A MODIFIED WATER INJECTION TECHNIQUE TO IMPROVE OIL RECOVERY: MISHRIF CARBONATE RESERVOIRS IN SOUTHERN IRAQ OIL FIELDS, CASE STUDY

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Received: 4 July 2018; accepted: 21 September 2018

ABSTRACT

A modified water injection technique has organized by this study to improve oil recovery of the Mishrif reservoirs using polymerized alkaline surfactant water (PAS-Water) injection. It is planned to modify the existing water injection technology, first to control and balance the hazardous troublemaker reservoir facies of fifty-micron pore sizes with over 500 millidarcies permeability, along with the non-troublemaker types of less than twenty micron pore sizes with 45 to 100 millidarcies permeability. Second to control Mishrif reservoirs rock-wettability. Special core analysis under reservoir conditions of 2250 psi and 90 °C has carried out on tens of standard core plugs with heterogeneous buildup, using the proposed renewal water flooding mechanism. The technique assures early PAS-water injection to delay the water-breakthrough from 0.045 – 0.151 pore volumes water injected with 8 – 25% oil recovery, into 0.15 – 0.268 pore volumes water injected with 18 to 32% improved oil recovery. As well as, crude oil-in-water divertor injection after breakthrough, within 0.3 to oil0.65 – 0.85-pore volume of water injected to decrease water cut 1 four 0 to 15%. The overall progress of the PAS-water injection has achieved residual oil mobility of 65%, and upgraded the 35 – 50% oil recovery range by less than three pore volume water injected with 20 – 60% water cut, compared with the same oil recovery range by more than ten pore volume water injected with around 70% water cut. The ultimate oil recovery improved by this technique is from 70% via more than 20 pore volume water injected with over 95% water cut by usual water injection, to
85 – 90% via 6.4 pore volume water injected with over 90% water cut by the modified water injection. The technique succeeded to lower the end-point mobility ratio to 1.5 from above five by usual water injection. It is highly recommended to use ten micron mesh filter at the main injection site and four or five micron mesh filter at the injector sites; to avoid more than 80% of the suspended particles and save as much as possible the overall reservoir facies from permeability damage.

Keywords: Reservoir troublemaker facies; Water-cut; PAS-water; Crude oil-in-water divertor; Residual oil mobility; Improved oil recovery

INTRODUCTION

The major south Iraq oil fields are located in the southeastern province of the Mesopotamian fore-deep, within Basra sub-zone of the tectonic framework of Iraq (Fig. 1). The fields are almost of north to south simple anticlinal structures, around 120km length and 10 to 15km width at North-Rumaila, South-Rumaila and West-Qurna oil fields. The second most prolific hydrocarbon-bearing Formation in south Iraq of late Cenomanian to Early Turonian Mishrif carbonates, is of 110 to 400 m thickness encountered from the mentioned fields towards Majnoon oil field. During the past decades, many usual water-oil lab displacement techniques carried on tens of Mishrif cores from the above fields to study secondary oil recovery characterization. Early water-breakthrough and continuous increase in water cut percent versus a decrease in cumulative oil recovery and increase residual oil were determined for Mishrif carbonates. The pioneers Reisberg and Doscher (1956) and Amott (1959) studied the important physical parameters from interfacial tension to wettability of crude – water system for improved oil recovery (IOR) technology. Leach (1962), Cook (1969), McAuliffe (1973 and 1974), Mungan (1981), Zhang (1993) and Awadeesian (2002) applied renewal methodologies to develop oil recovery from lab to field requirements, using different methods to control the rock-fluid interfacial tension and wettability adjustment. This study proposed a modified technique to the existing injected waters, to control rock-fluid interfacial tension and wettability adjustment of the Mishrif reservoirs. Reisberg and Doscher (1956) studied the importance of the interfacial phenomena and effects of the crude oil – water System, imperative to oil recovery.
Amott (1959) presented a surveillance attitude on the wettability importance of porous rocks, significant to oil recovery. Leach (1962) studied a laboratory and field consideration of wettability adjustment in the water flooding technique, using caustic soda and other chemicals. McAuliffe (1973) studied crude oil -in- water emulsion and their flow properties in porous media and to fluid flow characteristics in the oil reservoir. McAuliffe (1974) has applied a crude oil -in- water emulsion to improve fluid flow and oil recovery in an oil reservoir, Sunset oil field, Southern California, USA, with good economic results gained to oil recovery from this application. Drunchuk (1974) studied the effect of the addition of certain chemicals on oil recovery during water flooding encroachment, definitions and applications. Ehrlich (1974) studied the alkaline water flooding mechanism for wettability alteration to improve oil recovery, definitions, types and applications. Bansal (1978) studied the effect of caustic concentration on interfacial charge, interfacial tension and droplet size in oil recovery.

