A STUDY ON TERTIARY MODE OF SMART WATER (SMW) FLOODING ON IMPROVING OIL RECOVERY EFFICIENCY

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ABSTRACT: *During SMW flooding, oil displacement recovery efficiency can be improved by tuning its composition and salinity into the reservoir. Once smart water invades through the pore spaces, it destabilises crude oil-brine-rock (COBR) interactions that leads to change in wettability of the reservoir. The objective of this paper is to propose the salinity and composition of the injected smart water at which maximum oil recovery efficiency could be achieved. SMW core flooding experiment has been conducted in the laboratory at tertiary mode of flooding. Synthetic reservoir formation brine has been formulated considering the reservoir brine salinity 1500ppm with composition of salts KCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$, NaCl and FeSO4.7H2O. Here, saturated core sample has been flooded with synthetic reservoir brine followed by set of low saline brine 1400, 1200, 100 and 450ppm. Composition of brine has been kept same for all salinities synthetic brine to compare their efficiency. No oil recovery could be reported t 1000ppm and 450ppm. Oil recovery by 29.26% of original oil in place (OOIP) at reservoir formation brine salinity of 1500ppm was reported while maximum recovery has been reported at 1200ppm salinity with recovery efficiency of 34.06%. So, optimized smart water has been proposed with salts composition of KCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$, NaCl and FeSO4.7H2O with salinity 1200ppm has been proposed for maximum recovery efficiency in tertiary mode of flooding.*

Key Words: **Smart water, wettability, salinity, synthetic brine, polar compounds, oil efficiency**

1. INTRODUCTION: The potentiality in bringing the higher oil recovery just by tuning the composition of injected brine has drawn attention of researchers during last 30 years. Since then, there have been made lots of research on chemistry of injection brine and the results are found satisfactory worldwide. On an average, 5 t 25% of the total oil in place can be recovered by natural driving energy whereas 10 to 20% more oil may be extracted by secondary recovery. The remaining fraction of oil is left behind as residual oil saturation (ROS) in the reservoir [1, 2]. Injection of smart water in SMW flooding is considered as an emerging EOR technology which improves the microscopic displacement efficiency by alternating the rock wettability towards more water wet [4, 5]. The salinity of brine used in low saline smart water injection should be maintained lower to have the proper crude oil-brine-rock (COBR) interactions compared to connate water salinity of the reservoir [10, 14]. The impact of monovalent cations like Na^+, K^+ etc. and divalent cations like Mg^{2+}, Ca^{2+} etc. in increasing oil recovery was observed. A relationship between the effects of low salinity water with the amount of clay minerals present in the reservoir rock could be established [7]. The COBR interaction has been established by the reactivity of the ions in the injected water with polar organic compounds of crude oil which is crucial in controlling surface charge alteration [6]. The detachment of polar organic compounds from the clay surface of the reservoir rock happens during low saline core flooding experiment [9, 13]. The detachment of these polar compounds is replaced by the cations mainly bivalent cations such as Mg^{2+} and Ca^{2+}. The role of wettability of the reservoir rock is immense in the determination of ROS and recovery efficiency during SMW flooding experiment [3, 10, 11]. Out of different mechanisms proposed by different researchers, the main mechanism behind SMW flooding is the wettability alteration [8, 12]. To carry out the smart water flooding experiment, three prerequisites criteria have to be fulfilled which includes clay minerals in reservoir rock, polar organic compounds in crude oil and divalent cations in reservoir connate brine [6, 7]. In Upper Assam basin, water injection/flooding have been done in many oil fields. But practically, there is no reported research work or systematic study on smart water flooding to improve oil recovery in the oil fields Upper Assam basin oil. Considering this, this study on water flooding using smart water as EOR-fluid has been undertaken in a part of oil field of Upper Assam Basin, India. Tertiary mode of water flooding has been experimented in the laboratory to check the efficacy of smart water over recovery efficiency.

