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Visualisation of Oil Recovery by Water Alternating Gas (WAG) Injection Using High Pressure Micromodels - Oil-Wet & Mixed-Wet Systems

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Abstract

In reservoirs that have been waterflooded or gas injected, it is still possible to recover a significant amount of the remaining oil by water-alternating-gas (WAG) injection. WAG injection has been successfully implemented in some waterflooded reservoirs. However, the physical processes underlying the complex three-phase flow in WAG have not been well understood.

A series of WAG experiments has been conducted, using high-pressure glass micromodels, with high quality images of the oil recovery processes being video recorded. The experiments were performed using water-wet, oil-wet and mixed-wet micromodels. The authors presented the results of the experiments of water-wet models in SPE ATC&E 2000 (SPE 63000)[1]. This paper presents experimental results of oil-wet and mixed-wet models and demonstrates the difference in flow mechanisms of the WAG process under different wettability conditions.

Pore level fluid flow and distribution were studied and fluid saturations at different stages of the experiments were measured. The results showed that oil recovery was higher for WAG injection than for water or gas injection alone, under any of the wetting conditions. It was also observed that WAG recovery was higher for strongly oil-wet or mixed-wet models than for strongly water-wet one. Experimental results on water-wet models had highlighted the importance of corner filament flow of water in oil recovery process, with the initial water flood residual oil being trapped in the majority of pore space mainly surrounded by layers of water, and not in only large pores. The successive WAG cycles redistributed the fluids, creating fresh pathways for gas to enter the pores occupied by oil, hence, some of the oil which otherwise would not have been mobile under either gas or water injection alone was mobilised and produced. In a strongly oil-wet micromodel the flow resembled a piston type of displacement. The residual oil was only the amount staying in form of films on the pore surface, the filaments in the corners and some trapped in patches of pores surrounded by small throats. During gas injection following water injection, gas was observed to avoid entering most of the water-filled pores and preferentially invaded oil-filled pores. This is due to a much lower value of gas/oil interfacial tension than oil/water IFT. The mixed-wet model contained pores of varying degrees of wettability; from strongly water-wet and pores of intermediate wettability to strongly oil-wet pores. The displacement process in the mixed-wet model was a combination of those observed in the two extreme wettability conditions.

Introduction

WAG injection scheme was proposed by D. R. Parrish[2] as a method to improve sweep efficiency of gas injection mainly by utilising the water to control the mobility of the displacement and to stabilise the front.

Gas injection may include potential for higher oil recovery compared to water injection due to higher microscopic displacement efficiency. The problem, however, is the high mobility of the gas that limits the vertical and the areal sweep efficiencies of the gas injection. WAG injection combines the improved microscopic displacement efficiency of the gas flooding with an improved macroscopic sweep by the injection of water. In addition to better mobility control, oil recovery by WAG (in real reservoirs) is also considered to be due to contact of unswept zones, especially recovery of attic oil, as a result of rise of gas towards the top and deposition of water towards the bottom of the reservoir.

In an alternating injection scheme, due to a large density difference between gas and the liquid phases, gravity segregation may dominate the flow at some distance from the injection well. However, there will be regions where more than two phases are simultaneously mobile (especially in waterflooded reservoirs and around the injectors). This implies that two-phase relative permeabilities may not be able to describe the flow adequately in the WAG process.

To do reservoir development planning, for possible implementation of a WAG scheme, the operator needs reliable performance and hydrocarbon recovery prediction, required for accurate economic evaluation. To achieve this, good simulation incorporating proper reservoir fluid and rock description is needed. This requires accurate sets of relative permeability functions for each fluid phase and capillary pressures, in a three-phase fluid flow regime. But it is impractical to measure these for all the different rock types and fluids present in a reservoir and describe them in terms of IFT which, itself is a function of fluid composition and pressure. The approach we have adopted in WAG project at Heriot-Watt University is to develop a 3-phase 3-D mathematical network simulator, which has in it all the significant physical flow processes involved in WAG injection, formulated as accurately as possible. But to gain confidence that such a simulator can indeed reflect physics of the flow realistically, we need to test it against some actual physical experiments that involve the flow of all the three phases in a process that closely mimics the WAG injection in porous media. We have designed a micromodel system in which we can perform the WAG injection, observe and record the flow processes and measure the model wettabilities, fluid saturations and recoveries. However, all the experiments, carried out so far, were performed at one set of interfacial tension (IFT) values. We intend to test the effect of different IFTs, particularly with gas/oil IFT of near zero, to simulate miscible WAG.