Fig. 1: Regional map of Iraq; showing the main regional tectonic/ sedimentary subdivisions and related oil and gas fields, according to geographic locations, as well as; the studied oil fields at the southeast region of Iraq

Mungan (1981) studied useful methodology for alkaline water drive mechanism to IOR, via different laboratory measurements, calculations and evaluations. Tyssee and Vetter (1981) studied the chemical characterization problems of the water-soluble
polymers, definitions, types and effects. Awadeesian (2002) studied IOR methodology to Mishrif reservoirs in the North-Rumaila and West-Qurna oil fields south Iraq. Unpublished MSc thesis. The technique has used hydroxyethyl cellulose with caustic soda and low-to-high foam non-ionic type surfactant for Mishrif rock-fluid regulation. The used chemicals suitably controlled the Mishrif oil-wet characteristics and improved cumulative oil recovery. The aim of using an economic renewal (PAS-water) and oil-in-water divertor injection is to control the Mishrif rock-fluid performance system by lowering the interfacial tension and wettability adjustment. The presented procedure controls and retards water encroachment advance, in delaying water breakthrough, decreasing water cut percent, generating residual-oil mobility, and improves cumulative oil recovery.

**MATERIALS AND METHODS**


1. Preparation of injected waters, chemicals and polymers, base crude oil and basic emulsified oil, as well as crude oil-in-water divertor preparation.
2. Permeability (permo-facies) correction technique; stepped rock-permeabilities to water, and reservoir facies performance determination.
3. PAS-Water and crude-oil-in-water divertor arrangements and injections.

According to; the frontal advance theory given by Welge (1952), Buckley-Levertt in Amex (1960) and Craig (1971), the following equations have used for water flooding measurements and calculations:

1. \( Fo = \frac{d0}{dvi} \)
2. \( Oav = \frac{\text{Cumulative Oil Produced}}{2} \)
3. \( Vi = \frac{\text{Cumulative Water Injected}}{PV} \)
4. \( Sw1 = Oav - FoVi \)
5. \( Sw2 = (Sw1 \times 100) + Swi \)
6. \( F_w = 1 + \frac{1}{K_{ro}} K_{rw} \times \frac{\mu_w}{\mu_o} \)

7. \( F_o + F_w = 1 \)

8. Oil Recovery (% Oil in place) = Cumulative Oil Produced (PV)/ Initial Oil In Place \( \times 100 \)

9. Water cut % = Water Produced/ Total Production (Oil + Water) \( \times 100 \)

10. \( K_o = \frac{V_o \cdot \mu_o \cdot L \cdot 245}{A \cdot \Delta P \cdot T} \) (mD)

11. \( K_w = \frac{V_w \cdot \mu_w \cdot L \cdot 245}{A \cdot \Delta P \cdot T} \) (mD)

12. \( K_{ro}(Sw) = \frac{K_o(Sw)}{K_{li}(Sw = Swi)} \)

13. \( K_{rw}(Sw) = \frac{K_w(Sw)}{K_{li}(Sw = Swi)} \)

14. \( S_{oi} % = \frac{\text{Water Produced}}{\text{Pore Volume}} \times 100 \)

15. \( S_w % = 100 - S_{oi} \)

16. Porosity % = Pore Volume/ Total Rock Volume \( \times 100 \)

17. Mobility ratio (Mr) = \( 1 + \frac{1}{K_{ro} \text{ (end point)}} K_{rw} \text{ (end point)} \times \frac{\mu_w}{\mu_o} \)

18. Absolute Permeability (Ka) = \( \frac{Q \cdot L \cdot C}{A \cdot \Delta P} \) (mD).

Where: \( F_o = \) fractional oil, \( d_o = \) step oil produced, \( dvi = \) step water injected, \( O_{av} = \) average oil produced, \( V_i = \) Volume injected water, \( PV = \) pore volume, \( S_{w1} = \) water saturation, \( S_{w2} = \) water saturation post breakthrough, \( F_w = \) fractional water, \( K_o = \) rock permeability (perm) to oil, \( K_w = \) rock perm to water, \( K_{li} = \) rock liquid perm, \( K_{ro} = \) rock relative perm to oil, \( K_{rw} = \) rock relative perm to water, \( S_{oi} = \) initial oil saturation, \( S_{wi} = \) initial water saturation, \( \mu_o = \) viscosity of the oil (cp), \( \mu_w = \) viscosity of water, \( L = \) core plug length (cm), \( A = \) cross section area of standard plug (cm\(^2\)), \( \Delta P = \) differential pressure across the plug (psi), \( T = \) time in minutes, \( Q = \) flow rate (cc/min), \( C = \) constant factor of the analysis instrument, \( V = \) volume of produced fluid (brine, oil or water).