2. MATERIALS AND METHODS:

2.1 Core Sample:

Reservoir Core sample has been collected from depth range of 2875.53 – 2875.88m in the Barail formation range of the study area. To carry out SMW flooding in the laboratory, the core plug has been prepared by cutting, plugging and end facing. Further core plug has been cleaned in Sohxlet apparatus with CH_3OH and $CHCl_3$ solvent to strip out residual hydrocarbons present in the core plug. Final cleaning has been done in Ultrasonic cleaner and dried in the Humidity cabinet. The humidity and wet bulb temperature in the Humidity cabinet has been maintained at 40% and 63°C respectively. The physical dimensions of the dried core sample have been calculated and tabulated in the table (Table-1) below:

Table1: Physical dimensions of core plug for flooding experiment

Depth, (m)	Length, (cm)	Diameter, (cm)	Weight, (gm)	Bulk Vol, (cc)	Grain Density, (gm/cc)
2875.65	6.75	3.72	168.34	74.4732	2.364

2.2 Crude Oil Analysis:

To carry out the flooding experiment, 5 litres crude oil has been collected from the study area. The saturates, aromatics, resins and asphaltenes **(**SARA) analysis of crude has been conducted to determine the polar organic compounds, mainly resin and asphaltenes in the crude oil. As mentioned, presence of polar organic compounds in crude oil is an essential prerequisite for SMW flooding. Acid number of crude oil plays an important role in generation of in-situ surfactant that helps in reduction of interfacial tension between oil and water which should be greater than 0.2. Here, the acid number of the sample has been calculated in apparatus, HAMCO 81B and found to be 0.46. From specific gravity, the determination of API gravity has been calculated. The water content in the crude oil also calculated and found to be nil. The following table (Table-2) shows some important properties of crude oil of study area.

Table 2: Important Properties of Crude Oil of study area

Sl Nos.	Properties	Results
1	Water Content, % (v/v)	0
2	Sp. gravity of oil @ 60°F	0.8712
3	API gravity of oil @ 60°F	29.75
4	Wax Content, % (w/w)	10.76
5	Class of Crude	C
6	Resin Content, % (w/w)	5.02
7	Asphaltene Content, % (w/w)	0.08
8	Pour Point, °C	31
9	Acid Number	0.46

2.3 Petrographic Analysis:

To meet the prerequisite criteria for SMW flooding has been conducted. The main objective of this analysis is to check the presence of clay minerals in the reservoir rock. Core cuttings (Depth range: 2875.53 – 2875.88m) have been grinded in agate mortar in the laboratory and screened through 230 mesh (63micron particle size). Thin section photographs have taken in polarized microscope to analyze to trace the mineralogical composition. The following figure (Fig: 1&2) shows the thin section photographs for the rock sample of the study area.