Objective

The objective of the current micromodel studies is to improve our understanding of the physical principles underlying WAG injection in porous media and to develop a network model simulator that can produce complex three-phase relative permeability and capillary pressure functions. Observing and recording the fluid flow behaviour within the micromodel during the WAG injection process will help achieve this.

As the result of these micromodel studies, we now have a much better understanding of the flow process involved in three-phase flow particularly the WAG injection.

We have used, and will further use, the results of these experiments to generate and validate a network model simulator suitable for the WAG injection process. The video record of the fluid displacements is used to obtain qualitative and quantitative information on three-phase fluid flow during WAG injection. These will then be used to compare with the results of the network model, which will attempt to simulate the same processes, using the micromodel fluids and geometrical data. If the simulated results match the fluid distribution and the recovery data obtained by the experiments reasonably well, then it can be confidently used to simulate and obtain the three-phase relative permeability and capillary pressure functions, using realistic reservoir rock and fluid properties in three-dimensional space.

Experimental Facilities and Fluid System

These have been described in SPE 63000 presented in SPE ATC&E 2000.

Experimental Results

First a set of WAG experiments were conducted under conditions of strongly water-wet model and capillary dominated flow regime.

Having altered wettability of the glass micromodel from strongly water-wet to strongly oil-wet by ageing in a crude oil; we then conducted a set of oil-wet WAG experiment. To ensure conditions of strongly oil-wet, in this set of experiments; the micromodel was initially completely saturated with oil (as opposed to water-wet and mixed-wet experiments in which the micromodel was saturated with water at the beginning of experiments). The oil-wet experiment started by water flood followed by cyclic injection of gas and water.

Strongly water-wet and oil-wet experiments provide us with results of two extremes in conditions of wettability. To obtain some results at intermediate points between these two wetting extremes, an attempt was made to achieve mixed-wet wettability in the same glass micromodel. In the type of mixed-wet we achieved, some pores were oil-wet whereas some others were water-wet or neutral-wet. Some mixed-wet experiments were conducted. In each experiment micromodel wettability was defined by counting the number of oil-wet, water-wet and neutral-wet pores, as seen from the shape of water/oil interfaces within the micromodel. In each case around 1000 interfaces have been counted. In the mixed-wet experiment reported here, pore-wetting statistics showed almost equal number of oil-wet and water-wet pores.

Experiments with Water-Wet Model. The results of these experiments were reported in detail in SPE 63000. However a recovery curve representing a typical water-wet experiment will be shown here for the purpose of comparison.

Experiments with Oil-Wet Model. Having altered wettability of the micromodel from strongly water-wet to strongly oil-wet, by ageing in an asphaltic crude oil, a number of oil-wet WAG experiments were conducted.
To ensure wettability conditions of strongly oil-wet, the initial contact of blue-dyed water (dye was added to the water to help distinguishing it from the other phases) with the oil-wet micromodel was avoided (dye particles are surface-active hydrophilic materials which could be adsorbed onto glass surface). So, initially the oil-wet micromodel was saturated with dead oil (clear n-decane), no 'connate water' present. After pressurising the system to the experimental pressure of 500 psia, it was allowed to reach thermal equilibrium at the experimental temperature of 100?F. The clear n-decane was subsequently displaced with red live decane, equilibrated with gas at 500 psia and 100?F.

To resemble an initial water flood, water was injected into the fully oil saturated micromodel at the same low rate (0.01 cm^3/h) used for water-wet WAG experiments. Figure 1 shows fluid configuration, in the oil-wet micromodel, at the end of this initial water flood. As one would expect, because the porous medium is strongly oil-wet and the incoming water is a non-wetting phase, there is no imbibition of water into the micromodel nor is any layer or corner flow. Instead, the displacement of the resident oil by the injected water is all piston-like. This is in contrast with the pattern of flow of water, which was observed during water-wet experiments. In a water-wet model, during waterflooding, water would creep into the pores by spontaneous imbibition. No oil-filled pores would be by-passed and residual oil saturation would mainly be in the form of oil filaments in middle of the pores. As it can be noticed from Figure 1, in an oil-wet model, some of the oil-filled pores will completely be by-passed by the incoming water. This is a direct indication of the effect of change of wettability on the mechanisms of oil displacement by water flood.