**STRATIGRAPHY AND RESERVOIR FACIES**

The stratigraphy and reservoir facies of Mishrif carbonates is described as, biostromal buildups with fore and back shoals to inner-shelf lagoonal and open marine lithofacies cycles, subdivided into Upper, Middle and Lower Members, and three main (Ma, Mb1 and Mb2) reservoir units (Fig. 2). The Upper Mishrif Member; is bounded by maximum regression surface MR (SB-K150) sequence boundary type1 (SB-T1) at the top of Mishrif Formation with a limonitic litho-marker KH/1-1. This part consists of
two units, the Cap Rock One (CR1) of dense-compact restricted lagoonal facies, with very low porosity and permeability buildup, encounters between the Mishrif top and top of the upper reservoir unit (Ma). The upper reservoir unit Ma composed of frontal-shoals to open shallow marine setting, from North-Rumaila, West-Qurna, Majnoon to Buzurgan oil fields. MFS-K140: is a shaly lime-mudstone chrono-marker at the lowermost section of upper Mishrif. The Middle Mishrif; consists of two units, the Cap Rock Two (CR2) of open lagoonal facies, dense-compact, very low porosity-permeability buildup, between the base of Ma and the top of the reservoir Mb1. The top of CR2 is a regional disconformity boundary SB-T2 of typical facies change, marked as KH/1-2 litho-marker. The reservoir unit Mb1 is: Rudistid bioaccumulated bank to open-lagoonal facies subdivided into two sub-units, Mb11 and Mb12. The MFS6 (Chevron/SOC, 2006) or MFS-K130a chronomarker (Awadeesian, 2008); crossing or terminating the bank across the depositional basin. The Lower Mishrif (Mb2) unit; is of shoals to open shallow marine facies buildup. It is subdivided into Mb21, Mb22 & Mb23. The Mc unit is of open-marine to shoal facies buildups along West-Qurna and Majnoon oil fields, turns to more open marine facies along North-Rumaila (NR) oil field and westwards, subdivided into Mc1 and Mc2. MFS-K130: chronomarker of Sharland 2004: crossing the lower part of Rumaila Formation. Whereas; MFS-K120: chronomarker: represents lower Ahmadi shale. Ru/1: is a litho-marker at the top of Rumaila Formation. HST: Progradational High Stand System Tract. TST: Retrogradational Transgressive System Tract.

The Mishrif most important reservoir facies are itemized (RF101 to RF106) as in their sequential buildup, and summarized as in the following order:

**Bioclastic wackestone facies:** It represents reservoir facies (RF101) (Fig. 3), of well-defined mud to grain-dominated wackestone facies (basal bioclastic wackestone of pile-type floatstone texture) buildup. The facies is specifically characterized by different grain sizes mostly smaller than 2 mm, unsorted, rarely transported embedded in micritic groundmass, with matrix to separate-vuggy pore network of sizes less than 5 to 20 microns, partly upgraded by solution microchannels, differently cemented, petrophysical improved. Represents the basal part of the Mb1-2 reservoir unit. It categorized under; porosity (Phi) buildup of 12 to 20% and 45 to 100 mD permeability
range, mostly performs of non-TMF character, but in certain cases behaves semi-TMF character, especially in the secondary development projects.

Fig. 2: Representative stratigraphic section of the Mishrif Formation, North-Rumaila and West-Qurna oil fields, showing litho/biostrat and sequence stratigraphic buildups, and related sedimentary/reservoir subdivisions, given by Awadeesian (2008 and 2010)

Fig. 3: RF101; grain-dominated bioclastic wackestone facies; with poorly/moderately sorted Rudist fragments, with solution micro-channel, oily at lower right-hand side. Well improved from Rumaila/West-Qurna/Majnoon region to Amara district. West-Qurna oil-well/114: 2401 m. ———: scale-bar = 1 mm
Rudist-bafflestone facies: It represents reservoir facies (RF102) (Fig. 4a), well-defined bioaccumulated-bank core facies, thru baffled and trapped micritic matrix by the original Rudists in growth position and Condrodonta shells. It is obviously characterized by, matrix to composite intragranular and vuggy with solution microchannels pore network, differently cemented, petrophysically improved, with porosity range (10 – 15%) and permeability (60 – 100 mD). It categorized under semi-to-non troublemaker facies during field development plans.

