MECHANISTIC STUDY OF HEAVY OIL RECOVERY BY WATERFLOOD: EFFECT OF OIL VISCOSITY AND WETTABILITY

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ABSTRACT

The process of oil recovery by waterflood in conventional oil reservoirs has been studied extensively and a well-documented body of literature exists on the impact of rock and fluid parameters. However, waterflooding of heavy oil reservoirs have received much less attention and our current understanding of the active mechanisms in heavy oil waterflood is incomplete. The published information on heavy oil waterflooding indicates that the existing theories developed based on the physics of displacement in conventional oil cannot adequately explain observations made during heavy oil waterfloods.

This paper presents the results of a comprehensive set of visualisation (micromodel) experiments carried out to investigate the pore-scale mechanisms involved in heavy oil recovery by waterflood. The results of this study show that increasing oil viscosity can significantly change the active mechanisms in displacement and trapping of the oil before and after water breakthrough. Whilst the capillary forces are perceived to be negligible in heavy oil systems, our vivid micromodel images reveal that positive capillary forces (capillary imbibition) play a very important role in improving recovery, especially after water breakthrough. A comparison of the displacement processes under different wettability conditions shows that the highest recovery is achieved in strongly water-wet system and the recovery factor drastically drops as the system shifts towards increased oil-wet conditions. While waterflood of conventional (light) oil systems is generally believed to provide the highest recovery efficiency in intermediate-wet conditions, the results of our direct visualisation experiments suggest that the optimum state of wettability shifts towards more water-wet conditions as the viscosity of the oil increases.

INTRODUCTION

Water injection is the oldest assisted oil recovery method in the petroleum industry. In addition to pressure maintenance purposes, water is normally injected in oil reservoirs to drive the resident oil (tertiary oil recovery) or to dispose produced brine. Pore scale displacement mechanisms of waterflood in conventional oil reservoirs have been studied comprehensively and the impact of different parameters like pore structure, wettability and IFT has been investigated by many researchers. At the field scale, a well-documented body of literature exists on the design, performance prediction, and operation of light oil waterflooding. However, waterflooding of heavy oil reservoirs has received much less attention. The major issue with regards to the waterflood of heavy oil reservoirs is the large contrast in viscosity that exists between injected water (the displacing phase) and the resident oil (the displaced phase), which may cause high waterflood residual oil saturation, front instabilities, and fingering. Despite this unfavourable viscosity ratio, water is normally injected in heavy oil reservoirs for both pressure maintenance and oil displacement purposes. The main advantages of waterflooding, compared to other techniques of heavy oil recovery are: availability of water, low cost of utilization, and existence of significant experience in managing field application.

The published data on heavy oil waterflooding are limited in the literature (Brice and Renouf, 2008; Jenning, 1965; Kumar et al., 2008; Mai and Kantzas, 2010; Miller, 2006; Sutton, 1968; Vittoratos, 2010). While some of the field applications have been reported to be successful, with promising incremental recoveries as high as 40%, there are numerous cases of unsuccessful waterflooding in heavy oil reservoirs (Ahmadloo et al., 2010; Kumar et al., 2008). Furthermore, the production performance, sensitive operational parameters and efficient techniques of recovery improvement are not the same as the case of light oil waterflood; and they cannot be fully explained and simulated by the existing theories developed, based on the physics of light oils (Miller, 2006; Renouf, 2007; Vittoratos, 2010). Therefore, it is believed that the current understanding of the active recovery mechanisms in heavy oil waterflood and how these differ from waterflood of light oils is limited and inadequate, despite its vital importance and wide use in the industry (Kumar et al., 2008; Vittoratos, 2010). It is obvious that without this understanding, design and optimization of such projects is hardly practical.