Figure 2 shows a close-up picture of the oil-wet micromodel filled with water (non-wetting) and oil (wetting phase). In oil-wet porous media, oil resides mainly in narrow pores and corners as well as dead end pores. There are some relatively large pores that are surrounded by small pores and as a result of inadequate water pressure to overcome capillary pressure, those pores remain oil-filled. Figure 2 is a good indication of the wettability of the micromodel. As it can be seen both the relative positions of the water (blue) and the oil (red) and shape of water-oil interfaces shows conditions of strongly oil wetting.

At the end of the water flood, gas injection commenced again at the same low rate of 0.01 cm^3/h. Gas was observed to avoid water filled pores with water acting as an obstacle diverting gas front towards oil filled pores. The water being the non-wetting phase is located in the middle of the pores as a result of surface forces between glass and the other fluids. Also, the IFT of gas-water (65 mN/m) is more than four times higher than the IFT of gas-oil (15 mN/m), which makes it much more difficult for gas to enter water phase than oil phase. Moreover, due to oil being the wetting phase, it maintains its hydraulic continuity throughout the micromodel, which makes the drainage of oil through the oil-filled corners possible. These collective effects make circumstances in favour of gas invading oil-filled pores increasing oil recovery compared with water-wet experiments. The micromodel picture at the end of first cycle of gas injection is shown in Figure 3.

The experiments continued with successive injection of gas and water until five cycles were completed. Figure 4, shows the result of the last (fifth) cycle gas injection. Comparison of Figure 3 with Figure 4 reveals that, in strongly oil-wet system, as a result of alternation between gas and water injection, oil recovery was enhanced as more oil-filled pores have been invaded by gas. Along with increase in oil recovery, trapped gas saturation has also increased. However, there are some oil patches surrounded by water-filled pores, which have been by-passed and remained untouched by the invading gas.

Figure 5, shows the residual oil saturation as percentage of the micromodel pore volume, at the corresponding stages of the oil-wet experiment as shown on horizontal axis. With 46 %PV oil remaining at the end of the initial water flood, five cycles of successive injection of gas and water injection has reduced the residual oil saturation to 26.4%PV. Based on this plot the first couple of WAG cycles have been the most efficient ones and after the third cycle there has been no further oil production.

Experiments with Mixed-Wet Model. In this section the results of a mixed-wet experiment will be reported deploying the same glass micromodel and the same fluid system used for the reported strongly oil-wet micromodel experiments.
In mixed-wet micromodels, we have carefully observed every single pore regarding its tendency towards water or oil

wetness. For each experiment 700 to 1200 water/oil interfaces were examined and considered to be water-wet, oil-wet or neutral-wet. We observed that within some pores there were both water-wet and oil-wet sites.
We achieved mixed-wet micromodels with different degree of oil and water wetness. Here we report the results of a mixed-wet WAG experiment with almost equal numbers of water-wet and oil-wet pores. In this system about 38% of the interfaces showed water-wet tendency while 38% showed oil-wet tendency with the remaining 23% of the pores showing neutral wettability.

For mixed-wet experiments the same test procedure as used for water-wet experiments was followed. Initially, the micromodel was saturated with clear distilled water, which was subsequently displaced with blue live water. To simulate the primary drainage (initial migration of oil into the water bearing porous media), equilibrated oil (red n-decane), was injected from the top of the vertical micromodel, and continued until oil reached the base of the micromodel. The only difference between water-wet and mixed-wet procedure was the rate of this initial oil injection. In water-wet experiments, the primary drainage of water by oil (initial oil injection) was carried out at a slow rate of 0.01 cm^3/h. In mixed-wet experiments however, due to presence of oil-wet pores, initial oil injection at such low rates (0.01 cm^3/h) would result in oil imbibition into oil-wet pores. This would cause the oil to flow mainly through the oil-wet pores without displacing much water, which would in turn result in a rather low value of initial oil saturation. To achieve a reasonable value for the initial oil saturation, the injection of oil into water-filled micromodel was performed at a higher rate of 2 cm^3/h. After establishing the initial oil saturation (S_{oi}), water was reinjected, at our usual low rate (0.01 cm^3/h), into the micromodel simulating an initial water-flood into a mixed-wet porous medium. Then five cycles of gas followed by water injection were conducted at the same low rate (0.01 cm^3/h) as strongly water-wet and strongly oil-wet experiments.
The initial oil injection into fully water saturated micromodel in which oil was injected from the top of the micromodel displacing some of the resident water is shown in Figure 6.
Figure 17, shows a part of the mixed-wet micromodel, used for this experiment, in which water-wet, oil-wet and neutral-wet water/oil interfaces can be observed.