Bioclastic packstone facies (floatstone-texture): It represents reservoir facies (RF103) (Fig. 4b) well described as mud-dominated bioclastic wackestone to packstone facies buildup, of less than 10% bioclastic fragments larger than 2 mm in size, mainly forwards the flanks and bank core facies. It is specifically characterized by matrix/composite-pores to solution-enlarged voids and solution microchannels pore network, differently cemented, petrophysically improved, with porosity range (12 – 18%) and permeability (90 – 150 mD). It categorized under semi-to-non troublemaker facies during the field development policies.

Fig. 4: RF102 & RF103 transformed to RF104, a; Rudistid bafflestone facies, with over 2 cm Rudist, b; bioclastic packstone (floatstone) facies (less than 10% larger than 2 mm Rudists) and rudstone texture of (more than 10% larger than 2 mm Rudists), Embedded in micritic matrix. Intragranular, micro-meso/separate-vug pores (5 to < 20 microns), oily. Pore-system occluded by fine-coarse equimosaics. West-Qurna oil-well/20: 2317-2321 m, 1; : scale-bar = 2 cm, 2; : scale-bar = 2.5 mm

Bioclastic packstone facies (rudstone-texture): It represents reservoir facies (RF104) (Fig. 4b) (floatstone transition to rudstone), well-defined as grain-dominated bioclastic packstone facies, of fragments more than 10% larger than 2 mm in size. Represents coarsening-upward/ capping and flanking facies buildup, characterized by
critically leached intergranular to composite pores of differently cemented pore network, petrophysically improved with porosity range (12 – 18%) and permeability (100 – 150 mD). It categorized under semi-to-non troublemaker facies during the field development plans.

Coated-grain (bioclastic) grainstone (rudstone) facies: It represents reservoir facies (RF105), (Fig. 5). It is well-defined bank of shoal tendency facies, capping-type buildup. It signifies the terminal stage of the coarsening-upward cycle. Characterized by; intensely leached intergranular pores partly cemented as meteoric-phreatic grainstones, petrophysically improved, with porosity range of (15 to 25%) and permeability (188 to 500 mD), of acute troublemaker reservoir facies TMF type.

![Fig. 5: RF104 to RF105; Peloidal bioclastic grainstone (rudstone) facies; re-dissoluted Rudist fragments of composite inter/intra-granular/ solution-enlarged voids, well-connected pore-network. Partly cemented by equi-mosaics. Meso/ mega pores (15 to more than 20 microns), of (Mb1) unit TMF, oily. a: North-Rumaila oil-well/18, 2406.10 m, X8.5; b: North-Rumaila oil-well/18, 2407.00 m X25](image1)

Peloidal packstone-grainstone facies: It represents reservoir facies (RF106) (Fig. 6); this reservoir facies is described as a modified skeletal-texture into peloidal buildup by biogenetic destruction under shoal of moderate to high energy levels, abraded and rounded to well sorted.

It is extremely signifies a leached composite pores buildup, of highly open network, differently cemented, petrophysically improved with porosity range (18 to 28%) and permeability (188 to more than 500 mD), represents risky TMF character during the field development plans.

The core plugs representing TMF facies as shown in the photomicrographs 1, 2 and 3 in the same figure, have used in the water flooding experiments, and signify the final stage of PAS water and crude oil-in-water divertor injections.
Fig. 6: RF106; Coated grain (bioclastic) grainstone (rudstone) facies; highly leached inter/intra-granular pores. Multiple to leached pore-system by continuous dissolutions, of open channels, shoals of Mb1 unit with TMFs of up to 50-100 microns pores. Oil-droplets are of the injected-diverter blocking the pore throats used by the water flooding stage. 1: North-Rumaila oil-well/292, 2410.25 m; 2: North-Rumaila oil-well/253, 2337.00 m; 3: North-Rumaila oil-well/253, 2337.60 m. The main difference between micrographs 2 and 3 is the partial cementation to dissolution effect within the 60 cm. Scale-bar: —— = 2 mm

For integrated application of reservoir geology and reservoir engineering to field development aspects; it is very important to introduce an incorporated basis of reservoir facies/pore system per lithofacies cycle-set buildup as, RF101 to RF106, (Fig. 7). This introduced framework has arranged from base-to-tope as in their depositional order, and ordered from 1 to 6 as in the direction of drilling. It is illustrated as well, the reservoir TMFs and non-TMFs buildups.