Under the conditions of conventional oil reservoirs, the process of displacement of oil by water is usually assumed to be governed by capillary forces (capillary dominant). In such process, what initiates the displacement is the externally imposed force; however, what rules the events at the pore scale are the capillary forces (Moore and Slobod, 1956; Morrow, 1991; Rose and Witherspoon, 1956). Wettability and interfacial tension (IFT) are the principal factors controlling capillary forces and therefore displacement processes at pore scale. Interfacial tension for water-oil interfaces during waterflooding generally is in the range of 15 to 30 mN/m, and these relatively small variations are not thought to significantly affect the oil displacement process. This is, of course, different from the cases of interfacial tension lowering of orders of magnitude e.g. during surfactant flood, which might have important affects on the oil mobilization process, due to elimination of capillary forces in relation to viscous and gravity forces (Wardlaw, 1996b).

The oil/water viscosity ratio (μ_o/μ_w) is another important parameter; however, only when the displacement efficiency is considered at multi-pore level (Wardlaw, 1982; Willhite, 1986). The increase in oil viscosity causes earlier water breakthrough (lower oil recovery) and longer period of simultaneous oil and water production, before the final residual oil saturation is reached. Theoretically, velocity also has a large effect on viscous forces;

however, the extent to which this is the case for the relatively small range of velocity variations which is possible under field conditions of waterflooding, is likely to be small (Wardlaw, 1996b).

Therefore under reservoir conditions, the performance of waterflood and recovery efficiency before and after breakthrough, are primarily controlled by wettability and viscosity ratio. Jenning's experiments (1965) demonstrated that highly unfavourable viscosity ratios cause early water breakthrough and an extended period of simultaneous oil and water production for both water- and oil-wet cores. Conversely, when the oil/water viscosity ratio is very favourable (e.g. gas and water), there will be little oil production after breakthrough at any wettability (Anderson, 1987). In waterflood, at moderate oil/water viscosity ratio (light oils and water), wettability is the principal parameter in determining flood behaviour including entrapment mechanism, fluid distribution and displacement efficiency (Moore and Slobod, 1956). Wardlaw (Wardlaw, 1996a) introduced four mechanisms of oil trapping in water-swept reservoir rocks:

(1) *Viscous fingering* is believed to be caused by instabilities at the displacement front, whenever the viscosity of the displacing fluid is much less than that of displaced fluid. In such a system, water will finger through the oil phase and breakthrough will occur relatively early. It should be noted that viscous fingering is not dependent on pore structure, as it occurs between parallel plates in the absence of structure.

(2) *Capillary instability*, at the oil-water interface, may result in disconnection of the non-wet phase in pores or at pore throat junctions. The simplest form of capillary instability trapping is "snap-off" of oil in a simple pore-throat model with water-wet tendency whereby an oil bridge in the pore throat becomes unstable and ruptures resulting in trapping of oil in the pore body. Strong water-wet tendency and large pore-to-throat aspect ratios have been shown to increase oil trapping by a capillary instability mechanism.

(3) *Bypassing* of oil is "final separation of an isolated oil blob by filling of a pore body. This entrapment mechanism is related to differential travel paths of water-oil interfaces, caused by heterogeneities in pore structures. The bypassed oil blobs might be located in a single pore or extended over a network of pores and throats.

(4) *Surface trapping* occurs in preferentially oil-wet systems where the matrix retains oil by capillarity. Surface trapping is likely to be particularly important in rocks with highly irregular pore surfaces and large surface areas.

Of the four mechanisms of oil entrapment, all occur at the pore scale during waterflooding and mechanisms 1 and 3 also occur at larger scales. This results in formation of larger patches of residual oil extending over many pores, which are completely surrounded by water. A change from strongly water-wet to strongly oil-wet conditions increases immobile oil for "surface trapping" and "viscous fingering" mechanisms whereas it is expected to decrease immobile oil for “capillary instability” and “bypassing” mechanisms (Wardlaw, 1996b).

In a system with moderate oil/water viscosity ratio, waterflood in oil-wet systems is usually considered to be less efficient than waterflood in water-wet systems, because more water must be injected to recover a given amount of oil (Anderson, 1987); despite the fact that ultimate oil recovery might be similar if not higher in oil-wet systems. However, it is generally accepted that intermediate-wet systems yield the largest amount of ultimate recovery where the trapping by capillary forces is minimized.