At the end of this initial oil injection, water was reinjected into the micromodel simulating an initial water flood into a mixed-wet porous medium. Water flow was observed to have the characteristics of a wetting-phase flow (moving on the sides of pores) in water-wet parts and non-wetting characteristics (piston-like flow) in oil-wet parts. As a result of this dual characteristic of the invading water, some of the interfaces adopt water-wet shape and some others oil-wet and even neutral-wet shapes. Figure 8, shows the mixed-wet micromodel at the end of this initial water flood.

At the end of the initial water flood the micromodel was scanned and a set of images was taken. To examine the stability of the state of wettability, the experiment was stopped for 15 hours when the micromodel was scanned again and another set of images was taken. Comparison of these two sets of images showed no change in shape of interfaces and/or fluid positions. After 15 hours halt at the end of the initial water flood, successive injection of gas and water was commenced. Five cycles of gas followed by water injection were conducted. In each cycle, gas injection was followed by water injection, at the same low rate of 0.01cm^3/h, and the fluid injections continued until stabilised conditions attained.
Figure 9, shows the micromodel at the end of first cycle gas injection. Comparison of this Figure with its corresponding stage in strongly water-wet experiment (not shown here) and strongly oil-wet experiment (Figure 3) shows a difference in pattern of gas movement due to change of wettability conditions.

Figure 10, shows the micromodel at the end of the fifth cycle water injection. Comparison of the micromodel image at the end of the initial water flood (Figure 8) with the last stage of the experiment (fifth water injection Figure 10) reveals that as a result of alternating injection of water and gas some of the trapped oil, which would not have been recovered by continuation of the initial (conventional) water flood has been mobilised and recovered. Figure 11, is a plot of residual oil saturation versus different stages of the experiment. The vertical axis shows the amount of oil trapped at the end of the initial water flood and during the subsequent WAG injections. The horizontal axis shows the corresponding stages at which the saturation measurements were made. Based on this plot, initiating WAG injection at the end of an initial water flood with 27%PV trapped oil, the residual oil saturation was lowered to 15%PV.

Discussion

Using the same glass micromodel and 3-phase fluid system, under different wettability conditions, some WAG experiments were conducted.

In the water-wet model experiment, during the initial water flood growth of water layers surrounding oil in the pore bodies and snap-off at some pore throats was observed. The slow thickening of water layers at the sides and corners of oil-filled pores during the initial water flood highlights the importance of corner flow mechanism in wetting-phase flow through non-circular pores at strongly wetting conditions.
During the subsequent gas injection, as the gas-oil IFT is less than gas-water IFT, when faced with pores of equal effective radius, gas selects those filled with oil.
In each WAG cycle, during water injection following gas injection, water flow is governed by layer flow mechanisms. The gas channels, resulted from the preceding gas injection, were observed to become narrower as the water layers grew on the sides, and finally the gas became fragmented due to snap-off happening at some pore throats, resulting in gas being trapped in shape of rather large patches.

In the oil-wet model experiment, because of the water being a non-wetting phase it had to be driven into the model, against the capillary forces as opposed to spontaneous imbibition in water-wet model. As a result of change in wettability of the glass micromodel from strongly water-wet to strongly oil-wet, the mechanisms of flow of water into oil pores has changed from corner filament flow (water imbibition) to piston-like flow (oil drainage). A direct consequence of this change of water flow mechanism was a change in the pattern of the residual oil saturation from connected oil filaments in middle of pores (water-wet model) to by-passed patches of oil (oil-wet model)

Surface forces between the fluids and the solid (oil-wet glass), locate the water (non-wet) in the middle of the pores. Also IFT of gas-water is higher than IFT of gas-oil, consequently the gas which follows an initial water flood finds it difficult to displace water. When faced with water and oil, the injected gas selects the oil-filled pores, and bypasses water-filled ones. As a result of this gas tendency to displace oil rather than water, some more oil, in addition to what has been produced during an initial (conventional) water flood, would be recovered during the gas injection.

In the mixed-wet system, during the initial waterflood, both piston-type and film flow of water were taking place depending on the wettability of the pores. During the subsequent WAG injection again the system showed the characteristics that was previously observed in water-wet and oil-wet system.

Figure 12, compares oil recovery of WAG experiments with different wettability conditions. The vertical axis shows the oil recovery from the start of the experiments (including the initial water flood stages) based on initial oil in place. As it can be noticed, WAG efficiency has been higher for mixed-wet and oil-wet experiments as compared to water-wet experiment.

