Role of the Low Salinity Condensate Water during Steam Injection in Carbonate Reservoirs

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Abstract

Numerous laboratory and pilot tests have verified low salinity waterflooding (LSWF) as a promising enhanced oil recovery (EOR) method in carbonate reservoirs. The multi-ion exchange (MIE) and anhydrite dissolution mechanisms are widely accepted mechanisms for the LSWF. This study investigates the effects of the low salinity condensed water (LSCW) and anhydrite dissolution on oil recovery during steam injection in carbonate reservoirs. The work has been verified using actual laboratory and production data of an existing cyclic steam injection project in carbonate reservoir.

Several core samples were extracted from the reservoir under study. The wettability index of two cores was measured. The first core was taken from Well-01 before starting any steam injection in its area. However, the second core was extracted from Well-02, which was drilled in the area affected by steam injection. The analysis of the production data of the 9 oil wells was performed to study the effect of anhydrite percentage on oil recovery.

The analysis showed that the LSCW could alter wettability in the direction of water wet. The analysis also concluded that although the anhydrite dissolution caused alteration of wettability, the increase of anhydrite percentage could cause a reduction in reservoir quality and oil production.

Introduction

The LSWF is defined as waterflooding technique that decreases the total dissolved salts (TDS) of the injected water and/or modifies the injected water ionic content. The first core flooding experiment in the carbonate reservoir was conducted by Bagci et al. (2001), who documented higher oil recovery up to 18.8% by changing the injected water composition to 2% KCl plus 2% NaCl brine mixture. Furthermore, diluted sea water injection in carbonate plugs showed additional oil recovery up to 11% in several experiments performed by Shariatpanahi et al. (2011), Fathi et al. (2010), and Zekri et al. (2019).

The mechanism of the LSWF in carbonate reservoirs is still debatable. The proposed mechanisms include fine migration, multi-component ion exchange (MIE), calcite dissolution, interfacial tension (IFT) reduction, double-layer expansion, anhydrite dissolution, salting-in, water micro-dispersion, osmosis pressure effect, and surface roughness (Snosy et al. 2021). It should be highlighted that the MIE mechanism is widely accepted as the main controller for the performance of the carbonates' LSWF projects. The carbonate reservoir's MIE mechanism was supposed to be anion exchange and not cation exchange like sandstone reservoirs. The mechanism is attributed to the adsorption of potential determining ion (PDI) SO_4^{2-}, Ca^{2+} and/or Mg^{2+} onto the rock surface (Snosy et al. 2022a). The MIE evidence of the LSWF in the carbonate

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reservoirs was proposed by Austad et al. (2005). Then, this mechanism was accepted by Strand et al. (2008a), Ligthelm et al. (2009), Zhang and Austad (2006), Puntervold (2008), and Myint and Firoozabadi (2015). They demonstrated that the incremental oil recovery of sea water injection in carbonates is attributed to the high sulfate concentration. Moreover, Austad et al. (2011) and Pu et al. (2008) proposed that the anhydrite dissolution in the carbonates is a method of generating in-situ SO_4^{2-} which is thought to act as a catalyst in the wettability alteration process.

Furthermore, Al-Saedi et al. (2019) investigated the effect of the condensed steam (low salinity water) during steam injection in sandstone reservoirs. They reported that the wettability was altered towards more water-wet when the steam was turned into low saline (LS) water. In addition, they reported that the LSCW could act as a wettability modifier only without reducing the oil viscosity.

Moreover, there are no available studies for investigating the effect of condensed water during steam injection in carbonate reservoirs. Therefore, this work was performed to study the effect of LSCW and anhydrite dissolution in carbonate reservoirs using laboratory and field data of an existing cyclic steam injection project.

Reservoir Description

The reservoir under study is made up of dolomite, anhydrite nodules, shell fragments, and argillaceous materials. The dolomite is tannish gray, dark gray, light brown, brown, tannish brown, medium-hard to very hard, fine – cryptocrystalline, anhidrotic in parts, sandy in parts, glauconitic at rare parts, and vuggy in parts. While, the anhydrite is off white, milky white, white, light brown, colorless, medium-hard to hard, fine – cryptocrystalline translucent - opaque, with sucrose texture in parts.

The reservoir contains heavy oil accumulations and could not produce cold production. It has been producing under cyclic steam stimulation. Most of the trials performed to produce this zone as cold production were failed until the first cyclic steam trail was made. The formation contains extra heavy oil with 12-15 °API and viscosity of 4000 cP at standard conditions, 10% H_2S, 10% CO_2, and 15% asphaltene contents. The geochemical analysis and studies indicated that the biodegradation is due to bacterial action. **Table 1** summarizes the reservoir's average properties.

