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Key Words

LSWF, IOR, EOR, Reservoir Simulation, Residual Oil Saturation, Mature Field

Abstract

Worldwide carbonates hold almost 60% of oil reserves. The inherent heterogeneity and wettability characteristics of carbonates make improving oil recovery (IOR) under conventional IOR practices a challenging task. In recent years, Low Salinity Water flooding (LSWF) has emerged as an attractive Enhanced Oil Recovery (EOR) mechanism involving complex Crude Oil-Brine-Rock (COBR) interactions for improving displacement efficiency by tuning the injection water salinity. Various case studies indicate incremental benefits up to 10% of OIIP in laboratory as well as in field trials in carbonates^[4].

In India's biggest and most prolific oil field i.e. Mumbai High, challenges of reservoir heterogeneity, pressure depletion and high temperature (>100°C) coupled with offshore location proved to be a major limitation in application of conventional EOR methods. However, proven IOR strategy with sea water flood for medium gravity oil, favorable mobility ratio, high residual oil saturation and extensive network of offshore facilities provided an opportunity to implement LSWF for recovery enhancement.

A detailed multi-level approach was adopted to evaluate, simulate and conceptualize LSWF-EOR. Stage-wise screening program for lab to field implementation involved series of core flood studies and Single Well Chemical Tracer Test (SWCTT) followed by reservoir simulation to quantify oil gain under EOR. Encouraging results of in-house laboratory core studies (oil recovery: 6 to 16%) was the catalyst which led to further evaluation of the process.

For conceptualization of EOR pilot implementation, target area was chosen based on reservoir architecture, production/water flood performance and available surface facilities. Simulation results of pilot area estimated incremental oil recovery of 1.5% over sea water with ~30% pore volume injection and water salinity diluted to 25% of sea water.

Based on above studies and favorable techno-economics, LSWF-EOR scheme was approved for field implementation.

Within a span of 3 years, facility creation of low salinity plant in offshore was completed and the process was rolled out, a first of its kind in offshore. Comprehensive monitoring/surveillance plan was formulated and initial results indicate favorable response.

The paper deliberates LSWF-EOR from conceptualization to field implementation and summarizes early trends based on field observations.

Introduction

Mumbai High field is located at about 165 km North West of Mumbai city (figure-1) in the western offshore basin and is the largest oil field in India. The field has multiple reservoirs of which X1 reservoir contains more than 80% of oil in-place volumes and contributes more than 75% of field production. The field is under water injection for nearly 4 decades. Stratigraphically, X1 reservoir of Mumbai High belongs to the Burdigalian stage of early Miocene Epoch (figure-2).