In this study a total number of 20 micromodel tests have been carried out to investigate the pore scale mechanisms of displacement and entrapment during heavy oil waterflood and highlight differences with the case of light oil waterflood under different wettability conditions. The results of four of this series of micromodel tests have been selected which will be described in the following sections.

EXPERIMENTAL

A high-pressure micromodel rig was used to perform the micromodel experiments. Details of the experimental facilities can be found elsewhere (Sohrabi et al. 2000). In this study, rock-look-like pattern micromodels were used. The micromodel orientation was vertical with the inlet port at the top and the outlet at the bottom end of the model. Figures 1(a) shows a magnified section of the micromodel fully saturated with heavy crude oil (black colour) and Table 1 shows the dimensions of the micromodels and their pores. The effect of gravity forces on the recovery process was assumed to be negligible as the density difference between water and the heavy oil sample is very small. To show the images of the micromodel at a suitable magnification, only the image of a middle section of the micromodel, which is representative of the whole micromodel, is presented throughout this paper. As the depth of the pores of the micromodel is relatively uniform, by measuring the area occupied by different fluids using an image analysing software, the saturation of fluids within the model can be determined.

Table 2 presents the basic properties of the extra-heavy crude oil used in the micromodel tests. Distilled water (DW) was used as the aqueous phase in the tests. Water was injected from the top end of the vertical oriented micromodel at a very slow rate of 0.01 cm^3/hr (1 PV/hr) which corresponds to a capillary number of ca. 2.5 E-7. The full width of the micromodel was open to flow and the yellow arrows on the images show the flow direction.

The micromodels which were used in this series of tests showed strongly oil-wet behaviour after being created by acid etching technique. To alter wettability and prepare favourable wettability conditions an alkaline treatment procedure was employed. To make the micromodels more water-wet, they were soaked in a strong basic solution (pH=12). By extending the soak period slightly oil-wet, slightly water-wet and strongly oil-wet systems were created. The state of wettability was checked beforehand and after performing the micromodel tests which showed stability in wettability state in all tests.

A very similar experimental procedure was followed in the tests reported here. The micromodel was first saturated with DW and pressurised to 600 psig at 44 °C. To resemble the initial migration of oil in a water-bearing reservoir and to establish an initial oil and water saturation, the crude oil was then injected from the bottom end of the micromodel and continued until the oil front reached the other end of the porous medium. To simulated waterflooding of an oil reservoir, the model was then flooded with water for an extended period of time ($\geq$50 PV).

RESULTS

Test 1: In the first test, heavy oil waterflood of a strongly water-wet system was investigated. Figure 1a: shows a magnified section of the micromodel at the end of the period of oil injection. As can be seen, despite having a network of dead-end and inverted-cup pore pattern structure, the oil saturation at the end of the oil flood period reached a high value of 99%. This is attributed to both high viscosity ratio between oil and water and strongly water-wet characteristics of the micromodel. Basically, in water-wet porous media, oil injection results in very low connate water saturation. This is due to a counter-current displacement mechanism in which the injected oil invades pores from the centre of the pores and the resident water leaves the pore space through layers of water attached to the rock surface.

The micromodel was then flooded with DW. The pore-scale mechanisms of oil displacement by water were seen to start by a flow of water through the sharp corners of the pores that were still saturated with crude oil (corner filament flow). These water filaments were seen to thicken slowly pushing the oil away from the pore walls and towards the centre of the pores, finally causing snap-off at some pore throats. In other pores with low pore to throat aspect ratio, the thickening of the water films eventually resulted in evacuation of oil from the pore body (piston type withdrawal). Figure 1b illustrates the same section of the micromodel at water breakthrough. The fact that a continuous path of water flow did not form at breakthrough time is a good indication of strongly water-wet conditions of the system. Low oil recovery was achieved at breakthrough time, which was expected considering the very unfavourable viscosity ratio between resident oil and injected water. The water injection after the water breakthrough continued for 50 PV’s. As the water injection continued, more pores were observed to be gradually occupied by the injected water. Figure 1c illustrates the same section of micromodel after the extended period of waterflood, which shows a significant fraction of residual oil at breakthrough time (Figure 1b) has been produced after the extended period of waterflood.

