

INVESTIGATION OF LOW SALINITY WATER FLOOD IN CARBONATE RESERVOIRS

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by

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DEPARTMENT OF CHEMICAL ENGINEERING

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CERTIFICATE

This is to certify that the thesis entitled “**Investigation of Low Salinity Water Flood in Carbonate Reservoirs**” being submitted by **Mr. Vivek Raj Srivastava** to the Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy, is a bonafide record of original-research work carried out by him under the guidance and supervision in conformity with rules and regulations of the institute.

The results contained in it have not been submitted in part or full to any other university or institute for the award of any degree/diploma.



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Declaration

I declare that this written submission represents my idea in my own words and where others' ideas and words have been included, I have adequately cited and referenced the original source. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will come for disciplinary action by the institute and can also evoke penal action from the sources that have thus not been properly cited or from whom proper permission has not been taken when needed.

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Abstract

Low salinity water flood (LSWF) is a most promising enhanced oil recovery (EOR) method where injection water salinity/ ionic composition is modified to increase both microscopic and macroscopic displacement efficiency in carbonate/clastic reservoirs screened based on temperature, wettability, and potential determining ions (PDI) with the added advantage of reducing reservoir souring to a very large extent along with ease of injections into oil-bearing formations. Conventional liquid-based EOR methods struggle in India's western offshore carbonate oil fields due to factors like reservoir heterogeneity, pressure decline, high temperature, and the logistical challenges of an offshore environment. This research explores low-salinity waterflooding as a promising alternative EOR solution to address these limitations and maximize oil recovery. Very few EOR projects have been carried out in offshore environments to date and the majority of the projects have been miscible gas injection projects. While demonstrating the success of LSWF in a specific Indian offshore reservoir, this work extends beyond a single case study. It offers invaluable data relevant to the unique challenges faced in Indian offshore environments, including salinity variations, specific mineralogy, and distinct crude oil composition compared to other LSWF applications. This detailed data significantly addresses a critical knowledge gap for LSWF implementation in such settings. The research provides a comprehensive framework, encompassing laboratory studies, field observations, and a first-of-its-kind high-pressure high temperature (HPHT) evaluation of wettability alteration. Furthermore, it establishes guidelines for screening carbonate reservoirs for their suitability with LSWF. This comprehensive approach offers essential answers for maximizing oil recovery in Indian offshore carbonate reservoirs using LSWF technology.

A multi-pronged approach integrating laboratory experiments, simulations, and field-scale evaluation was employed. Key areas of investigation include the Impact of brine composition, rock-fluid interactions & fluid-fluid compatibility.

Experimental components included: compatibility between the injection water and the formation water, as well as the examination of the interactions between fluid/fluid and rock/fluid in carbonate reservoirs, sequential core flood displacement tests at reservoir conditions using low salinity brines to assess the impact of salinity on oil recovery, an interfacial tension (IFT) study was used to assess the interface between the fluids, while the contact angle and Zeta potential measurements were employed to evaluate the compatibility of the interface between the rock and the fluid, investigation of wettability alteration in an HPHT imbibition cell. Simulation components considered oil/brine/rock interactions and linked

laboratory data to the reservoir. Laboratory experiments revealed that the Wettability Index (WI) and Spontaneous Imbibition (SI) studies serve as effective screening tools for identifying suitable carbonate reservoirs for LSWF. These tests confirmed the occurrence of wettability alteration, where the rock surface became more water-wet. This shift resulted in a significant reduction in residual oil saturation, with recoveries exceeding traditional methods by up to 19 units. Compatibility tests demonstrated the successful use of diluted seawater. Compared to traditional seawater injection, core flood experiments demonstrated a significant 14-20% increase in oil recovery using LSWF. Notably, a 25% dilution of seawater proved to be the optimal salinity for this enhanced oil recovery method. Zeta potential measurements indicated a consistent decrease in values towards more negative levels as the seawater became more diluted. Elevating the concentration of SO_4^{2-} ions in the brine may lead to more pronounced negative zeta potential values in comparison to a 25% diluted seawater solution.

A one-dimensional (1D) core flood simulation model with a single porosity was created to adjust the parameters received from the laboratory. The goal was to generate a relative permeability curve for field scale simulation by matching the oil recovery and pressure profiles obtained from core flooding. An adequately accurate history match was achieved.