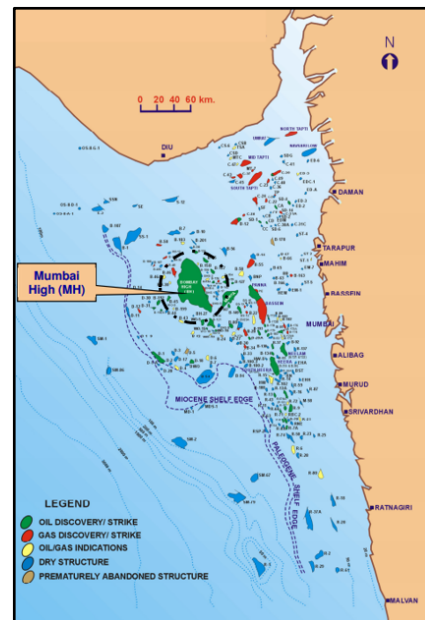


Figure-1: Location map of Mumbai High Field

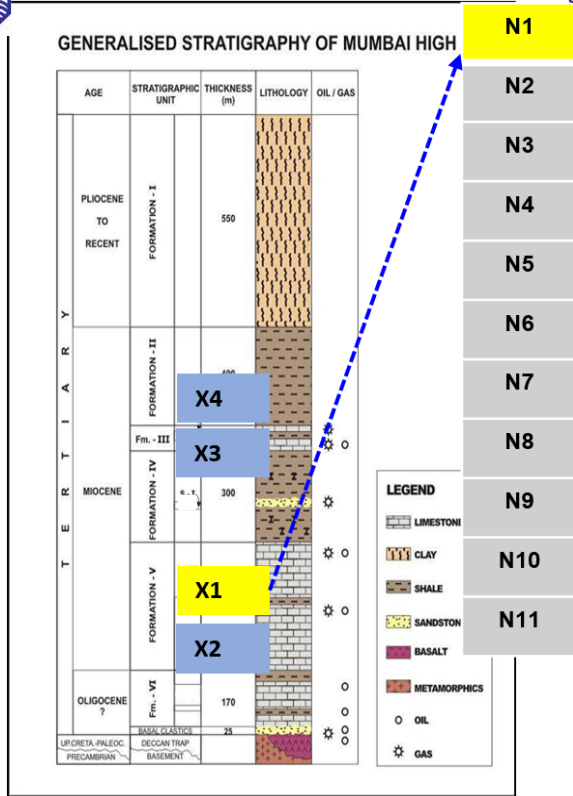
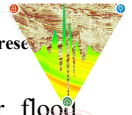


Figure-2: Stratigraphy of Mumbai High Field

Apart from various steps taken for arresting production decline, major redevelopment (IOR) schemes have been implemented with emphasis on targeting by-passed oil & improving water injection for better pressure support and volumetric sweep. In the endeavor to further improve recovery, EOR processes have been critically scrutinized for Mumbai High field since mid-1980s but high salinity, high reservoir temperature and decline in reservoir pressure proved to be major impediments for application of conventional gas or chemical based EOR. In this quest, Low Salinity Water Flooding (LSWF) was found to be a suitable EOR technique with commercial viability.

Reservoir Description

X1 reservoir of Mumbai High is a multilayered saturated carbonate reservoir. Key reservoir parameters are listed in Table-1. Current production forecasts estimate oil recovery of about 37% by 2040 under conventional sea water flood.

Average reservoir permeability, md	50-200
Porosity, fraction	0.25
Dykstra-Parson Coefficient	0.8
Pay thickness, m	40
Formation water salinity, ppm	23000
API gravity, deg	38°

Table-1: Average values of key reservoir parameters

In view of favorable mobility ratio, good water flood response, low free gas saturation and available surface infrastructure, N1 layer of X1 reservoir located in the western periphery of Mumbai High field was evaluated for pilot implementation of LSWF EOR (figure-3).

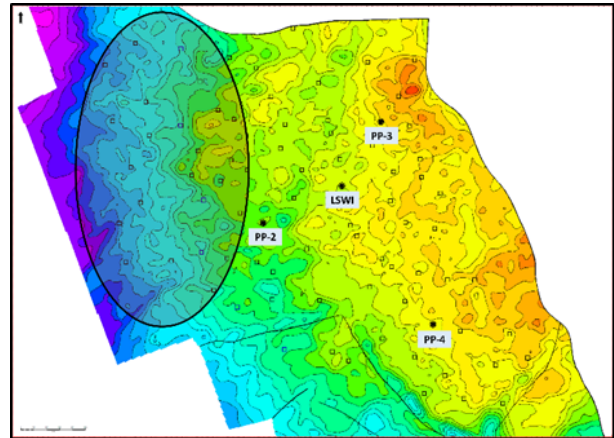


Figure-3: X1 Reservoir Top and EOR pilot area.

The target area consists of >100 completions in N1 layer (including ~40 injection strings) and contributes about 20% of total oil production from the reservoir with average GOR and water cut of 170 v/v and 72% respectively. Production performance of the study area is shown in figure-4.