Test 2: The second test was performed using the same micromodel and experimental procedure as the first test, however, the wettability of the micromodel in this test was slightly water-wet. Figure 2a shows the magnified section of the micromodel at the end of the period of oil injection where an oil saturation of 98% has been achieved. Micromodel was then flooded with water. The pore scale displacement took place first and foremost through piston type displacement mechanism and in few pores through corner filament flow mechanism followed by snap-off. This caused formation of a distinct water flow path in the middle of the micromodel unlike the case of the strongly water-wet system (previous test). Figure 2b illustrates the same magnified section of the micromodel at the time of water breakthrough. Low oil recovery was obtained at breakthrough time due to the high viscosity ratio between the resident oil and injected water. The water injection continued for more than 50 PV's after the water breakthrough. As can be seen in Figure 2c, water layers on the pore surfaces became thicker in the pores near the flowing path of water; however, the water/oil distribution remained unchanged in most of the pores.

Test 3: In the next micromodel test, waterflood in a slightly oil-wet system was simulated. Figure 3a shows a magnified section of the micromodel at the end of the period of oil injection. An oil saturation of 90% was achieved which was lower than the case of water-wet systems in the previous two tests, despite the fact that experimental conditions and fluids were not altered. It was explained earlier that high oil saturation in the case of strongly and slightly water-wet systems was due to a counter-current flow process at the pore scale during oil flood period, where the injected oil entered the pores from the middle and the resident water left the pore through water layers on the pore surfaces. However, under the wettability conditions that water layers do not exist from the beginning or rupture easily (oil-wet systems), the resident water loses connectivity throughout the micromodel; therefore, the counter-current displacement process cannot take place. This results in higher irreducible water saturation and lower initial oil saturation in oil-wetted systems.

The micromodel was then flooded with water. The displacement of the oil by water was observed to take place through piston type displacement mechanism which left connected oil layers on most of pore surfaces. Low oil recovery was achieved at water breakthrough as can be seen in Figure 3b. Water injection continued for more than 50 PV's after the water breakthrough. Despite very minor changes in oil/water distribution (red arrows in Figure 3c) the oil-water distribution remained largely unchanged and negligible additional oil was recovered. This behaviour was contrary to the observations made in the cases involving water-wet systems.

Test 4: The last test was carried out with the intention of simulating the process of waterflood in a strongly oil-wet system. Figure 4a shows a magnified section of micromodel at the end of the period of oil injection. An oil saturation of 88% was achieved at the end of the period of oil injection. The micromodel was then flooded with water. Piston type displacement was the only displacement mechanism observed at the pore scale in which water displaced oil from larger pore bodies, whilst the stable layers of oil remained attached to the pore walls. Figure 7b illustrates the same section of micromodel at the time of water breakthrough. The brown colour of the glass in the pores that are flooded by water indicates presence of wetting layers of oil at the glass surface which confirm the strong oil-wet tendency of the micromodel in this test. The volume of oil recovered by water at breakthrough time in oil wet systems (including this test and previous test) was slightly higher compared to the cases of strongly water-wet and slightly water-wet tests (test 1 and 2). The water injection period continued for an extended period of time after the water breakthrough; however, it did not result in further oil production and oil/water redistribution (Figure 4c)