The field-scale simulation study envisages incremental oil of 1.373 MMt with 35% PV of LSWF which has envisaged additional oil gain of 4.2% of total oil production in the prediction period of 17 years due to LSWF in field M and an additional 0.86 million metric tons of oil recovery using LSWF for field H. At last, a pathway is developed for implementing LSWF in a carbonate reservoir. Field M exhibited a promising response to LSWF, characterized by increased oil production rates, stabilized water cut, and a significant reduction in produced water salinity. The results of this research also expected to play an important role in the 2nd field application of LSWF in the Western offshore Indian Basin.

Overall, this research presents a novel LSWF/Smart water flood (SWF) implementation approach for Indian offshore carbonate reservoirs. It significantly contributes to LSWF knowledge by addressing the unique challenges of these environments. The research establishes screening methods, evaluates wettability alteration mechanisms at high pressures and temperatures, and provides guidelines for optimal LSWF implementation as has already been achieved in the ongoing LSWF pilot in Field M.

सारांश

निम्न लवणता जल फ्लड (लो सैलिनिटी वाटर फ्लड) एक अत्यंत प्रभावी सुधारित तेल पुनर्प्राप्ति विधि है, जिसमें इंजेक्शन जल की लवणता और आयनिक संरचना को इस प्रकार संशोधित किया जाता है, ताकि कार्बोनेट और क्लास्टिक जलाशयों में सूक्ष्म और विशाल विस्थापन दक्षता दोनों में वृद्धि हो सके। यह विधि तापमान, वेटेबिलिटी और संभावित निर्धारित आयनों के आधार पर चयनित की जाती है, और इसके अतिरिक्त, यह जलाशयों के खट्टापन को काफी हद तक कम करने के साथ-साथ तेल-धारण करने वाली संरचनाओं में इंजेक्शन की प्रक्रिया को सरल बनाती है। पारंपरिक तरल-आधारित तेल पुनर्प्राप्ति विधियाँ भारत के पश्चिमी तटीय कार्बोनेट तेल क्षेत्रों में जलाशय की विषमताओं, दबाव में गिरावट, उच्च तापमान, और समुद्रतटीय पर्यावरण की लॉजिस्टिक चुनौतियों के कारण संघर्ष करती हैं। यह शोध निम्न लवणता जल फ्लडिंग को इन सीमाओं को दूर करने और तेल पुनर्प्राप्ति को अधिकतम करने के लिए एक प्रभावी वैकल्पिक समाधान के रूप में प्रस्तुत करता है। अब तक समुद्रतटीय क्षेत्रों में बहुत कम तेल पुनर्प्राप्ति परियोजनाएँ की गई हैं, और अधिकांश परियोजनाएँ मिश्रणीय गैस इंजेक्शन पर आधारित रही हैं।

इस अध्ययन में भारतीय समुद्रतटीय जलाशय में निम्न लवणता जल फ्लड की सफलता को प्रदर्शित किया गया है, और यह एकल केस अध्ययन से आगे बढ़ते हुए, भारतीय समुद्रतटीय वातावरण में उत्पन्न होने वाली विशिष्ट चुनौतियों से संबंधित अमूल्य डेटा प्रदान करता है। इसमें लवणता के परिवर्तन, विशिष्ट खनिजविज्ञान और अन्य निम्न लवणता जल फ्लड अनुप्रयोगों के मुकाबले कूड तेल की विशेष रचना शामिल हैं। यह विस्तृत डेटा निम्न लवणता जल फ्लड को इन वातावरणों में लागू करने के लिए एक महत्वपूर्ण ज्ञान अंतर को समाप्त करता है। यह शोध एक समग्र ढांचा प्रस्तुत करता है, जिसमें प्रयोगशाला अध्ययन, क्षेत्रीय अवलोकन और उच्च दबाव उच्च तापमान पर वेटेबिलिटी परिवर्तन का मूल्यांकन किया गया

है। इसके अतिरिक्त, यह कार्बोनेट जलाशयों की उपयुक्तता के लिए स्क्रीनिंग दिशा-निर्देशों की स्थापना करता है। इस समग्र दृष्टिकोण से भारतीय समुद्रतटीय कार्बोनेट जलाशयों में निम्न लवणता जल फ्लड तकनीक का उपयोग करके तेल पुनर्प्राप्ति को अधिकतम करने के लिए आवश्यक समाधान प्राप्त होते हैं।

