	38.6	
SK8	48.6	4.2	39.8	
SK9	47.8	4.1	38.9	
SK10	48.1	4.0	37.8	

Mercury injection capillary pressure (MICP) measurements were performed by Stratum Reservoir, Stavanger, to evaluate the pore throat size distribution of the rock material and is given in **Fig. 1**.

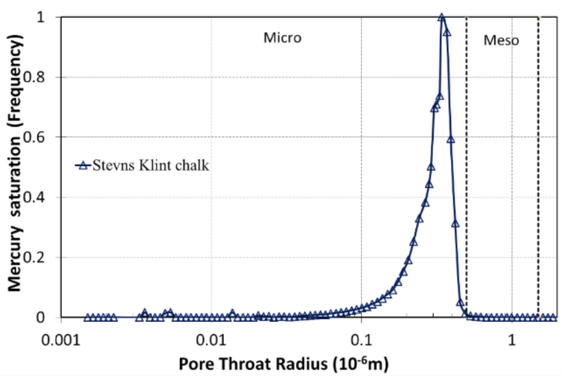

Fig. 1. Pore throat size distribution by MICP for SK outcrop chalk material.

Under the scanning electron microscope (SEM), it is possible to see the grain structure in detail. Cocolithic rings and their fragments as well as the heterogeneity of the chalk surface are clearly visualized in **Fig. 2**.

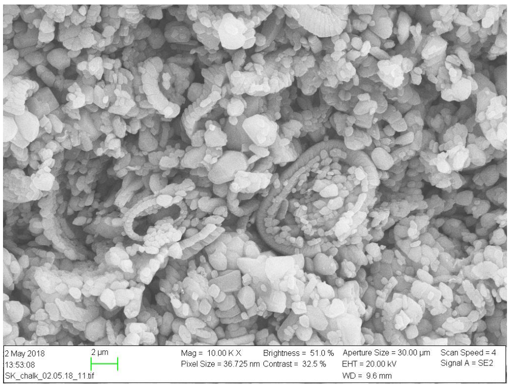

Fig. 2. SEM image of uncleaned SK outcrop chalk at 10000X magnification.

2.2 Crude Oil

A low asphaltenic stock tank oil was used as base oil with an acid number (AN) of 2.90 mg KOH/g and a base number (BN) of 0.95 mg KOH/g. This base oil was diluted with 40% heptane and filtered through a 5 µm Millipore filter to obtain an oil with an AN of ~2.1 mg KOH/g. The surface active polar organic components were removed using silica gel to obtain an oil with ~0 AN. Mixing the diluted oil and silica-treated oil resulted in Oil A with an AN of 0.58 mg KOH/g and BN of 0.30 mg KOH/g. AN and BN of the oil samples were analyzed by potentiometric titration. Measured Oil A density was 0.81 g/cm3 with a viscosity of 2.4 cP at ambient conditions.

2.3 Brines

Reagent-grade salts were mixed with distilled water (DW) to prepare synthetic seawater and formation water brines used in the experiments. All brines were filtered through a 0.22 µm Millipore filter after overnight mixing by magnetic rotation. The composition of seawater (SW) was based on North Sea seawater, and the formation water (FW) was based on a North Sea Chalk reservoir. Table 2 provides the properties of the brines.

Table 2. Properties of brines.

Ions	SW (mM)	FW (mM)
Na^+	450.1	997.0
K^+	10.1	5.0
Ca^{2+}	13.0	29.0
Mg^{2+}	44.5	8.0
Cl^-	525.1	1066.0
HCO_3^-	2.0	9.0
SO_4^{2-}	24.0	0.0
TDS (g/L)	33.34	62.83
Density (g/cm^3)	1.02	1.04
Bulk-pH	7.8	7.3

2.4 Core restoration

To ensure accurate and comparable experimental results, all Stevns Klint (SK) cores were precleaned with DW to remove easily dissolvable salts prior to core restoration that could affect the initial core properties (Puntervold et al., 2007). To minimize number of experimental variables, all restored cores have the same initial water saturation and have been exposed to the same amount of oil.

2.5 Initial water saturation (S_{wi})

The precleaned cores were dried at 90°C to a constant weight. Then 10% initial water saturation (S_{wi}) with formation water (FW) was established using the desiccator technique described by Springer et al. (2003). After reaching the target S_{wi} = 0.10 ± 0.01 by weight, the core was equilibrated in a closed container for at least 3 days to ensure even ion distributions inside the core.