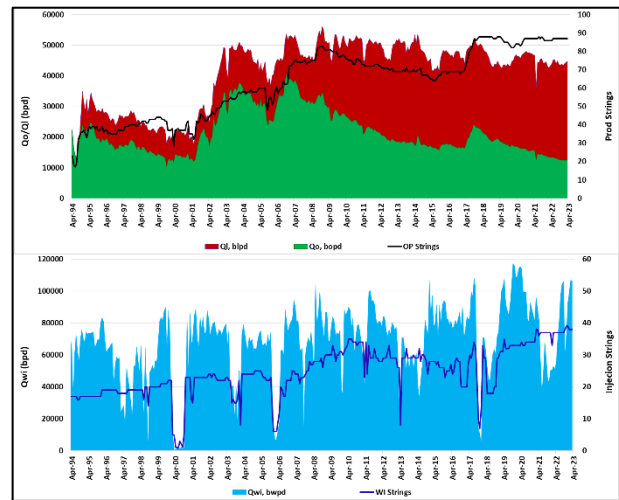
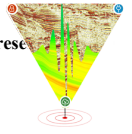


Figure-4: Performance of LSWF Pilot Area.

Laboratory Core Studies

To understand the efficacy of LSWF process, spontaneous imbibition studies were carried out on representative core samples which indicated cumulative oil recovery of around 4% for X1 reservoir cores. Subsequently, core flood displacement studies were conducted in sequential manner with 50%, 25%, 10% and 1% diluted sea water in tertiary mode and there was an increase in oil recovery from 5% to



over sea water (figure-5). Further, based on coreflood, optimized low salinity concentration for target reservoir was found to be about 25% of sea water salinity. Literature survey also indicates, sequentially diluted SW injection over conventional SW flooding is very effective for oil recovery enhancement^[1].

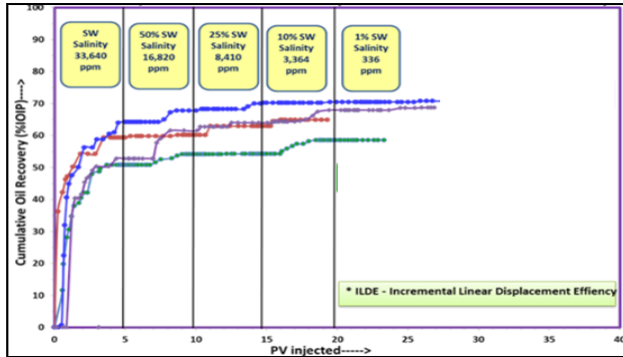


Figure-5: Oil recovery Vs. Pore volume of injected fluid

For reservoir simulation, studies were conducted to generate salinity dependent oil-water relative permeability curves.

Simulating core flood study

A 1D core model was used to simulate recovery trends obtained in core flood experiments with similar gross rock volume and porosity-permeability values. To model fluid injection, one injector and one producer was defined at each end of the model grid. In the base case, the core was flooded with sea water at the rate of 10 ml/hr. At the end of the process, recovery observed was 50.67%. In a subsequent variant, sequential dilution of injection water was carried out and a good match in recovery trends was obtained vis-a-vis lab obtained displacement efficiency.

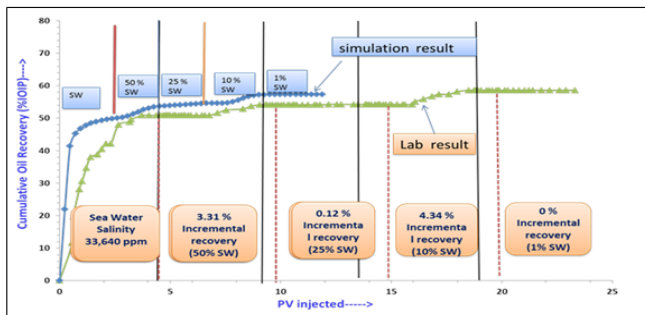


Figure-6: Comparison of lab and simulated core flood results

Based on wettability alteration captured through relative permeability curves, cumulative incremental recovery with different salinities is observed to be around 7% in line with coreflood study results (Fig-6).