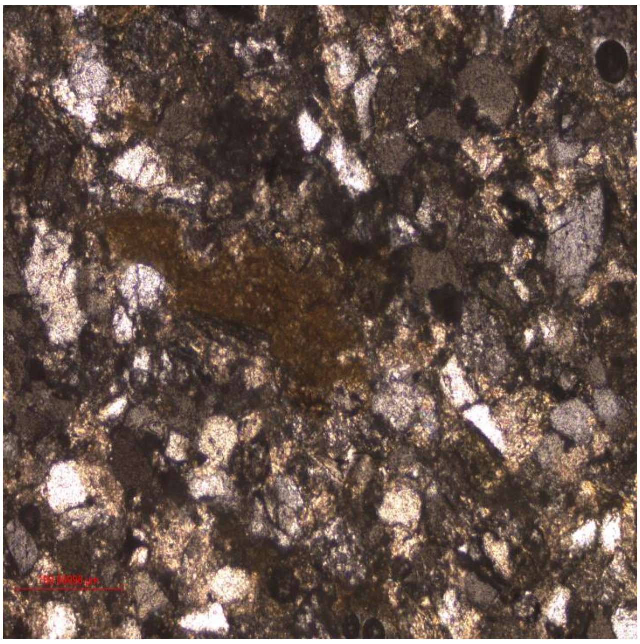

Fig1: Dominance of clayey materials

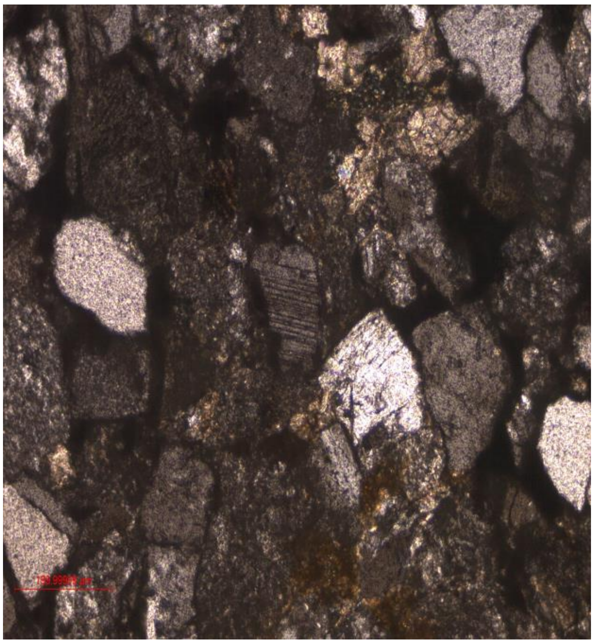

Fig2: Plagioclase feldspar

2.4 Petrophysical Properties:

Petrophysical properties of the reservoir rock play a very important role in determination of hydrocarbon reserves which includes effective porosity, air permeability and liquid permeability. Core sample (depth range: 2875.53 – 2875.88m) has been chosen for the determination of petrophysical properties. Air permeability and effective porosity have been determined by Air Permeameter and Helium Porosimeter respectively. Liquid permeability was calculated through Klingkenberg effect by extrapolating the curve to Y-axis. The following table (Table-3) shows the petrophysical properties of the core sample:

Table3: Petrophysical properties of core sample of the study area

Depth (m)	Depth Range (m)	Effective Porosity	Air Permeability (md)	Liquid permeability (md)
2875.65	2875.53 – 2875.88	21.54%	81.52	70.27

2.5 Formation Brine Analysis:

Reservoir formation brine has been collected from the study area and analysed in the laboratory. Composition and brine salinity have been determined. Presence of divalent cations in the formation brine plays an important role in enhancing oil recovery efficiency through cation exchange and multiple ion exchanges (MIE) mechanism. Analysis of brine showed the presence of Mg^{2+} and Ca^{2+} alongwith other ions. The following table (Table-4) shows the analysed results of formation brine.

Table4: Laboratory analysis of reservoir formation brine

Characteristics	Unit	Concentration
Total Dissolved Solid(TDS)	mg/L	2856
Salinity	mg/L	1500
As^{3+}	mg/L	Below detectable limit
Chloride	mg/L	962
Carbonate	mg/L	455
Na^{+}	mg/L	66
Ca^{2+}	mg/L	9.2
Mg^{2+}	mg/L	6.8
Fe^{2+}	mg/L	1.05

2.6 Preparation of Synthetic Brine:

Based on the analysis of the reservoir formation brine, synthetic reservoir has been prepared in the laboratory with KCl, NaCl, MgCl2.6H2O, CaCl2.2H2O and FeSO4.7H2O to provide K+, Na+, Mg2+, Ca2+ and Fe2+ respectively in synthetic formation brine. To carry out core flooding experiment in tertiary mode, different synthetic brine with salinities brine 1400, 1300, 1200, 1000ppm and 450ppm have been prepared. As the flooding pattern would be in tertiary mode where saturated core sample has been flooded with synthetic formation brine followed by 1400, 1300, 1200, 1000 and 450ppm smart water. While preparation of different brine, same brine composition with KCl, NaCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$ and FeSO4.7H2O have been maintained to compare their efficacy on improving oil recovery efficiency. The Cl^- ion concentration has been maintained from KCl, NaCl, $MgCl_2$.6H2O and $CaCl_2.2H_2O$. The following table shows the composition of reservoir synthetic brine with different ionic composition and their concentration.