2.6 Oil exposure

The core with established Swi was mounted in a hassler core holder, vacuumed to vapor pressure of water, and saturated and flooded with the oil, 1.5 PV in each direction at 50°C. The core was then wrapped in Teflon tape to avoid unrepresentative wetting on the outer surface before aging in the same oil at 90°C for 2 weeks to establish a more homogeneous core wetting.

2.7 Oil Recovery by Spontaneous Imbibition

Spontaneous imbibition (SI) experiments were carried out on restored cores surrounded by the imbibing brine. Based on the speed and cumulative oil production, this method is a direct measurement of the efficiency of positive capillary forces to mobilize oil from heterogeneous pore systems.

Fig. 3 describes the experimental setup with controlled back pressure, allowing experiments to be performed at higher temperatures to describe presence of capillary forces in cores exposed to oils with and without polar organic components (POC). The SI setup was designed in a manner that the core can be imbibed by the brine from all sides.

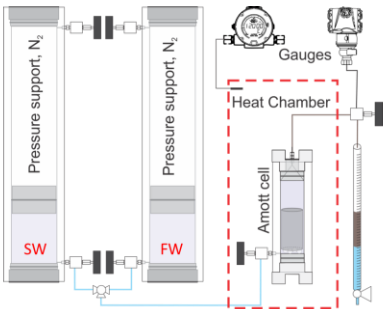

Fig 3. Schematic setup for spontaneous imbibition of a restored core at elevated pressure and temperature using FW and/or SW as Imbibing brines (IB).

Produced oil was calculated as percentage of original oil in place (%OOIP) versus time. The wettability as Amott water index ($I_{w_{SI}}$) can be calculated for a restored core when the reference for a very water wet core of the same kind is known, $(\%OOIP)_{ref}$ [14].

$$I_{w_{SI}} = \frac{(\%OOIP)_{core}}{(\%OOIP)_{ref}} \qquad (1)$$

2.8 Oil Recovery by Viscous Flooding (Forced Imbibition)

Viscous flooding experiments, also known as forced imbibition, were conducted to study the oil recovery potential from a restored core with applied viscous forces. The restored core was placed in a Hassler core holder with a confining pressure of 20 bar and a back pressure of 10 bar. Brine injection was performed at a constant rate, controlling the applied viscous forces. The pressure drop and the oil recovery were recorded and presented against the volume of brine injected. The experimental setup is illustrated in **Fig. 4**. Viscous flooding experiments were carried out at 90 and 130 °C using FW or SW brines at an injection rate of 1 PV/day.

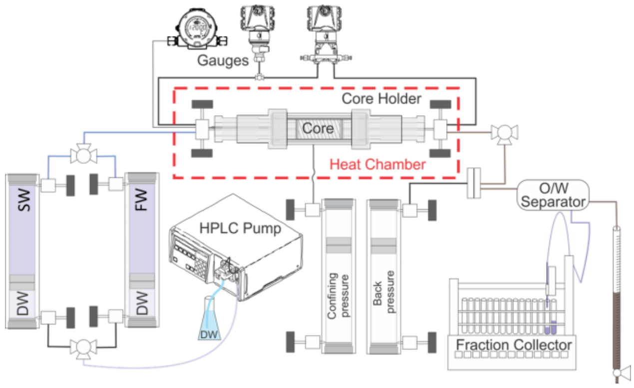

Fig. 4. Schematic viscous flooding setup in hassler core holder at elevated pressure and temperature using FW and/or SW as injection brines.

3 Results and Discussion

The mobility and fluid flow of oil and water in porous rock systems is controlled by viscous, gravity, and capillary forces [15]. Numerical models based on Darcy's law are focusing on the viscous forces to describe fluid flow in reservoirs, without directly considering the contribution of capillary forces in oil recovery experiments.

To demonstrate the importance of capillary forces in the oil mobilization processes, a series of oil recovery experiments were performed on low-permeability heterogeneous Stevns Klint outcrop chalk cores restored to initial state with only limited amount of positive capillary forces. The tests combine spontaneous imbibition (SI) and viscous flooding (VF) experiments to verify presence of capillary forces, and how capillary forces influence oil mobilization during viscous flooding experiments at static and dynamic wettability alteration processes with Smart Water.

The SK chalk is known to be a very good reference to the North Sea chalk reservoirs [10]. It belongs to the same chalk deposition taking place more than 65 million years ago having the high porosity and low permeabilities. The pore size distribution for SK chalk obtained from Mercury injection capillary pressure (MICP) test is presented in **Fig. 1**. A heterogenous pore size distribution was observed with the main parts of pores in the micro–pore region with pore throat radius less than 500 nm.