Table 1—Average Reservoir Properties

Parameters	Value
Estimated original oil in place	1.1×10^9 STB
Reservoir average depth	850-1000 ft
Average initial water saturation	30%
Average porosity	35%
Average reservoir permeability	10-35 mD
Initial reservoir pressure	500 psi
Initial reservoir temperature	100 °F
Oil viscosity at standard conditions	4000 cP
Oil gravity	10-12 °API

Results and Discussion

Effect of LSCW on the Wettability. Two cores from two wells were used to study the effect of LSCW. The two cores have the same rock compositions: dolomite, anhydrite nodules, shell fragments, and argillaceous materials. The first core was taken from Well-01 before starting any steam injection in its area. However, the second core was taken from Well-02, which was drilled in the area affected by steam injection.

Amott wettability index for several core samples from the two wells (Well-01 and Well-02) was measured as shown in **Table 2**. The core samples of Well-01 reported Amott wettability index ranges from -0.10 to -0.51 with an average value of -0.29. These values reveal that the core samples have oil to neutral wettability index. While the core samples of Well-02 reported Amott wettability index ranges from -0.11 to -0.26 with an average value of -0.15. These values reveal that the core samples have a neutral wettability index.

Table 2—Amott Wettability Index for Core Samples of Well-01 and Well-02

Well-01			Well-02		
Sample	Amott Wettability Index		Sample	Amott Wettability Index	
A-2	-0.51	Oil Wet	B-1	-0.26	Neutral
A-3	-0.10	Neutral	B-2	-0.12	Neutral
A-4	-0.23	Neutral	B-3	-0.11	Neutral
A-5	-0.20	Neutral	B-4	-0.12	Neutral
A-6	-0.25	Neutral			
A-7	-0.39	Oil Wet			
A-8	-0.34	Oil Wet			

These results reveal that the LSCW alters the rock wettability from oil-neutral wet to neutral wet. The average Amott index changed from an average of -0.28 in Well-01, which had no effect of steam, to -0.15 average in Well-02, which has an effect of steam injection. It should be highlighted that these results are consistent with those obtained by Hjelmeland and Larrondo (1986), Wang and Gupta (1995), Punase et al. (2014), and Rao (1999). They reported that carbonate became water-wet with temperature increase. Furthermore, the results of this study agree with those of Blevins et al. (1984), who suggested that the rock wettability of the Qarn Alam field in Oman became more water-wet with an increase in temperature.

It should be highlighted that the alteration of wettability was attributed to the presence of LSCW in carbonate reservoirs. This can be clarified as a result of two mechanisms which were proposed to study the effects of sulfate anion in carbonates: anhydrite dissolution and MIE mechanisms.

For the anhydrite dissolution mechanism, Worden and Smalley (1996) documented that anhydrite and hydrocarbons were reacted together, in carbonate reservoirs of hotter than 140°C, to produce calcite and H_2S. It should be stated that the sharp increase of H_2S in produced oil in the current study after steam injection in all wells up to 10% was a strong evidence for anhydrite dissolution. Austad et al. (2011) stated that the anhydrite ($CaSO_4$) dissolution generates in-situ SO_4^{2-} ions which act as a catalyst agent in the wettability alteration process.

The MIE mechanism was attributed to the adsorption of potential determining ion (PDI) SO_4^{2-}, Ca^{2+} and/or Mg^{2+} onto the rock surface. Adsorption of SO_4^{2-} decreases the positive charge density on the rock surface. It minimizes electrostatic repulsive force and causes co-adsorption of Ca^{2+} and Mg^{2+} on the rock surface. Ca^{2+} reaction with carboxylic acid groups breaks the attractive interactions between the oil and rock interface, which changes rock surface into more water wet (Snosy et al. 2022b).

Furthermore, Fathi et al. (2010) proposed that the high temperature (above 90 °C) could cause substitution of Ca^{2+} ions on the carbonate surface by Mg^{2+} ions from the injected water. Therefore, the displaced Ca^{2+} ions bond to carboxylic acid molecules and cause absorption of them in the form of calcium-carboxylate complexes. Thereby further improving oil recovery is achieved. Moreover, Strand et al. (2008b) and Hognesen et al. (2005) concluded that sulfates could act as a catalyst at high temperature and below a certain concentration (1.0 g/L and 2.31 g/L, respectively). That will cause a decrease in IFT and alteration of wettability to more water wet.

Effect of Anhydrite on the Oil Recovery. The oil production data of 9 wells were collected. The 9 wells have almost the same reservoir characteristics and same completion strategy. The wells were cased hole wells, drilled in the same period, and showed encouraging production behavior. These 9 wells are selected because they have less heterogeneity and minor natural fracture. It is believed that the oil production from the wells has occurred through matrix dominant with minor natural fracture. The anhydrite percentage varies significantly in the selected wells as it ranges from 2% up to 10%. **Table 3** shows the rock properties, anhydrite percentage, fracture density, and well production data in the selected wells.