DISCUSSION

Displacement Efficiency

Jenning (1965) suggested that as the crude oil viscosity increases, the recovery at breakthrough becomes less dependent on the state of wettability of the system. This is due to the fact that in such systems most of the trapping takes place due to the viscous forces, and oil/water viscosity ratio becomes the prime parameter controlling recovery performance. Similar behaviour was observed in the micromodel tests which were performed at different wettability conditions. The breakthrough recovery was calculated to be 12.5%, 11.2%, 13.9% and, 13.5 % OOIP for the strongly water-wet, slightly water-wet, slightly oil-wet and strongly-oil-wet systems, respectively. A total number of 20 micromodel tests performed using this extra-heavy crude oil and micromodel pattern all resulted in a recovery between 10 to 15 % OOIP at water breakthrough whilst the oil/water distribution could be different. This shows the effect of wettability on breakthrough recovery is insignificant in viscous oils. After water breakthrough, however, wettability significantly affected the rate of heavy oil recovery and final residual oil saturation. The oil recovery after water breakthrough was highest in the case of strongly water-wet system and decreased as the system shifted towards increased oil-wet conditions. Figure 5 plots the oil recovery versus the pore volume of injected water in the micromodel tests 1 to 4 which shows the oil recovery in the strongly water-wet system has improved to more than twice the recovery at breakthrough time (from 12.5 to 33%OOIP) when water injection continued. The incremental recovery after water breakthrough was calculated to be 5.25% and 1.3% OOIP in the slightly water-wet and slightly oil-wet systems and no additional oil was recovered in the strongly oil-wet system after water breakthrough.

Neutral and intermediate-wet conditions are generally considered as the most favourable conditions for recovery of light oils, due to the fact that in this wettability state trapping capillary forces will be minimized. However, the results from this set of micromodel tests suggests that the optimum state of wettability can be a function of crude oil viscosity and as oil viscosity increases, the optimum state of wettability shifts towards more water-wet conditions. In the case of the extra- heavy oil used in this study, waterflooding was observed to be most efficient under strongly water-wet conditions where the positive capillary forces (spontaneous imbibition process) are strongest. Theoretically, production of oil phase in the porous media should continue as long as the residual oil is continuous and there is a pressure difference across the porous medium. However, the fact that in these experiments oil recovery after the water breakthrough was very much dependent on wettability of the system reveals that capillary forces also play a very important role in recovery of heavy oil after water breakthrough.

In the systems where oil trapping takes place due to viscous forces (high oil/water viscosity ratio) the distribution of residual oil at breakthrough time is not stable from capillary forces viewpoint. Therefore, as injection continues after water breakthrough, the capillary forces attempt to mobilize a fraction of the residual oil and adjust distribution of oil and water in a capillary stable shape through "capillary imbibition" mechanism. The micromodel results presented above show that in water-wet systems where positive capillary forces are present, this redistribution of oil and water does take place and it may result in significant oil production (test 1). However, in the tests with intermediate- or oil-wet tendency the redistribution process weakens (tests 2 and 3) and eventually stops (tests 4). There are two hypotheses for this distinctive behaviour of heavy oils under different wettability conditions.

1. Heavy crude oils are recognized to have non-Newtonian rheology due to their high asphaltene content (e.g. above 10% in this extra-heavy oil). When these crude oils are in static conditions, asphaltenes can self assemble through physical interactions and form structural viscosity. Therefore, a certain amount of force has to be applied to the oil to break this structure and the crude oil flow in the porous media (Saniere et al., 2004; Wang et al., 2006). The driving force due to the pressure difference on both sides of the porous media is small after water breakthrough, which on its own might not be enough to break the structure and displace the oil. Under capillary dominant conditions the capillary forces are orders of magnitude higher than viscous forces at the pore scale, so if positive capillary forces can be present in the system (water-wet systems), they can assist the initial displacement of oil from the pores by overcoming the structural resistance. This explains why in systems where positive capillary forces are not present or are small, water cannot displace the residual oil after breakthrough or the oil production rate is lower than the case of water-wet systems.

2. Another factor that causes weakening of heavy oil recovery process after water breakthrough in oil wet systems is the fact that friction forces between oil and rock are significantly larger for heavy oils compared to light oils and water. In laminar flow regime, there is a direct relationship between viscosity and shear stress, therefore, as the oil viscosity increases the resistance to shear force increases as well. This can slow down or even stop flow of high viscous oils in porous media strengthening surface trapping mechanism. In the water-wet systems, existence of very thin layers of water between the rock surfaces and the heavy oil dramatically reduce the friction forces and promote oil flow.