Table5: Ionic concentration of Smart Synthetic Reservoir Brine at 1500ppm salinity

Ions	Associated Salts	Ions Conc. (mg/L)
K^+	KCl	661.07
Na^+	NaCl	6
Ca^{2+}	CaCl2.2H2O	9.2
Mg^{2+}	MgCl2.6H2O	6.8
$SO4^{2-}$	FeSO4.7H2O	2.4
Fe^{2+}	FeSO4.7H2O	5
Cl^-	KCl, NaCl, CaCl2.2H2O, MgCl2.6H2O	811.53
Salinity		1500

2.7 Core Flooding Experiment:

Core flooding experiment has been performed in tertiary mode in the laboratory. Here, saturated core plug has been flooded with high salinity brine. Ruska positive displacement pump was used to provide required delivery for core flooding. Saturated core plug has been imbibed with 20PV of 1500ppm salinity synthetic brine. Next, core flooding was followed by 1400, 1200, 1000 and finally 450ppm by 10 pore volume each. No additional recovery was observed for 1000ppm and 450ppm. Before flooding, core plug was kept in Hassler Core Holder at 200psi pressure to ensure proper crude oil-brine-rock equilibrium. It has been found 29.26% of OOIP has been calculated at room temperature. For comparison of the salinity over recovery, same salt concentration (KCl, NaCl, CaCl2.2H2O, MgCl2.6H2O, and $FeSO_4.7H_2O$) was maintained in the injected smart water. Additional oil recovery of 4.8% has been reported at 1400ppm synthetic brine. Core flooding rate of 2.1cc/min has been maintained throughout the experiment. The following table (Table-6) summarizes the parameters calculated during core flooding experiment.

Table 6: Important parameters determined during core flooding experiment

Swc (%)	ROS (%)	Displacement Efficiency (%)	Salt Used	Salinity, (ppm)	Oil Recovery (% of OOIP)
27.58%	49.25%	29.26%	KCl NaCl MgCl2.6H2O CaCl2.2H2O FeSO4.7H2O	1500	29.26 %
				1400	22.56%
				1200	4.8%(Additional)
				1000	NIL
				450	NIL

3. Conclusion:

From the above experiment, the authors inferred the following conclusions

(i)The prerequisite criteria which include presence of polar organic compounds (4.78%, w/w resins and 0.09%, w/w asphaltenes) in crude oil, clay minerals in reservoir rock and divalent cations in reservoir formation brine have been satisfied.

(ii) Acid number of the study area crude oil has been calculated as 0.41 that satisfied the criteria for reduction in IFT. For generation of in-situ surfactant in the reservoir leading to reduction in IFT between oil and water must be greater than 0.2.

(iii) Core flooding experiment showed oil recovery as 29.26% of OOIP at reservoir formation brine salinity i.e 1400ppm while additional recovery was reported as 4.8% with total recovery as 34.06% (29.26% + 4.8%) of OOIP at 1400ppm salinity.

(iv) It has been proposed that maximum oil recovery could be achieved for the study area by injecting smart water at 1400ppm in tertiary mode of flooding with brine composition KCl, NaCl, $MgCl_2.6H_2O$, $CaCl_2.2H_2O$ and $FeSO_4.7H_2O$.

(v) No recovery could be achieved with 450ppm salinity brine with same composition of other salinities indicating that too much lower salinity would not give the satisfactory results.

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