Figure 1 presents the relationship between the anhydrite percentage and the oil production rate before and after acidizing and steam injection in the selected wells. The acid stimulation was performed to remove skin damage after drilling and open channels for steam injection. However, **Figure 2** represents the relationship between the anhydrite percentage and (1) the 5 years cumulative oil production, and (2) 5 years cumulative oil production per net pay thickness. Figures 1 and 2 document that increasing of the anhydrite content in the reservoir causes reduction of the oil recovery as a result of reservoir quality decrease. It is obviously clear that the anhydrite amount in the reservoir has a negative impact on the oil production rate. The oil wells which are located in reservoir area of high anhydrite percentage show less oil production rate and less cumulative oil production.

It is concluded that the anhydrite dissolution causes alteration of wettability. However, the increase of the anhydrite percentage could cause a reduction in the reservoir quality and oil production.

Table 3—Average Properties of the Selected Wells

Well*	Net Thickness, ft	Anhydrite Content, %	Φ, %	S_{wi}, %	Fracture Density /ft	Cold oil Prod. Rate, STB/D	5 Years Cum. Oil, STB	(5 Years Cum. Oil / Thickness) STB/ft
W-02	81	2%	27	40	0.04	25	64,295	794
W-03	102	5%	23	37	0.16	13	48,363	474
W-04	107.5	10%	24	36	0.16	15	49,663	462
W-05	112	5%	29	40	0.03	13	63,763	569
W-06	123	11%	25	35	0.13	4	44,025	358
W-07	112	4%	26	40	0.06	15	61,971	553
W-08	120	8%	25	35	0.13	6	37,843	315
W-09	118	6%	26	37	0.17	25	53,053	450
W-10	112	4%	26	37	0.06	25	56,755	507

* Well-02, Well-03,..Well-10 are drilled at the same time and completed with the same strategy. However, Well-01 was drilled earlier and completed with different technique (Open hole section) so it is not included in this analysis.

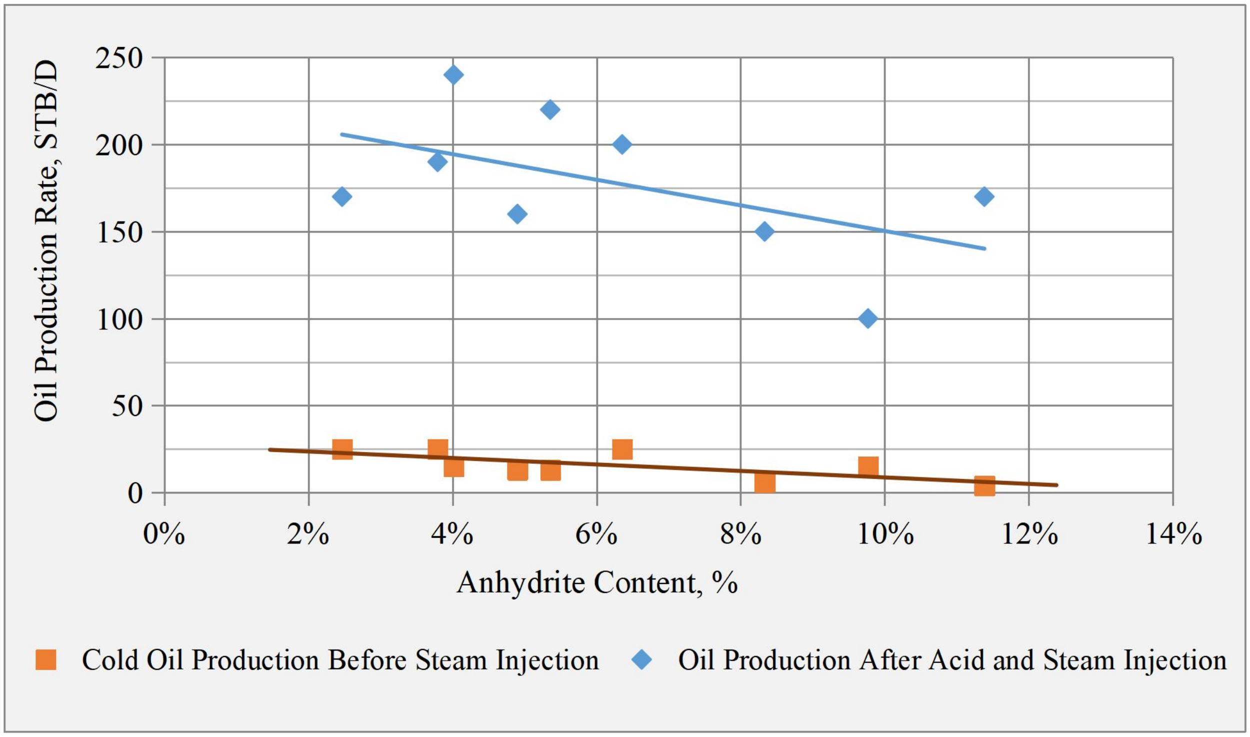

Figure 1—Relationship Between the Anhydrite Content and the Oil Production Rate Before and After Acid and Steam Injection for the Selected Oil Wells.