Trapping Mechanisms

In a water-wet system with moderate oil/water viscosity ratio, trapping of oil takes place due to the *capillary forces*, in which the residual oil remains in the porous media in the form of completely disconnected and scattered blobs. As the trapping viscous forces become stronger (due to the higher viscosity contrast between crude oil and water), the residual oil blobs become increasingly larger extending over a network of several pores. If the oil/water viscosity ratio is high enough, the network of residual oil may remain continuous throughout the porous media. This type of trapping is due to the *viscous forces* and was observed in the presented micromodel tests where big patches of oil remained connected in the porous media, after water breakthrough.

An increase in oil viscosity increases the relative importance of the viscous fingering mechanism, compared to other entrapment mechanisms. At the same time, the increase in oil viscosity can alter the strength of other trapping mechanisms compared with the case of conventional oil systems. Our micromodel tests results show that while the effect of increase in oil viscosity on the capillary instability mechanism seems to be insignificant (as long as the process remains capillary dominant), it can significantly affect the surface trapping mechanism in oil-wet systems. The results show that as the oil viscosity increases, the thickness of the oil films on oil-wet pore surfaces increases as well strengthening the surface trapping mechanism.

Field Applications

The results of these micromodel tests show that the trapping forces and the distribution of residual oil are different in heavy and light oil systems. In the case of light oils, trapping forces are capillary type; therefore, a reasonable option to enhance oil recovery is eliminating these forces. The rationale behind a wide use of surfactant and alkaline or their derivatives in EOR processes, is reducing the capillary forces by reducing the value of the interfacial tension (IFT) by orders of magnitude. In the case of heavy oils, most oil entrapment is induced by viscous forces, thus elimination of capillary forces by IFT reduction has no considerable impact on this type of trapping on its own (this is a different scenario if IFT reduction results in other displacement mechanisms e.g. emulsification).

A solution to improve oil recovery by waterflood in heavy oil reservoirs might be to alter wettability towards more water-wet conditions by employing different techniques, e.g. injection of suitable alkaline and alkaline-surfactants solutions or by changing composition of injected water. In heavy oil reservoirs, most of oil production takes place after water breakthrough at high water-cuts, even a slight improvement in water cut can make a significant contribution to ultimate oil recovery. The other important point that should be taken into account is that wettability alteration from water-wet to oil-wet (which is known as an EOR technique in conventional oil reservoirs) cannot be employed in heavy oil reservoirs. Even if the wettability alteration towards an oil-wet condition is a side effect of other operational activities in the field it needs careful consideration before being applied in the field as it can significantly reduce the rate of heavy oil recovery.

CONCLUSIONS

- The results of this study suggest that the extensive experience gained from conventional waterflood projects are not directly applicable to heavy systems. Oil entrapment in conventional (light) oils is due to the capillary forces which result in the remaining oil to be in the form of separated pieces of oil surrounded by water, however, in heavy oils, trapping is primarily due to the viscous forces (viscous fingering mechanism) and the residual oil remains continuous in the porous media.

Therefore, to remobilize the trapped oil and improve recovery in heavy oil reservoirs a different approach from that of light reservoirs is needed.

- Heavy oil recovery before water breakthrough was observed to be principally controlled by the oil/water viscosity ratio and was not a strong function of wettability of the system.
- The capillary forces and the state of wettability of the system play very important roles in determining heavy oil recovery after the water breakthrough, which is different from the general assumption that capillary forces are not greatly involved in recovery process due to the high viscosity of these crudes.
- In our experiments, the highest amount of oil recovery was achieved in strongly water-wet systems where the positive capillary forces were strongest and oil displacement process was supported by “capillary imbibition” mechanism. The efficiency of waterflooding dropped as the system shifted towards intermediate- and oil-wet conditions.