Heterogeneous sedimentary rocks with small pore sizes are capillary systems. With a wettability on the water wet side, positive capillary forces are present, and water could imbibe and mobilize trapped oil in the pores. This is clearly demonstrated in an Amott test performed on a SK chalk core SK0 with pore space of 30.6 ml restored with an initial brine saturation (S_{wi}) of 10% and 90% heptane (S_o) as oil phase. When SK0 was Spontaneous Imbibed with the brine very active capillary forces were observed, **Fig. 5**.

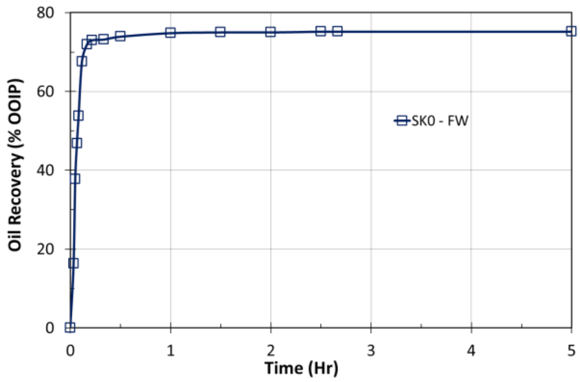

Fig. 5. Spontaneous imbibition (SI) test of SK chalk core SK0. The core was restored with S_{wi}=0.1, and fully saturated with heptane. The same brine was used in to establish initial water saturation and as an imbibing fluid.

72 % of original oil in place (OOIP) was produced in only 10 minutes and the ultimate oil recovery plateau of 75%OOIP was reached after 60 minutes. SK outcrop Chalk behaves strongly water wet, and by only capillary forces the initial oil saturation (S_{oi}) was reduced from 90% to a residual oil saturation (S_{or}) of 15% which is very low for a heterogeneous core system. The Spontaneous Imbibition experiment confirms the importance and efficiency of capillary forces in oil mobilization from heterogeneous pore systems on core scale.

3.1 Oil Recovery by capillary and viscous forces.

To evaluate combined effects of capillary and viscous forces at mixed wet state, a series of oil recovery experiments were performed using initially strongly water wet SK outcrop chalk cores. The cores were restored to initial water saturation of 10 % using FW brine. The core was then exposed to 4 PV of Oil A containing POC before aging.

Core SK7 was initially Spontaneous Imbibed with FW, the same brine representing the initial water saturation of 10 %. After reaching the oil recovery plateau, the core was also flooded with FW at a rate of 1 PV a day until the ultimate recovery plateau was reached. The oil recovery results are presented in **Fig. 6**.

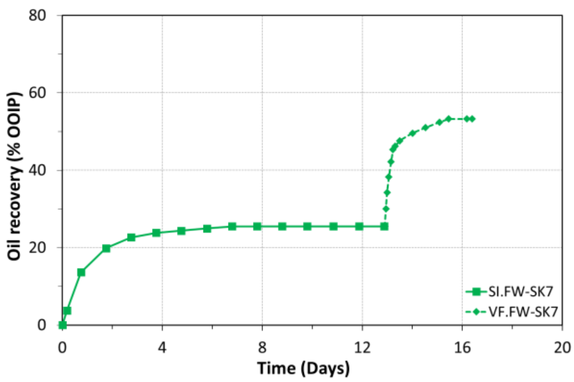

Fig. 6. Oil recovery test on core SK7 at 90°C. The SK chalk core was restored with Swi=0.1 with FW and Oil A (AN of 0.58 mg KOH/g, BN of 0.30 mg KOH/g). The core was Spontaneously Imbibed with FW, followed by viscous flooding with FW at a rate of 1 PV/D.

Spontaneous imbibition with FW will not facilitate any chemically induced wettability alteration during the imbibition process. Core SK7 reached an oil recovery plateau of 25%OOIP after 8 days, confirming presence of positive capillary forces. The restored core wettability could be described as mixed - slightly water wet.

After 13 days, core SK8 was viscous flooded with FW at an injection rate of 1 PV/day. After 3 PV, a new ultimate oil recovery plateau of 53 %OOIP was reached, representing the effect of applied viscous forces which will force FW mainly through larger pores combined with a potential capillary contribution mobilization oil from smaller and less accessible pores in the heterogenous pore network.