Pilot Area Simulation

For conceptualization of EOR pilot, reservoir simulation remains the most cost effective tool for quantifying additional oil recovery from low salinity water injection beyond existing conventional sea water. For evaluating LSWF response in target area, it is essential to understand simulation approach for LSWF in Black-oil simulator linking the salinity of the brine in the reservoir to relative permeability curves as introduced by Jerauld et al.^[3]. In the present study simulator has a brine tracking function which is activated using certain keywords. Model adds an additional salt phase to already existing phases and a mass conservation equation for the new phase is solved for each grid block in the reservoir model. Simulator tracks water salinity and an additional set of “low salinity” saturation functions is defined based on laboratory inputs. For fluid mobility, based on grid block salinity, either the original “high salinity” functions or the new “low salinity” functions are used whereas for intermediate salinities, relative permeability is estimated through interpolation. The low salinity oil recovery mechanism is modelled by calibrating relative permeability and residual oil saturations as a function of salinity. During simulation, salinity dependent relative permeability curves are generated using weighing function as follows:

$$K_{rw} = F_1 K_{rw}^L + (1 - F_1) K_{rw}^H$$

$$K_{ro} = F_1 K_{ro}^L + (1 - F_1) K_{ro}^H$$

$$F_1 = \frac{C_{s2} - C_s}{C_{s2} - C_{s1}}$$

Where:

C_s : interpolated salinity concentration

C_{s2} : Lower limit of Salinity

C_{s1} : Upper limit of Salinity

K_{rw} : Relative permeability of water

K_{ro} : Relative permeability of oil

The superscript “L” and “H” indicate low and high salinity data respectively.

In the pilot area simulation, based on lab generated salinity dependent relative permeability curves, Sor reduction up to 10 units was considered in the model for low salinity water of 8000 ppm salinity. Mixing response after low salinity water injection (figure-7) was observed with corresponding shift in oil and water mobility.

Base case prediction were run considering conventional sea water flood resulting in estimated recovery of about 38% with 54% of pore volume injection.

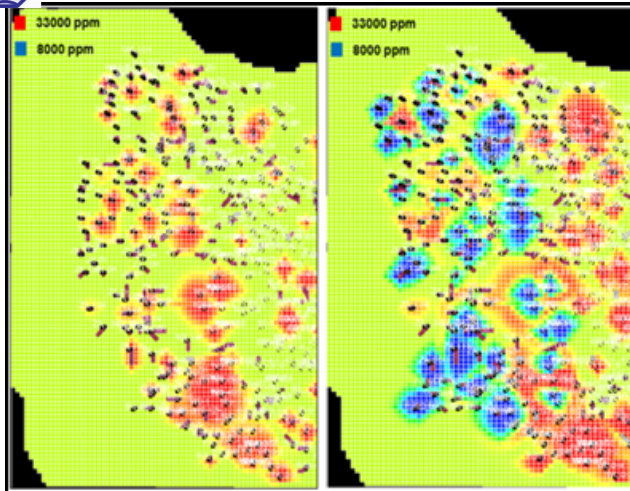
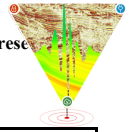


Figure-7: Salinity Changes with sea water flood (Red)/low salinity water (blue) in simulation

LSWF prediction runs were made with WI salinity of 25% sea water salinity. It is estimated that after pore volume injection of about 30% incremental oil recovery of 1.5% is achieved over Base case (Sea Water).

Based on the studies, offshore facility for low saline water was created for field implementation with capacity of about 125K bwpd (schematic shown in figure-8).