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Table 1: Dimensions of the micromodel and its pores.

Height	4 (cm)
Width	0.7 (cm)
	0.01 (cm^3)
Ave. depth	50 (μm)
Pore Dia. Range	30-500 (μm)

Table 2: Basic properties of the extra-heavy crude oil used for the experiments.

API	10
Viscosity	8670 @ 50 °C
Asphaltene Content	11.6 (wt/wt%)
Acid Number	3.38 (mgKOH/gr)

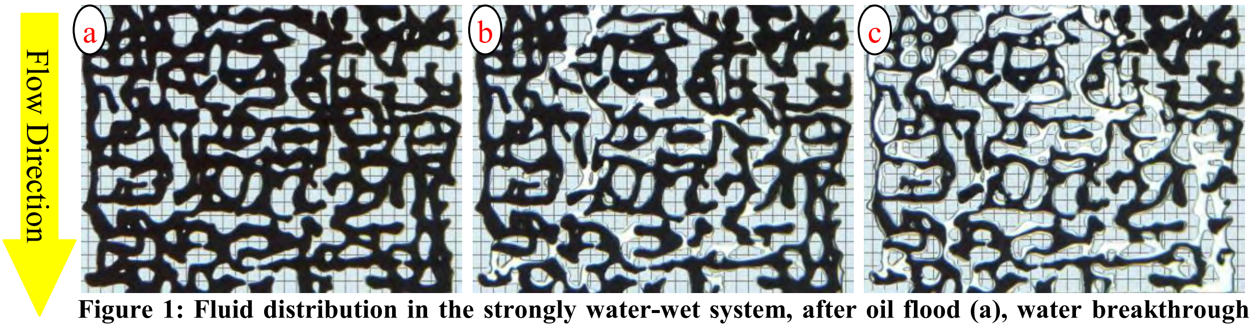

Figure 1: Fluid distribution in the strongly water-wet system, after oil flood (a), water breakthrough (b) and, 50 PV's of water injection (c). In these pictures the un-etched part of the micromodel which represents rock texture in real porous media is digitally filled by a blue square pattern. The oil and water phases are black and colourless, respectively which are their real colour in micromodel. Similar colour code has been used in the following figures.

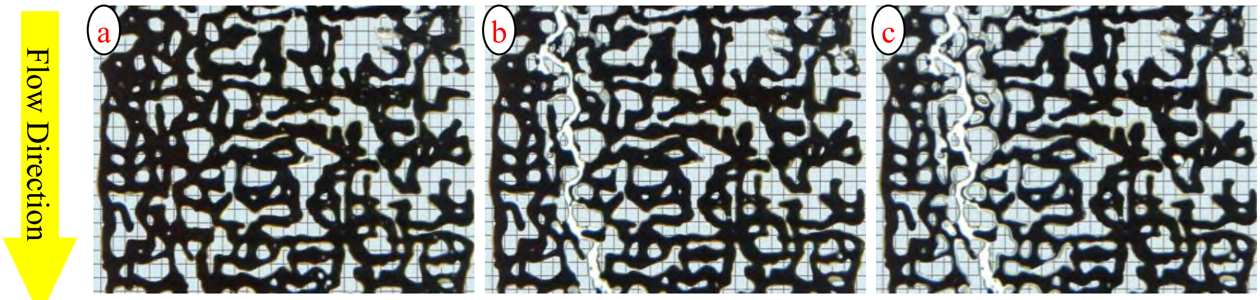

Figure 2: Fluid distribution in the slightly water-wet system, after oil flood (a), water breakthrough (b) and, 50 PV's of water injection (c).