To investigate the effect of capillary forces on the oil mobilization during viscous flooding experiments, a parallel experiment was performed on core SK8. Spontaneous imbibition with FW gave an ultimate oil recovery of 23 %OOIP after 9 days, **Fig. 7**, confirming reproducible behavior in the core restoration process.

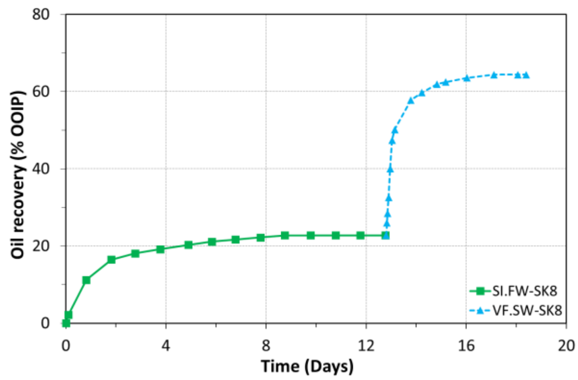

Fig. 7. Oil recovery test on core SK8 at 90°C. The SK chalk core was restored with Swi=0.1 with FW and Oil A (AN of 0.58 mg KOH/g, BN of 0.30 mg KOH/g). The core was spontaneously imbibed with FW, followed by viscous flooding with SW at a rate of 1 PV/D.

By injecting SW instead of FW at the same injection rate of 1 PV/day, the ultimate oil recovery plateau reached 64%OOIP after 5 days, confirming that a significant amount of extra oil was mobilized compared to FW even though the viscous forces applied were the same.

To be able to explain this increased displacement efficiency using SW, a new series of spontaneous imbibition experiments were performed comparing the capillary forces available during spontaneous imbibition with FW and SW. Core SK1 and SK2 went through the same core restoration process as for SK7 and SK8. Both cores were spontaneously imbibed at 90 °C, SK1 with FW and SK2 with SW, **Fig. 8**.

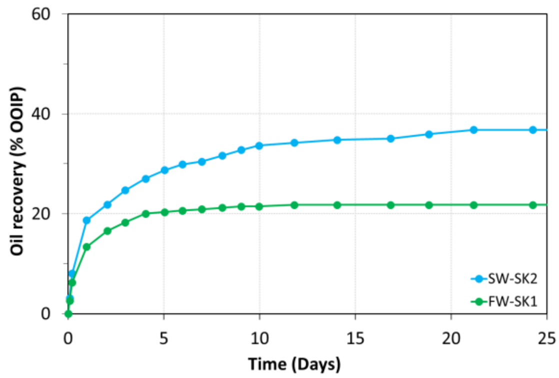

Fig. 8. Oil recovery test on core SK1 and SK2 at 90°C. Both SK chalk core have been restored with S_{wi}=0.1 with FW and Oil A (AN of 0.58 mg KOH/g, BN of 0.30 mg KOH/g). Core SK1 was imbibed with FW and SK2 with SW.

Core SK1 reached an ultimate oil recovery of 22 %OOIP after 11 days, confirming initial restored conditions in line with SK7 and SK8. When SW was used as imbibing brine for core SK2, a significant increase in both speed of imbibition and ultimate oil recovery was observed, reaching 37 %OOIP after 21 days. The extra oil mobilization could only be explained by increased positive capillary forces, facilitated by a chemically induced wettability alteration, in line with the general understanding of Smart Water EOR processes, and specific to SW as a Smart Water in Chalk as observed during viscous flooding of Core SK8 in **Fig. 7**.

Table 3 provides a summary of the experimental results from the mixed wet chalk cores at 90 °C.

Table 3. Experimental results from mixed wet SK cores at 90 °C

	SK01	SK1	SK2	SK7	SK8
S_{wi}, %	10	10	10	10	10
Oil	Heptane	Oil A	Oil A	Oil A	Oil A
SI FW, %OOIP	75	22		25	23
SI SW, %OOIP			37		
VF FW, %OOIP				53	
VF SW, %OOIP					64
$I_{w_{SI}}{}_{FW}$	1	0.29		0.33	0.31
$I_{w_{SI}}{}_{SW}$			0.49		

Spontaneous Imbibition test results confirm a dramatic reduction in capillary forces and oil mobilization when the cores were exposed to Oil A instead of heptane. The restored core wettability could be expressed by an Amott water index ($I_{w_{SI}}$) calculated for all SI experiments performed by using 75 %OOIP as the reference for a very water wet core, **Fig. 5**.