This framework will be of important target in dedicating facies/pore/fluid distribution outline of Mishrif carbonates at each field, subsequently cooperative for full planning of water injection technology.
Fig. 7: A Mishrif carbonates reservoir facies compliance based on; lithofacies and pore system buildup, successively itemized as RF101 to RF106, per high-frequency lithofacies-cycle-set. It is ordered from base to top representing the main Mb1 reservoir, North-Rumaila, West-Qurna and Majnoon oil fields, (Awadeesian, 2010 and Awadeesian et al. 2015)

From reservoir standpoint, the high-frequency lithofacies cycle-set, may or may not contain a complete series of reservoir facies buildup (Fig. 8A, B, and C). For example the main reservoir Mb1 of Mishrif formation; consists multiple HF-cycles of almost complete series, whereas; the overlain Ma and underlain Mb2 reservoirs of a non-complete cycle(s) due to; no Rudistid-bank development, and restricted progress of RF105 to RF106 reservoir facies within both latter units. The bank-shoal development highly depends on the depositional setting of the units per each oil field. The Mishrif reservoir problematic facies as termed (troublemaker facies TMFs (Awadeesian, 2002) of vastly heterogeneous rock fabric and extremely leached composite pore-network system, especially the types of pore sizes larger than 50 micron, with permeabilities over 500 mD; has considered a characteristic manifest for dissolution to cementation relationship with respect to relative grain-to-grain compaction effect. For instance, a shoal grainstone facies undergone into successive burial with active grain compaction; created less effective reservoir facies RF105 in flow-unit dynamics, in contrast, the same facies at another set of short burial stage with high effective
dissolution over cementation; created very good reservoir facies RF106 for fluid-unit dynamics. The RF105 to RF106 upgrading in the reservoir dynamics has leveled to rock-fabric/pore-geometry framework with 18 to 28% porosity range and 188 to over 500- mD permeability, creating increase in water cut percent and by-passed oil versus decrease in oil recovery. Whereas; the non-TMFs reservoir facies RF101, RF102 and RF103; create stable water encroachment process during water injection drive, of less water cut percent and less by-passed oil. The identification of the MFS-K135 marker that crosses or terminate the Rudistid bioaccumulated bank, is stratigraphically important due to; its direct controlling the Mishrif facies/fluid dynamic buildup and framework.

Fig. 8: A schematic screening of the Mishrif sequential reservoir (cycle-set) facies of the main Mb1 reservoir in the studied oil fields, useful for water injection techno: The basal mud/grain bioclastic wackestone facies to Rudistid bafflestone-floatstone facies (green) of micro to meso of 5 – 20 µ pores, differently cemented. Upgraded to Rudistid bioclastic packstone/grainstone (floatstone to rudstone) facies buildup (red) of greatly dissolved intergranular pores (20 to over 75 µ in size), variably cemented. The cements considered active fluid obstacle. The TMFs create serious water-channels. A: a complete series (green-to-red arrows) of the Mb1 reservoir buildup. B: indicates reservoir buildup of RF101/RF102 to RF103/RF104 and cemented-RF105. C: signifies RF101 to leached-RF105 series graded to leached-RF106 buildup
RESULTS AND DISCUSSION

Based on the methodological principles of McAuliffe (1973 and 1974), Bansal (1978), Mungan (1960 and 1981) and Tyssee and Vetter (1981), the following three work-stages has been applied to study the fluid-flow behaviors within the porous system of the Mishrif reservoir rocks:

**Fluid preparation and treatments**

This represents a first stage concerns preparation and treatments of fluids used in the technique, from the initial filtration of injected waters by 10 µ millipore mesh, taken from Garmat Ali river near the water injection plant west of Basra city. The fluids were biologically treated by 5 ppm/lt of hypo-chlorine with 0.2 ppm/lt as a clean-level at the terminal stage. Forwarded by; adding 0.1 ml/lt polyacrylamide with mechanical stirring to precipitate the clays and suspended particles in the water, and 0.4 mg/lt of sodium dichromate as a corrosion inhibitor. Preparation of alkaline-surfactant water using suitable economic doze 0.05 – 1.5% by weight caustic soda for pH more than 10, to control; capillary forces and reducing the interfacial tension between the injected fluids and crude oil. Certain measured interfacial tension data has not done on Mishrif crude oil, and by its 23 – 25 API°, the expected interfacial tension may exceed 30 dyne/cm. Selected dose of 0.75 – 0.95 % by-weight has used for high-to-low foam non-ionic surfactant, to get a water-wet system. The process followed by; adding suitable doze 0.2 – 0.55 % by weight of hydroxy ethyl cellulose (HEC) polymer, with 10 to 15 minutes of mechanical stirring for good mixing stability. All the prepared fluids have undergone, into basic filtration process by 3-µ millipore mesh filter.

Base-crude-oil had been prepared by a compatible dead-oil of 3:1 fresh heavy Fuqua and Buzurgan crude oils, no water content neither chemicals for core-plug samples saturation. The measured physiochemical parameters: specific gravity = 0.945, API° = 18.3, asphaltenes content 6.89% by weight, total acid number = 1.59 mg KOH/gm crude oil, and viscosity range = 200 cp at 60 °F to 25.88 cp at 160 °F. The Emulsification (divertor) preparation has been prepared by the above base-emulsified-oil preparation stage, the crude oil-in-water divertor of 0.75% by volume which has mixed with modified injected water, undergone into mechanical stirring for 10 to 15 minutes, to form; precise emulsified-oil droplets size, morphology, stability and
viscosity. The latter varied between 4 to 10 cp under reservoir conditions, 5 to 8 cp is favored for more convenience displacement process.

**Rock permo-facies-correction technique**

This is a second stage done based on McAuliffe (1973) technique specified in a special lab equipment under reservoir conditions 1750 – 2250 psi and 85 – 90 ºC in which, the divertor is installed in special accumulators to inject into core plugs. Accordingly, three standard core-plug samples of 1.5 inch diameter and 3 inch length with measured liquid base initial-permeability (Kwi) for each sample were chosen, from the North Rumaila oil field to represent the heterogeneous reservoir rock-facies of the Mishrif multi-cycles, differently characterized by TMFs. They have been separately installed in three special core holders connected in parallel, installed in a specially designed equipment working under the above reservoir conditions. The absolute and initial rock-permeabilities to water for the three samples measured and calculated. **The prepared crude-oil-in-water divertor**; injected at the same time into the core samples, the rock-permeabilities to water (Kw); measured and calculated at every injection-step during the overall process, as illustrated in the following Table 1 and (Fig. 9).

*Sample 1*: NR-186, Ka = 3540 mD, Kwi = 1567 mD. *Sample 2*: NR-36, Ka = 1858 mD, Kwi = 1079 mD. *Sample 3*: NR-253, Ka = 784 mD, Kwi = 249 mD.

The fluid-flow efficiency (FFE) percent identifies; that the divertor-droplets blocking the pores-throats at 0.25 pore-volume injected (PVi) as in sample number 1 (NR-186) of extreme TMF, with FFE = 20% versus; 85 and 90% for the samples 2 (NR-36) and 3 (NR-253) respectively.

**Table 1: Rock permeability and cumulative pore volume fluid injected**

<table>
<thead>
<tr>
<th>Total Cumulative Time (minutes)</th>
<th>Rock Permeability to Water (mD)</th>
<th>Cumulative Pore Volumes Fluid Injected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NR-186</td>
<td>NR-36</td>
</tr>
<tr>
<td>0.00</td>
<td>1567</td>
<td>1079</td>
</tr>
<tr>
<td>2.26</td>
<td>305</td>
<td>927</td>
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<td>5.07</td>
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<td>11.06</td>
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<td>11</td>
<td>35</td>
</tr>
<tr>
<td>27.45</td>
<td>11</td>
<td>34</td>
</tr>
</tbody>
</table>
Fig.9: Prermofacies correction technique by divertor injection

Whereas; at 0.50 PVi of divertor injected, the FFE for the first sample become 5% and 45% for the second sample at 0.45 PVi, versus, a stilly-stand nature of fluid flow with efficiency 86% at 0.57PVi for the third sample. A distinctive lowering of the FFE to 22% created for this sample at 0.91PVi, reflecting; at this stage of divertor injection the rock water permeabilities of the three samples were balanced and nearly equalized, and good water encroachment stability is created at and after 0.50 PVi.