Nomenclature

IFT = interfacial tension
S_{orw} = residual oil saturation to waterflood
S_{orWAG} = residual oil saturation after 5 cycles of WAG injection.
OW = oil-wet micromodel
MW = mixed-wet micromodel

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2. Parrish, D.R., 1966 US Patent No. 3,244,228.

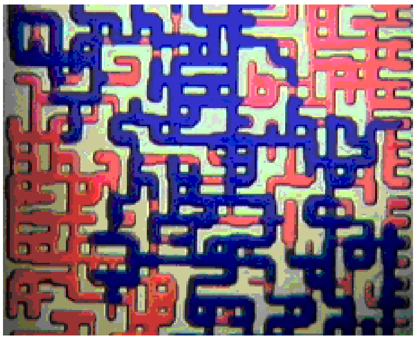

Fig.1- Initial water flood (OW)

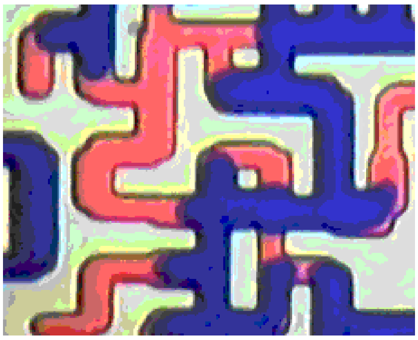

Fig.2- Water/oil interfaces (OW)

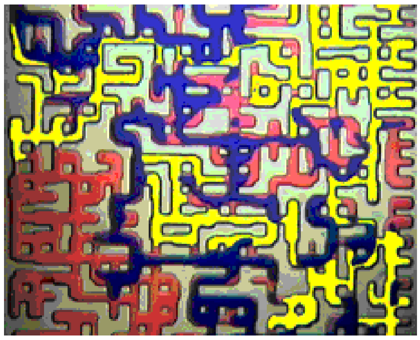

Fig.3- First cycle gas injection (OW)

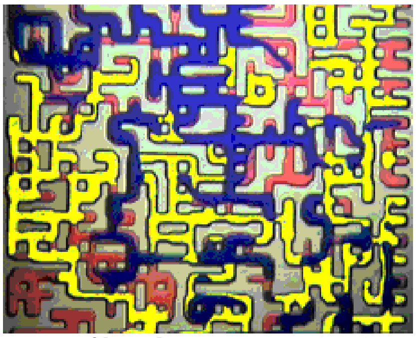

Fig.4- Fifth cycle gas injection (OW)

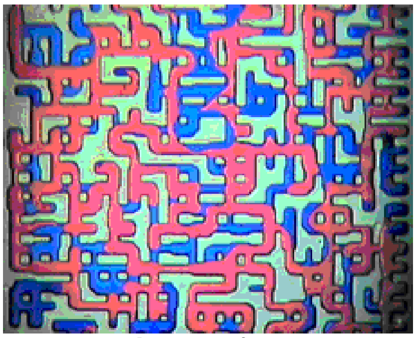

Fig.6- Primary drainage of water (MW)

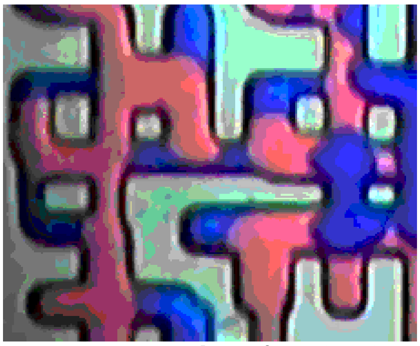

Fig.7- Water/oil interfaces (MW)

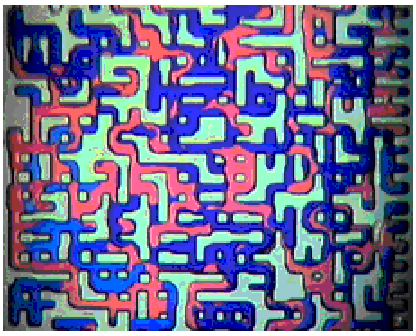

Fig.8- Initial water flood (MW)