$$I_{w_{SI}} = \frac{(\%OOIP)_{core}}{(\%OOIP)_{ref}} \tag{1}$$

The Amott Water index gives an average initial $I_{w_{SI}}{}_{FW}$ = 0.31 for the restored SK cores using Oil A. By introducing SW as an imbibing brine, the final Amott Water index for core SK2 increased to $I_{w_{SI}}{}_{SW}$ = 0.49. This relatively small change in water index towards more water wet conditions has a significant effect on capillary forces. During SW injection into core SK8 the increased positive capillary forces mobilized 11 %OOIP or actually 21 % extra oil compared to the FW flooding of core SK7.

All the experiments presented have been performed at 90 °C. To evaluate how temperature affect capillary forces during core restoration and recovery potentials, a new series of experiments have been performed. All cores were prepared following the same core restoration procedure as described previously.

Cores SK3 and SK4 were spontaneously imbibed at 110 °C, where FW was used as the imbibing brine for core SK3 and SW for core SK4. The results are given in **Fig. 9**.

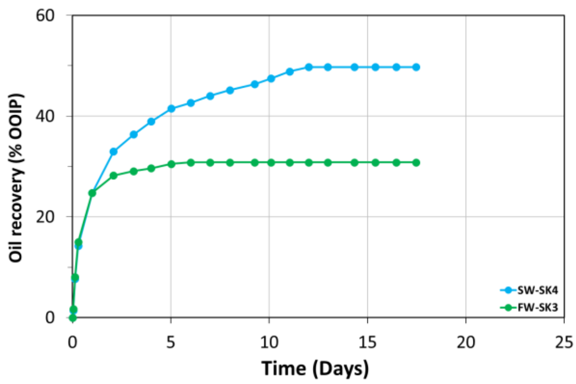

Fig. 9. Oil recovery test on core SK3 and SK4 at 110°C. Both SK chalk cores have been restored with S_{wi}=0.1 (FW) and Oil A. Core SK3 was imbibed with FW and SK4 with SW.

In **Fig. 10**, the spontaneous imbibition is performed at 130 °C, where core SK9 is exposed to FW and SW for core SK10.

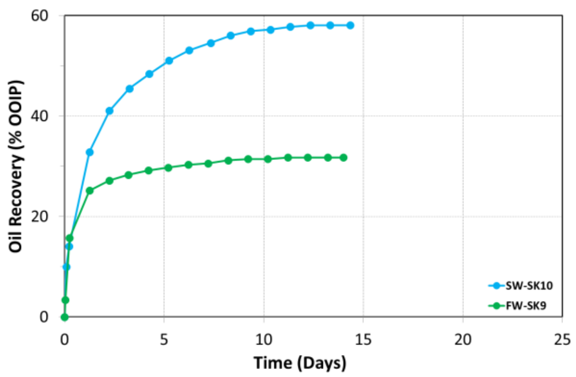

Fig. 10. Oil recovery test on core SK9 and SK10 at 130°C. Both SK chalk cores have been restored with S_{wi}=0.1 (FW) and Oil A. Core SK9 was imbibed with FW and SK10 with SW.

It was observed that as the temperature increases, the oil recovery and capillary forces increases during FW imbibition. At 90 °C, the recovery was 22 %OOIP, while increasing to 31 %OOIP for SK3 at 110°C, and further to 32 %OOIP for SK9 at 130°C.

By using SW as an imbibing brine, increased speed of imbibition and ultimate oil recoveries were observed as the temperature increased. The ultimate oil recovery reached 37 %OOIP at 90 °C, 50 %OOIP at 110°C, and 58 %OOIP at 130 °C. This represents a significant increase in capillary forces compared to FW and demonstrates the reported Smart Water EOR effects for SW with increasing temperature (refs).

To verify if increased capillary forces present will also influence the ultimate oil recovery during viscous flooding experiments, two core flooding experiments were performed at 130 °C to assess the oil recovery potential of FW and SW brine in the secondary mode. By employing a rather low injection rate, the capillary forces were permitted to contribute to the oil mobilization process, **Fig. 11**.