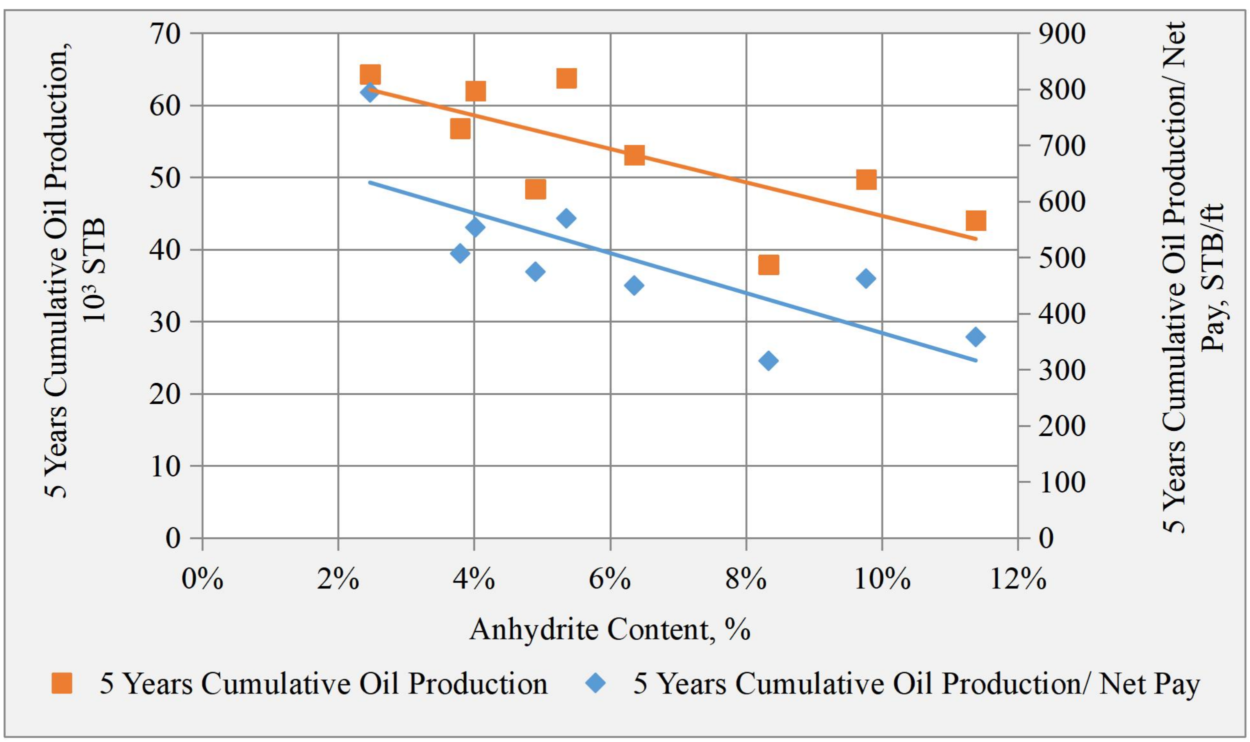

Figure 2—Relationship Between the Anhydrite Content and the Oil Production Data of the Selected Wells.

Conclusions

1. The wettability index measurements for several core samples indicate that the rock wettability may be alerted after steam injection to the direction of water wet.
2. The alteration of wettability is attributed to the presence of low salinity condensed water after.
3. The multi-component ion exchange mechanism may be the primary mechanism of wettability alteration due to LSCW.
4. The anhydrite dissolution in the reservoir under study may help in wettability alteration.
5. Although the anhydrite dissolution causes alteration of wettability, increasing anhydrite percentage reduces the reservoir quality and oil production.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

Nomenclature

API	=	American Petroleum Institute oil gravity
Cum.	=	cumulative production
EOR	=	enhanced oil recovery
Φ	=	porosity, fraction
LS	=	low salinity water
LSCW	=	low salinity condensed water
LSWF	=	low salinity water flooding
MIE	=	multi-component ion exchange
OOIP	=	original oil in place
PDI	=	potential determining ion
S_{wi}	=	initial water saturation, fraction
TDS	=	total dissolved salts

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