इस अध्ययन में एक बहुआयामी दृष्टिकोण अपनाया गया, जिसमें प्रयोगशाला प्रयोग, सिमुलेशन और क्षेत्र-स्तरीय मूल्यांकन शामिल हैं। प्रमुख अनुसंधान क्षेत्रों में बाइन संरचना का प्रभाव, शिला-तरल इंटरएक्शन और तरल-तरल संगतता शामिल थे।

प्रयोगात्मक घटकों में इंजेक्शन पानी और गठन पानी के बीच संगतता, कार्बोनेट जलाशयों में शिला/तरल और तरल/तरल के बीच इंटरएक्शन की जांच, जलाशय की स्थितियों में निम्न लवणता ब्राइन का उपयोग करके अनुक्रमिक कोर फ्लड विस्थापन परीक्षण, जो लवणता के तेल पुनर्प्राप्ति पर प्रभाव का मूल्यांकन करते हैं, और इंटरफेसियल टेंशन अध्ययन शामिल थे, जो तरल पदार्थों के बीच इंटरफेस का मूल्यांकन करते हैं। इसके अलावा, संपर्क कोण और जेटा पोटेंशियल माप का उपयोग शिला और तरल के बीच इंटरफेस की संगतता का मूल्यांकन करने के लिए किया गया, और उच्च दबाव उच्च तापमान इम्बिबिशन सेल में वेटेबिलिटी परिवर्तन की जांच की गई।

सिमुलेशन घटकों में तेल/ब्राइन/शिला इंटरएक्शन और प्रयोगशाला डेटा को जलाशय से जोड़ने पर विचार किया गया। प्रयोगशाला प्रयोगों ने यह साबित किया कि वेटेबिलिटी इंडेक्स और स्वैच्छिक इम्बिबिशन अध्ययन लो सैलिनिटी वाटर फ्लड के लिए उपयुक्त कार्बोनेट जलाशयों की पहचान करने के प्रभावी स्क्रीनिंग टूल के रूप में काम करते हैं। इन परीक्षणों ने वेटेबिलिटी परिवर्तन की पुष्टि की, जिसमें शिला की सतह अधिक जल-प्रवृत्त हो गई, जिससे अवशिष्ट तेल संतृप्ति में महत्वपूर्ण कमी आई और पारंपरिक विधियों की तुलना में 19 यूनिट तक अधिक पुनर्प्राप्ति संभव हुई। संगतता परीक्षणों ने पतला समुद्री जल के सफल उपयोग को प्रदर्शित किया। पारंपरिक समुद्री जल इंजेक्शन की तुलना में, कोर फ्लड परीक्षणों ने लो

सैलिनिटी वाटर फ्लड का उपयोग करते हुए तेल पुनर्प्राप्ति में 14-20% की महत्वपूर्ण वृद्धि दिखाई। उल्लेखनीय रूप से, समुद्री जल का 25% घोल इस सुधारित तेल पुनर्प्राप्ति विधि के लिए आदर्श लवणता साबित हुआ। जेटा पोटेंशियल मापों ने यह संकेत दिया कि जैसे-जैसे समुद्री जल अधिक पतला हुआ, वैल्यूज में लगातार गिरावट आई और अधिक नकारात्मक स्तरों की ओर झुका। ब्राइन में सल्फेट आयनों की सांद्रता बढ़ाने से 25% पतला समुद्री जल घोल की तुलना में अधिक नकारात्मक जेटा पोटेंशियल मान उत्पन्न हो सकते हैं।

एक एकल पोरसिटी के साथ एक-आयामी कोर फ्लड सिमुलेशन मॉडल तैयार किया गया ताकि प्रयोगशाला से प्राप्त मापदंडों को समायोजित किया जा सके। लक्ष्य यह था कि कोर फ्लडिंग से प्राप्त तेल पुनर्प्राप्ति और दबाव प्रोफाइल से मेल खाते हुए क्षेत्रीय सिमुलेशन के लिए एक सापेक्ष पारगम्यता वक्र उत्पन्न किया जाए। एक उपयुक्त रूप से सटीक इतिहास मिलान प्राप्त किया गया।