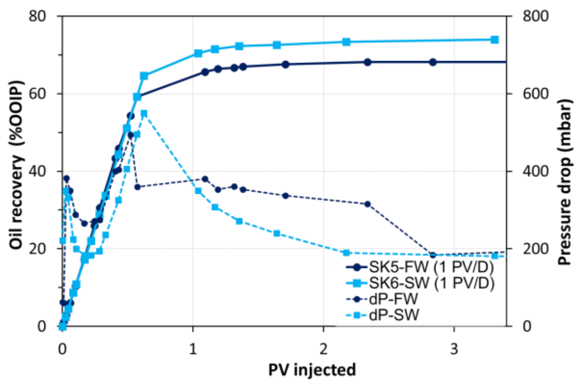

Fig. 11. Oil recovery test on SK chalk core SK5 and SK6 at 130°C, restored with S_{wi}=0.1 (FW) and Oil A. Both cores were viscous flooded with an injection rate of 1 PV/day, core SK5 with FW and core SK6 with SW. Oil recovery (%OOIP) and pressure drop (mbar) were plotted against PV injected.

A piston-like fluid displacement was observed on both cores. The first produced water for core SK5 exposed to FW was observed after 60%OOIP and 0.57 PV injected. The recovery %OOIP and the PV injected at the time of water breakthrough might be different due to uncertainties in dead volume calculation and produced fluid volume reading. For core SK6 exposed to SW, the numbers are 64 %OOIP and 0.62 PV. Increased positive capillary forces during SW injection significantly improved the displacement efficiency, giving an ultimate oil recovery plateau of 74 %OOIP after 2 PV injected, compared to 68 %OOIP for FW.

The pressure drop observations showed similar trends for both FW and SW injection, confirming that that the additional oil recovery with SW should be attributed to stronger positive capillary forces. It is important to highlight that an injection rate of 1 PV/day into a core with a length of 70 mm represents 0.2 ft/day which is quite low for core experiments. Still, pressure drop of more than 500 mbar after 0.6 PV injected was observed, stabilizing at 200 mbar at residual oil saturation (S_{or}).

A core typically represents the properties of a matrix block in a reservoir. If the pressure drop at S_{or} is scaled up using a linear tube flow model, a matrix block with a length of 1 m will see a pressure drop of 2.8 bar. On the reservoir scale with well distances of 300 meter from injector to producer, the pressure drop will then be above 850 bar (12 000psi) which is unrealistic in nature. This excludes matrix flow in low permeable reservoirs, and the pathways for viscous water through the oil-bearing zones are fractures, high permeable zones and/or the largest matrix pores. The reservoir matrixes normally hold more than 90% of the reserves and mobilization of the matrix oil is then completely dependent on the presence of positive capillary forces and the access to water from the pathways. In Smart Water EOR the aim is to improve the capillary forces and mobilize even more oil. The same water pathways will also control the main flux of oil from the matrix to the producers.

The same phenomena have also been reported from low permeable reservoir sandstone cores. Aghaeifar et al. (2019) highlighted the importance of capillary forces in oil mobilization processes by Smart Water injection. Low Salinity (LS) brine improved the positive capillary forces compared to FW, SW, and modified SW brines, and improved the displacement efficiency giving significantly higher ultimate oil recoveries in low-rate core flooding experiments. The findings highlighted the importance of including capillary forces in fluid flow models for porous systems. The contribution from capillary forces have also to be accounted for in reservoir simulators to give reliable estimates of oil production on reservoir scale, and to improve reservoir management decisions [17].

Conclusions

The results highlight the importance of understanding the effect of capillary forces on fluid flow in porous media. Selected core restoration procedures in the laboratory will influence the capillary forces present in restored cores, and replication reservoir properties are important before performing expensive and time–consuming laboratory core experiments.

The main findings of this results are-

- Cores represent reservoir matrix blocks and are heterogeneous pore systems. Presence of positive capillary forces in the cores is very important for oil mobilization.
- Only small improvements in capillary forces have a significant effect on oil mobilization and ultimate oil recoveries during brine injection, both in cores at constant capillary forces, and in cores with dynamic increase of positive capillary forces facilitated by Smart Water.
- Very high pressure drop is observed during 2 phase flow in low permeable cores even at very low injection rates, excluding the importance of viscous forces in matrix flow.
- Improved core restoration procedures are needed to replicate the capillary forces in reservoir matrix blocks. SCAL analyses should be performed at conditions present in the main part of the reservoir.

The effect of capillary forces needs to be accounted for when oil recovery processes from core experiments should be explained and mathematically modeled. Capillary forces need also to be included during upscaling of laboratory results to reservoir scale, to estimate oil production in reservoir simulators, and to improve reservoir management decisions.

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