The almost stable decrease occurred in the rock-perms to water (Kw), reflecting the semi-TMF characteristics of the NR-253 rock facies. It reveals as well, a semi-stable fluid-flow conduct during the encroachment stages. The divertor injection to 0.50 PVi stage, has considered the period of TMFs controlling and fluid-flow governing.

For technical warranty test to confirm the crude-oil-in-water divertor flow in porous media, it is important to improve the anomalous flow with varying pressure of the divertor based on pseudo-non-Newtonian flow. Principally the rock permeability to a fluid is changing according to the pressure differential. Thus; a special pressure differential test (successive/ alternative ∆P, 10 psi/ft to 20 psi/ft), has undergone; on a selected core plug of Ka = 1926 mD and initial rock permeability to water Kwi = 1429 mD. The results of the measured and calculated rock permeabilities to water versus cumulative pore-volumes of the injected divertor; has cross-plotted and
illustrated in the (Fig.10). The injected divertor properly performs decrease of rock permeability to water and fluid-flow reduction under the low-pressure differential: improving the pseudo non-Newtonian effect under reservoir conditions. By field perspective, the advantage of divertor injection deep into the reservoir depends on; the large pressure change across the unit distance occurs at the vicinity of the injection well. Consequently, through the radial flow phenomena; the pressure change per unit distance is logarithmically decreased as the distance increase from the injection well, versus; simultaneous Kw decrease.

**Fig.10:** Successive and alternative differential pressure technique applied on divertor flow through the porous media under reservoir conditions

**Mishrif dead crude oil**

This is the third stage that has been conducted which started by preparation of Mishrif dead crude oil with 0.889 – 0.915 specific gravity, 2.5 – 3% by-weight asphaltene, 1.15% by weight sulphur, and viscosity of 6.75 cp at 60 °F and 2.97 cp at 160 °F, free of salty-water and no chemicals content. Twenty-five standard core plugs (1.5 -inch diameter x 3 -inch length) of heterogeneous rock-fabric/pore system and poro-perm characteristics with TMFs per measured Kwi; have saturated by the dead crude oil. The samples stored in special containers, left to age for 2 to 3 weeks to create good rock-fluid wettability. The Soi %, Ko and Sw%, successively measured and calculated for each sample, separately forwarded into water-oil displacement
technique, under pressure 2250 psi and temperature 85 to 95 °C; as in the following work scheme: Injection of polymerized alkaline surfactant (PAS-water) as a first step of the injection until the water breakthrough has created, and continued injection shortly after the breakthrough. The second step, started by successive injection of crude oil-in-water-divertor within the intervals 0.3 – 0.5, 0.6 – 0.8 and 0.85 – 1.1 to 2.5 PVi to control the TMFs as early as possible. The progressive blocking of the small/large oil-droplets; continuously recognized upon the medium/large pore-throats of differently interconnected channel-network of the TMFs.

The oil-droplets blocking action; is well illustrated in the thin-sectioned core plugs of the same coated-grain (bioclastic) grainstone facies, after the terminal stage of divertor injection, refer to the same preceding (Fig. 6). The well-developed composite pore system, highly leached-vuggy and solution-enlarged-voids to interparticle-voids, partially cemented by equi-mosaics and isopach-rims, clearly influenced by the injected oil-droplets. Successive restrictions of water-channels by oil-blockers in the TMFs leave good chances to PAS-water to recover more oil from non-TMF types. This controlling agent aptly produces more stable water-oil displacement system, under decreased water-oil mobility ratio. Accompanied calculations of Kw, Sw % and oil-recovery %, versus; water-cut % and Krw, Kro were carried out, for first group of Mishrif core samples, NR field; finally averaged and cross-plotted in the (Figs. 11, 12 and 13).

The oil-water relative permeability Kro/Krw, water-cut% and Fw, versus; pore volumes fluid injected indicates: the maximum recovered oil at water-breakthrough by the prepared PAS-water is around 32% by 0.268 PVi, and perm-ratio infinite. A divertor of 0.5 to 0.75% of emulsified-oil; with 50% oil-droplets of 20 – 75 µ, 25% larger than 75µ and 25% less than 20 µ, injected at 0.35 to 0.45PVi. The perm-ratio reached 4.3 at 46.5% Sw and Fw = 0.09 versus 29.5% Sw at the producing end, as well as; 39.44% recovered oil at Sw 32%. The second case: perm-ratio 1.8 at 54% average water saturation, with Fw = 0.210, 37% Sw at the producing end and 55% recovered oil, by 0.4 to 0.6 PVi.