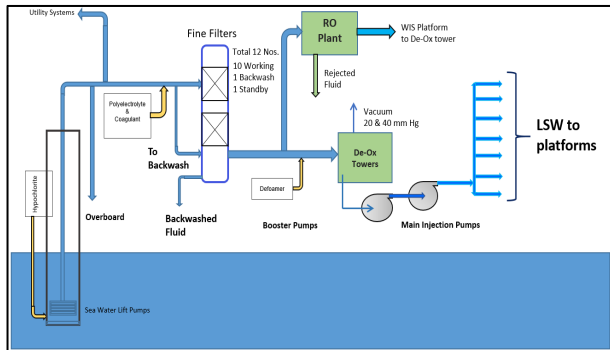


Figure-8: Low Salinity Water Inj. facility: Process diagram.

Surveillance and Monitoring Program for LSWF process

Low salinity water flood is under implementation in the field since last one year. For systematic appraisal and operational feasibility, 53 key wells (28 oil producers and 25 water injectors) were identified.

Monitoring activities have been classified into two categories viz. activities to be carried out on oil producers and activities on water injectors. Tables-2 & 3, summarize the operation/activities to be carried out in oil producers and water injectors.

Oil Producers:

Activity	Frequency
Testing of wells (Oil rate, liquid rate, Water cut, Salinity and pH)	Monthly
Collection of produced water and measurement of ionic concentration (Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻)	Quarterly

Table-2: Monitoring activities in Oil producers

Water Injectors:

Activity	Frequency
Testing of wells (WI rate, ITHP, Salinity)	Monthly
Collection & measurement of water quality parameter of injection water (including ionic conc. Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻ , Cl ⁻) and backwash samples, filterability (Salinity, TSS, pH etc.)	Quarterly

Table-3: Monitoring activities in Water injectors

Frequent well head sampling of oil producers and water injection wells is important to monitor changes of salinity in the study area. Also, for injection water salinity conformance at well header vis-à-vis water injection salinity at LSWF facility, well head sampling at WI platform is necessary. These parameters are required to ensure proper salinity of injection water is being injected and also to quantify impact of LSWF in producers. Hence, well head samples are being collected and are being analyzed by different teams identified for the purpose.

Primary monitoring parameter of low salinity water injection is the reduction in produced water salinity (figure-9). Reduction in salinity (>500 ppm) is observed in oil producers of pilot area compared to base line salinity under conventional flood. In the given figure, pre LSWF data values are represented in blue color bars and post LSWF values are represented in red color bars.