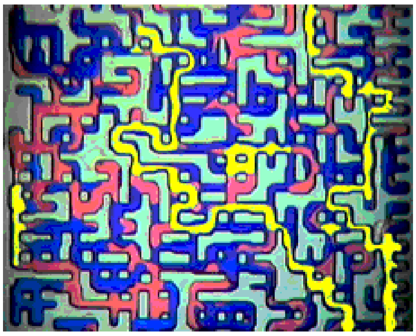

Fig.9- First cycle gas injection (MW)

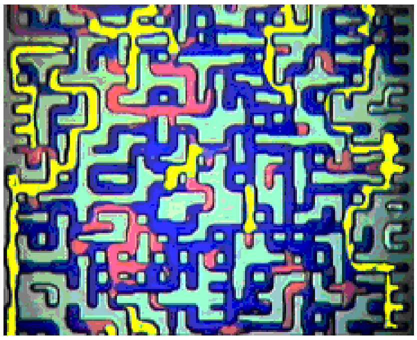

Fig.10- Fifth cycle water injection (MW)

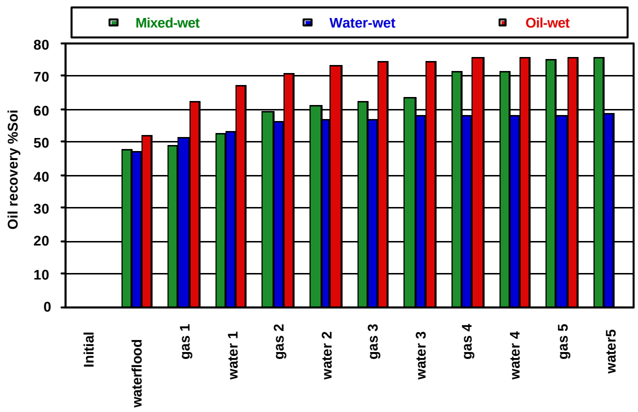

Fig.12- Oil recovery shown as percentage of original oil-in-place for the five WAG cycles and different micromodel wettabilities.

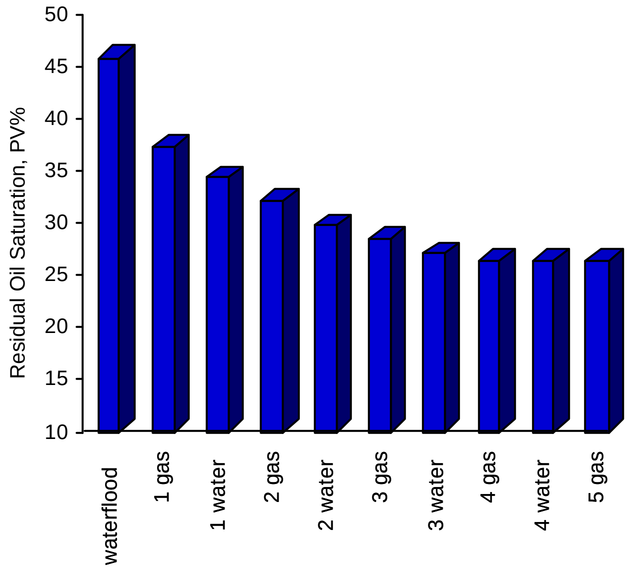

Fig.5- Residual oil saturation %PV in oil-wet WAG experiment (waterflood and five WAG cycles)

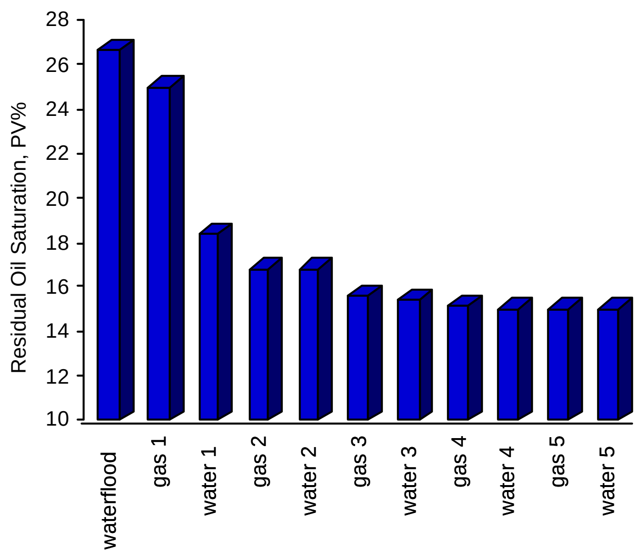

Fig.11- Residual oil saturation %PV in oil-wet WAG experiment (waterflood and five WAG cycles)