The second group of core-samples; undergone into an injection of divertor of more than 50% oil-droplets greater than 75 µ of the effective blocking character of on pore-throat system, with almost same perm-ratios of the group-one, with nearly the same Fw behaviors. The water-oil relative permeability cross-plot has illustrated in the (Fig. 14).
Fig.11: Divertor injection technique displays the water-oil relative permeabilities versus water saturation for group1 samples of Mishrif reservoir, North-Rumaila oil field

Fig.12: Average fractional flow of water vs. end face water saturation by conventional technique (blue) and the new oil recovery technique presented by this study (Red) for Mishrif Formation, North-Rumaila oil field
Fig. 13: Oil recovery versus fluid injection of the Mishrif reservoir, North-Rumaila oil field; using different techniques

Fig. 14: Improved oil recovery technique done by this study illustrates water-oil relative permeabilities versus water saturation for group2 samples of Mishrif Reservoir, North-Rumaila oil field
Regular injection within 0.65–0.75 PVi and 0.85 – 1.3 PVi; the perm-ratio ranged to 0.5 – 1 and to 0.1 – 0.5, versus; Sw 65 – 80% and 80 – 90% respectively. The Fw varied between 0.3 – 0.75 and 0.75 – 0.95, the end face water saturation between 40 – 50% and 55 – 70% with improved cumulative oil recovery 65 to 75% and 80 to 90% respectively. The final improved mobilized residual oil has determined around 65% with end-point mobility-ratio between 0.5 to 1.5.

The Mishrif reservoirs in the West-Qurna oil field, characterized almost same descriptive rock-fabric/ pore-geometry system, in relation to the equivalents at the North-Rumaila oil field.

The selected core-plugs from West-Qurna oil field; undergone into the same methodological stages of this technique. Most of the tested samples achieved same improved oil recovery performance, and other related parameters, for which the final results illustrated in the (Fig. 15). The TMFs of the multi-shoal buildups of the main Mb-unit severely create premature water-breakthrough within 0.045 – 0.151 PVi, by using usual water injection for the development projects of this reservoir in both fields.

Fig. 15: Oil recovery versus fluid injected of the Mishrif reservoir, West-Qurna oil field; using different techniques
It is worthy to mention that the Basra oil company's technical reports; approved usual lab waterflooding technique carried during the past decades on tens of core-plugs of heterogeneous rock-system with TMFs, the blue lines in (Figs. 13 and 15). The achieved oil recovery is 8 to 25% at water breakthrough by 0.065 – 0.175 pore volumes fluid injected, with increasing water cut to over 50% at 0.35Pvi. The ultimate oil recovery is 70.35% by 78 PVi with 99.9% water-cut and residual oil saturation more than 55%, same mentioned figures.

Generally, the usual water drive mechanism produces high initial oil-yield of increased wet-oil buildup by the TMFs, thru the high-interfacial tension between the heavier components of Mishrif crude oil and the rock-fabric/pore-network character. As well as; successive water-passageways differently cap the oil-bearing units, and extremely bypassed-oil will be created by the continuous usual water injection, without any possibility of good oil recovery.

The expensive advanced tertiary recovery techniques may or may not resolve such problem in the latter stages of Mishrif development.

**CONCLUSIONS**

The final findings from this study can be drawn as follows:

- The use of the presented PAS-water injection technique at early injection stages, delays the water breakthrough from 0.045 – 0.151PVi with 8 to 25% oil recovery, into 0.15 to 0.268 PVi, with 18 to 32% improved oil recovery.
- The successive injections of the crude-oil-in-water divertor after water breakthrough, within 0.3 – 0.5PVi, 0.6 – 0.8 PVi and 0.85 – 1.1 PVi, create water/oil ratio lowering by 10 to 15%.
- The technique used in this study improves a residual oil mobilization by 65%, and depresses the end-point mobility ratio between 0.5 – 1.5.
- By the proposed technique as an alternative plan to the ongoing usual water injection, the ultimate oil recovery will be 85 to 90% at 6.5 PVwi.
- It is highly important to use 10-micron mesh filter at the main injection site and 4 or 5 micron filter at the injectors, to save 80% of the pore system from permeability-damage.
ACKNOWLEDGEMENTS

We deeply grateful to the Ministry of Oil and Basra Oil Company employees in charge, mainly to all geologists, reservoir engineers, physicists, chemists and technicians for their great work done by different ways especially in the laboratories part of the research department of BOC to accomplish this study.

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