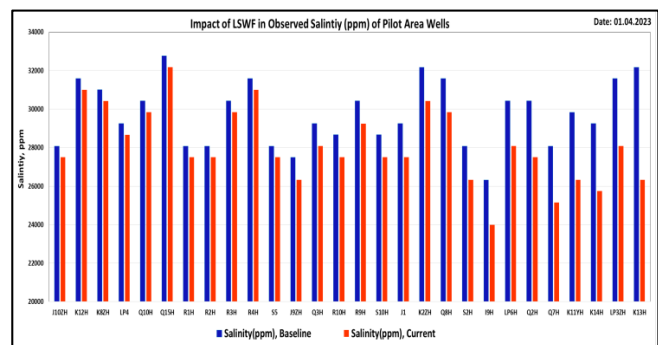


Figure-9: Salinity reduction in pilot area producers

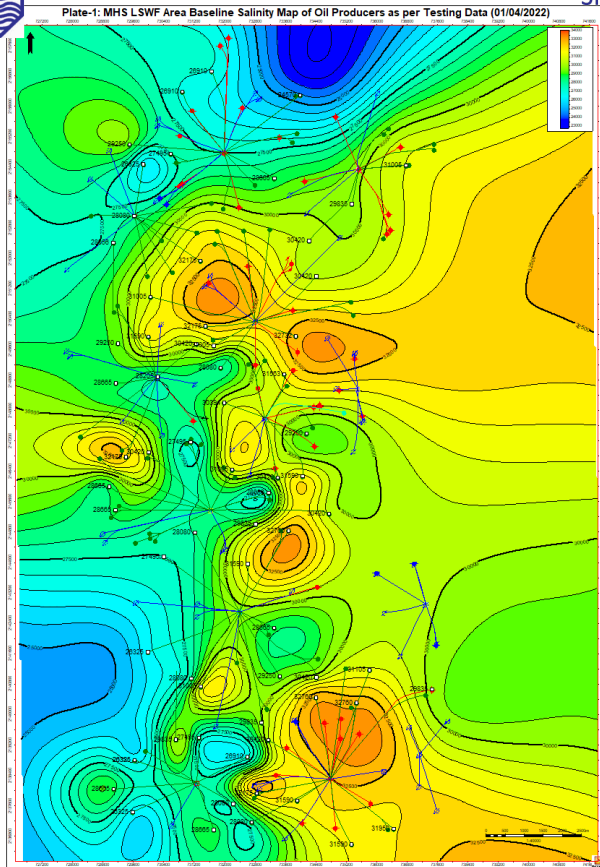
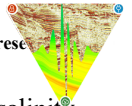


Figure-10: Pre-LSWF salinity distribution map

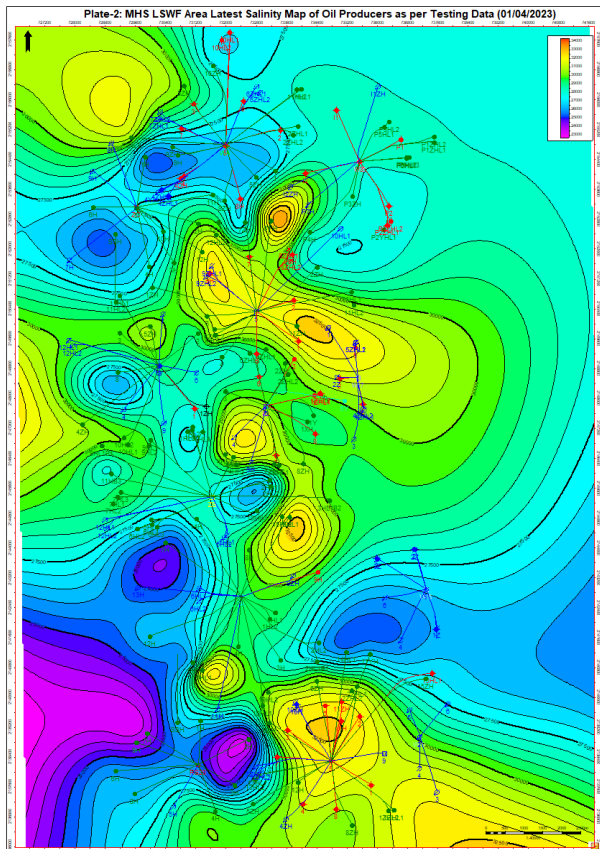


Figure-11: Post-LSWF salinity distribution map

In order to view the changes in salinity aerially, salinity distribution map of pilot area were prepared before and after LSWF and are shown in figure-10 & 11 respectively.

Detailed analysis was carried out to observe the impact of LSWF on oil rates and water cut of the producers. About 28 wells have indicated salinity reduction of up to ~6000 ppm. Moreover, increase in oil rate is observed in about 10 wells as shown in figure-12 with corresponding decrease in salinity and stabilization in water cut, a major key performance indicator showing encouraging trends. Hence, at well level, there seems to be improvement in oil production during LSWF.