क्षेत्र-स्तरीय सिमुलेशन अध्ययन ने 35% पोर वॉल्यूम लो सैलिनिटी वाटर फ्लड के साथ 1.373 मिलियन मीट्रिक टन तेल के अतिरिक्त उत्पादन का अनुमान लगाया, जिसमें लो सैलिनिटी वाटर फ्लड के कारण क्षेत्र M में 17 वर्षों की भविष्यवाणी अवधि में कुल तेल उत्पादन का 4.2% अतिरिक्त तेल प्राप्ति का अनुमान है, और क्षेत्र H में लो सैलिनिटी वाटर फ्लड का उपयोग करके 0.86 मिलियन मीट्रिक टन अतिरिक्त तेल पुनर्प्राप्ति का अनुमान है। अंत में, कार्बोनेट जलाशयों में लो सैलिनिटी वाटर फ्लड को लागू करने के लिए एक मार्ग विकसित किया गया। क्षेत्र M ने लो सैलिनिटी वाटर फ्लड के प्रति एक आशाजनक प्रतिक्रिया प्रदर्शित की, जिसमें तेल उत्पादन दरों में वृद्धि, जल कटौती का स्थिरीकरण और उत्पादित जल लवणता में महत्वपूर्ण कमी दिखाई दी। इस शोध के परिणामों को भारतीय पश्चिमी तटीय क्षेत्र में लो सैलिनिटी वाटर फ्लड के दूसरे क्षेत्रीय आवेदन में भी महत्वपूर्ण भूमिका निभाने की उम्मीद है।

कुल मिलाकर, यह शोध भारतीय समुद्रतटीय कार्बोनेट जलाशयों के लिए लो सैलिनिटी वाटर फ्लड/स्मार्ट वाटर फ्लड लागू करने का एक नवीन दृष्टिकोण प्रस्तुत करता है। यह इन पर्यावरणों की विशिष्ट चुनौतियों को संबोधित करके लो सैलिनिटी वाटर फ्लड ज्ञान में महत्वपूर्ण योगदान करता है। यह शोध स्क्रीनिंग विधियों की स्थापना करता है, उच्च दबाव और तापमान पर वेटेबिलिटी परिवर्तन तंत्र का मूल्यांकन करता है, और लो सैलिनिटी वाटर फ्लड को सर्वोत्तम तरीके से लागू करने के लिए दिशा-निर्देश प्रदान करता है, जैसा कि पहले से चल रहे लो सैलिनिटी वाटर फ्लड पायलट परियोजना में क्षेत्र M में हासिल किया गया है।

Contents

Certificate	iii
Declaration	iv
Acknowledgments	v
Abstract	vi
Contents.....	xii
List of Figures.....	xv
List of Tables	xvii
List of Symbols, Abbreviations and Nomenclature	xix
Chapter 1	1
Introduction.....	1
1.1 Field Overview.....	3
Chapter 2.....	5
Literature Review	5
2.1 Research Gaps.....	21
2.2 Motivation for the Present Work	21
2.3 Research Objectives.....	22
2.4 Workflow Adopted for the Study	23
Chapter-3.....	24
Materials and Methods	24
3.1 Materials	24
3.1.1 Rock and Fluid Characterization	24
3.1.1.1 Rock Characterization (Core Plugs)	25
3.1.1.2 Fluid Characterization (Crude oil)	28
3.1.1.3 Fluid Characterization (Brines)	30
3.2 Methods.....	32
3.2.1. Spontaneous Imbibition & Wettability Index	32
3.2.2. Core Flooding	33