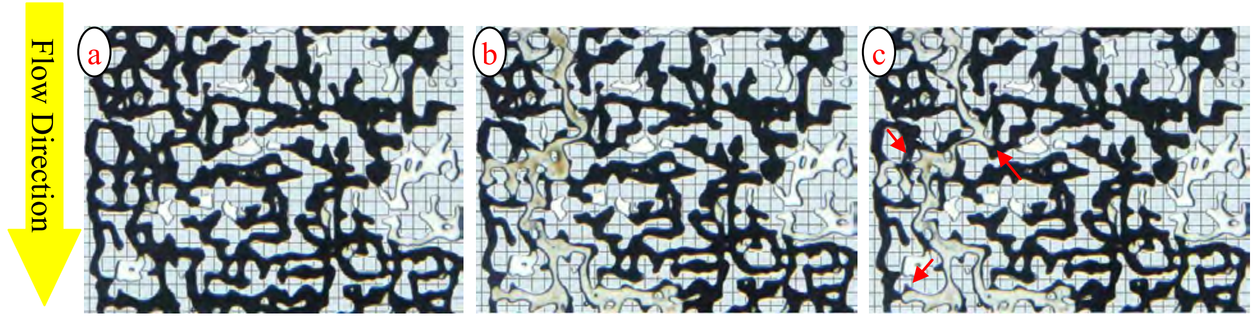

Figure 3: Fluid distribution in the slightly oil-wet system, after oil flood (a), water breakthrough (b) and, 50 PV's of water injection (c).

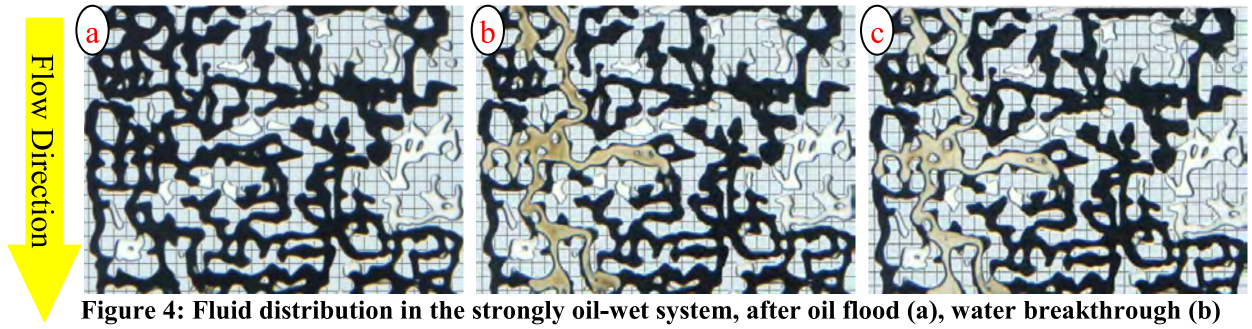

Figure 4: Fluid distribution in the strongly oil-wet system, after oil flood (a), water breakthrough (b) and, 50 PV's of water injection (c).

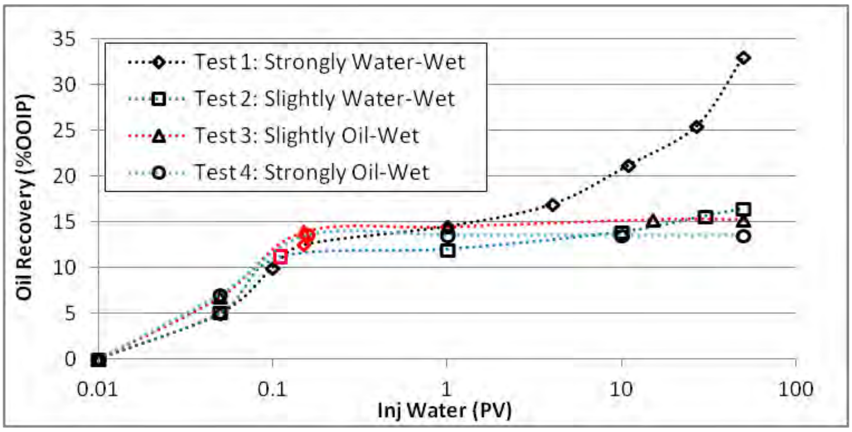

Figure 5: Extra-heavy oil recovery versus total PV of injected water in different wettability conditions.