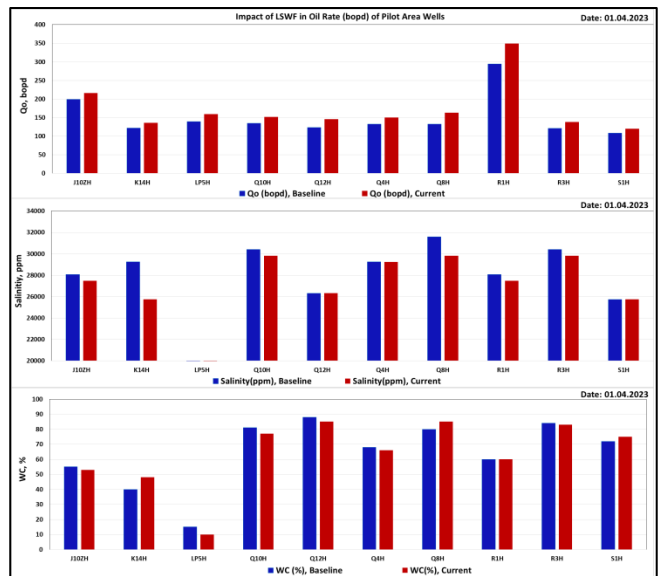


Figure-12: Key Performance Indicators of LSWF

Rise in pH is observed in some of the wellhead samples taken as shown in figure-13. It can be seen that the earlier average pH value (~7) has increased to ~7.5 post LSWF which is a positive indication of LSWF.

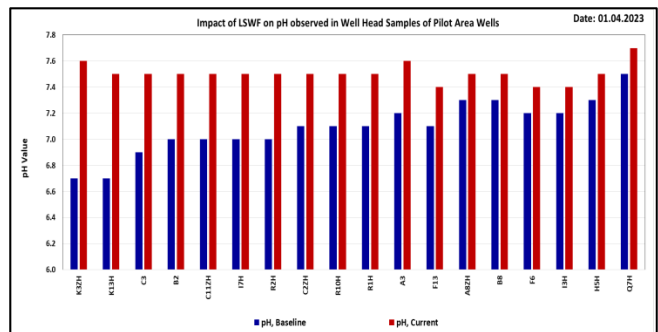
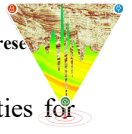


Figure-13: Increase of pH value in oil producers

Reduction in sulphate ions concentration is also observed in few wells which corroborated with the positive impact of LSWF. Though the results are encouraging, it is still is the



inning of the process. As more data is gathered with time and larger area is swept through low salinity water, one can expect better confidence in endorsing the efficacy of LSWF towards improving production from a matured field like Mumbai High.

Summary

The paper summarizes the entire workflow from initial screening, laboratory studies, reservoir simulation, and facility creation leading to field implementation of LSWF EOR process in mature field like Mumbai High. The case study is possibly the largest multi-well LSWF-EOR program in carbonates globally and a first in Indian Offshore. With creation of offshore surface facility having capacity of 125Kbwpd, LSWF is targeting nearly 10% of in-place volumes and consists of more than 100 strings.

A comprehensive surveillance and monitoring program has also been put under practice to ascertain the impact of this process. It includes regular measurement of well testing, well head sample studies and ionic composition analysis of fluid samples to monitor the impact of reduced salinity on oil and water production.

Conclusions

Comprehensive multilevel approach was adopted to evaluate, simulate and conceptualize LSWF process for field implementation in Offshore Carbonate reservoir.

Based on early trends of monitoring and surveillance program, following conclusions can be drawn:

1. Salinity reduction observed in few wells under LSWF process
2. Improvement in oil rate and stabilization of water cut with reduction in salinity indicate positive impact of LSWF process
3. Changes in sulphate ions concentration and pH are indicative of activity of ion exchange mechanism.

LSWF seems to be an effective EOR strategy for enhancing recovery and provide new opportunities in rejuvenating mature brown fields worldwide.

Acknowledgement

Authors express their sincere gratitude to Oil and Natural Gas Corporation Limited (ONGC) for providing opportunity to submit this manuscript. Authors gratefully acknowledge the team at Institute of Reservoir Studies (IRS), ONGC, Ahmedabad and Mumbai High Asset,

Mumbai for providing necessary support and facilities for successful execution of this project.

Disclaimer: The views expressed in this paper are solely of the authors and do not necessarily reflect the view of ONGC.

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