3.2.3. Contact Angle Measurement (Rock-oil-Brine interaction).....	34
3.2.4. Zeta Potential Study (Rock-Brine interaction).....	36
3.2.5. Interfacial Tension (IFT) Study (Oil-Brine interaction).....	36
3.2.6. Single Porosity Model	37
Chapter 4.....	39
Experimental Results and Discussion	39
4.1. Fluid-Fluid Compatibility Study	39
4.2. Wettability Index Studies.....	40
4.2.1. Wettability Index of Field H.....	41
4.3. Spontaneous Imbibition Study	42
4.3.1. Spontaneous Imbibition Study (Field M).....	42
4.4 Displacement Studies	47
4.4.1 Sequential Core-flood Displacement Recovery Studies (Field M)	47
4.4.2 Sequential Core-flood Displacement Recovery Studies (Field H)	50
4.4.2.1 <i>Smart Water Flood (SWF)</i>	53
4.5. Interfacial Tension (IFT) Study (Oil-Brine interaction)	57
4.6. Zeta Potential Study (Rock-Brine interaction)	58
4.7. Contact Angle Measurement (Rock-oil-Brine interaction).....	59
4.8. Salinity Optimization Studies.....	60
4.8.1. Salinity Optimization Studies (Field M)	60
4.8.2. Salinity Optimization Studies (Field H).....	63
Chapter 5.....	66
Core Flood and Field Scale Simulation.....	66
5.1 Single Porosity Model.....	66
5.1.1 Field M	66
5.1.2 Field H.....	67
5.2. Pilot Area Simulation	70
5.2.1 Field M	70
Pilot Area Reservoir Description:.....	71
LSWF Pilot Design and Simulation Results:.....	71
5.2.2 Field H.....	73

Chapter 6.....	76
LSWF Pilot & Monitoring (Field M)	76
6.1. Single Well Chemical Tracer Test (SWCTT)	76
6.2.1. Innovative Water Injection Infrastructure	77
6.2.2. Pilot Area Monitoring	78
Chapter 7.....	82
Summary & Future Work.....	82
7.1. Summary	82
7.2. Future Work	86
References.....	88
Appendix	93
1) Communication regarding seeking permission for the use of the image shown in Figure 1.....	93
Bio-data of Author	95
Publications from Thesis	98

List of Figures

Figure 1: Workflow Adopted for The Study	23
Figure 2: Semi-Quantitative Mineralogical Estimation of Core Samples from Fields “(A) Field H. (B) Field M. (C) Field D”	26
Figure 3: X-Ray Diffractogram of Samples Used for the Study	27
Figure 4: Pictorial Representation Of Carbonate Core Plugs Used for the Study “ (A) Field H. (B) Field M.”	27
Figure 5 : Average Compositions of Major Elements Present in the Rock Samples During the XRF Study	28
Figure 6 : Composition of Dead Oil Used in the Fluid Model (Field H)	29
Figure 7 : Spontaneous Imbibition Studies (Automatic Imbibimeter)	32
Figure 8 : Core Flood Set Up (PID) At IRS (ONGC), Ahmedabad	33
Figure 9 : Contact Angle Monitoring Process During Spontaneous Imbibition Study (25%SW)	34
Figure 10 : Zeta Potentiometer	36
Figure 11 : Single-Continuum Reservoir Model	37
Figure 12 : Experimental Result of Spontaneous Imbibition Studies (Field M)	43
Figure 13 : Experimental Result of Spontaneous Imbibition Studies (SI Exp 4)	44
Figure 14 : Experimental Result of Spontaneous Imbibition Studies (Field H)	46
Figure 15 : Spontaneous Imbibition Experimental Results for Different Ion Compositions (Field H) ..	46
Figure 16 : Spontaneous Imbibition Experimental Results of Different Fields	47
Figure 17 : Core Flood Displacement Results of Core Plugs 1 To 5	48
Figure 18 : Core Flood Displacement Results of Core Plugs 1 To 5	49
Figure 19 : Effect of Different Parameters in Low Salinity Water Flood Study for Core Plug 3	49
Figure 20 : Core Flood Displacement Results with Diluted Seawater	51
Figure 21 : Combined Plot of Core Flooding Experiments Showing Flow Rate and Pressure Drop vs Brine Pore Volume Injected	52
Figure 22 : Viton Tubing, End Effects Plug, and Core Holder	53
Figure 23 : Smart Brine Flooding	54

Figure 24 : Displacement Recovery with Different Injection Water	57
Figure 25 : Variation of IFT with Dilution (Field H)	57
Figure 26 : Zeta Potential vs Brine Type	58
Figure 27 : Contact Angle Variations with Exposure Time During Spontaneous Imbibition Study	59
Figure 28 : Contact Angle Monitoring Process During Spontaneous Imbibition Study (25%SW)	60
Figure 29 : Incremental Oil Recovery Over Water Flood vs Pore Volume Injected	61
Figure 30 : Relative Permeability Curve for Simulation	62
Figure 31 : A Combined Plot of the Oil-Water Relative Permeability Curve for Core Plug A1	64
Figure 32 : Comparison of Results of Core Simulation vs. Core Flood Experiment	67
Figure 33 : Oil-Water Relative Permeability Curve Generated Through Core Flood Simulation	68
Figure 34 : Oil Recovery vs Pore Volume (PV) Injected	69
Figure 35 : Differential Pressure Vs PV Injected	69
Figure 36 : Field Performance with Pore Volume Injection	72
Figure 37 : Location Map of H Field	73
Figure 38 : Comparison of Field Performance Between BAU (Business As Usual with Conventional Waterflood) vs LSWF Case	75
Figure 39 : Process Diagram of Low Salinity Water Injection Facility	77
Figure 40 : Salinity Variations in Produced Water Samples In LSWF Pilot Area Wells	80
Figure 41 : Oil Production Variations in Produced Water Samples In LSWF Pilot Area Wells	80
Figure 42 : Water Cut Variations in Produced Water Samples in LSWF Pilot Area Wells	81

List of Tables

Table 1 A review of some literature reported on LSWF in carbonates.....	8
Table 2 Physical parameters of crude oil	28
Table 3 Composition of sea and produced water collected from fields H, M, and D.....	30
Table 4 Ionic concentrations, TDS and ionic strength of diluted brines of seawater (Field H).....	31
Table 5 Composition of Smart Brine prepared for spontaneous imbibition /sequential core flood studies.....	31
Table 6 Basic rock and petrophysical properties used in the model (Field H)	38
Table 7 Fluid compatibility (scaling) studies (Temperature: 93°C; Time:96 hrs; Field H)	40
Table 8 Spontaneous water imbibition details	41
Table 9 Spontaneous oil imbibition details	41
Table 10 Amott Harvey Wettability Index	41
Table 11 Amott Harvey Wettability Index of field M H & D	41
Table 12 Reservoir rock properties of core plugs used for spontaneous imbibition studies	42
Table 13 Petrophysical properties of core plugs used for spontaneous imbibition studies (Smart Water)	45
Table 14 Petrophysical properties of core plugs used for spontaneous imbibition studies (LSWF)	45
Table 15 Reservoir rock properties used for displacement studies.....	48
Table 16 Core flood displacement recovery results	48
Table 17 Reservoir rock properties of core plugs used for sequential core flood studies.....	50
Table 18 Core flood displacement Results for different experiments.....	51
Table 19 Petrophysical properties of combined core plugs used for smart flood studies	54
Table 20 Comparison of composition of Smart Brine after Sequential Core Flood Studies	55
Table 21 Details of the core plugs used for the study	56
Table 22 Maximum change in contact angle during spontaneous imbibition study (Field H)	59
Table 23 Reservoir properties of core plugs used for salinity optimization study	63
Table 24 Results of relative permeability experiment on Core Plug A1	63
Table 25 Summary of relative permeability experiment on Core Plug A1.....	63
Table 26 Comparison of results of core simulation vs. core flood experiment.....	66

Table 27 Comparison of results of core simulation vs. core flood experiment.....	68
Table 28 Average values of key reservoir parameters of the simulated sector	74
Table 29 Boundary conditions	74

List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
Cs	Interpolated salinity concentration
Cs ¹	Minimum salinity
Cs ²	Maximum salinity
K _{rw}	Relative permeability of water
K _{ro}	Relative permeability of oil
P _{cow}	Capillary pressure
C _s	Upper limit of salinity range
ζ	Zeta Potential (mV)
ppm	part per million
Ø	Porosity
S _{oi}	Initial oil saturation
K _{air}	Air permeability
mD	Milli Darcy

Abbreviations

AN	Acid Number
EDL	Electric Double Layer
EOR	Enhanced Oil Recovery
HPHT	High-Pressure High Temperature
LSWF	Low-Salinity Water Flooding
SWF	Smart Water Flooding
MIE	Multi-Ion Exchange
PDI _s	Potential Determining Ions
PV	Pore Volume
SW	Seawater
x% dSW	A diluted brine which has x% Seawater
TDS	Total Dissolved Solids (TDS), ppm
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
IFT	Interfacial Tension
CMG	Computer Modelling Group
DSA-100	Drop Size analyzer-100
NMR	Nuclear Magnetic Resonance