INVESTIGATION OF CO- AND COUNTER CURRENT FLOW BEHAVIOR IN CARBONATE ROCK CORES

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ABSTRACT
Imbibition constitutes a key recovery mechanism in oil carbonate reservoirs – its manipulation can potentially improve oil recovery in water flooding as an Enhanced Oil Recovery (EOR) process. In this study, six carbonate cores were investigated with porosity and permeability of 18% and 32 mD, respectively. In each case, three types of faces in contact with brine were considered i) one open face (OOF) ii) two open faces (TOF) iii) one open face and another face isolated from brine with a special tube that allows collection of the co-current produced oil during the imbibition test (OOCO). These arrangements were used to investigate ionic solution effects on the amount of co- and counter-current produced oil and to evaluate the effect of currents on each other when the lateral surface of cores is coated and one or two faces are contacted with brine. The results showed that generally during Smart Sea Water (SSW) injection with respect to 5times diluted Sea Water Brine with distilled water (5dSW,) total recovery increased as more ions were activated in wettability alteration and IFT reduction. In OOF cores, oil recovery was also about 10% more than OOCO, perhaps due to elimination of co-current flow in OOF. The amount of oil recovery increased by 15% in SSW in TOF cases because of simultaneously co- and counter-current oil flow production at the two faces of the cores. For OOCO counter-current oil production was smaller than OOF and TOF cases at the other face, because the end face is isolated from brine which allows produced oil to go across it and accumulate in the tube. Overall, the oil production of the six cores in different types of brine were ranked as follows:
TOF-SSW > OOE-SSW > TOF-5dSW > OOF-5dSW = OOCO-SSW > OOCO-5dSW

INTRODUCTION
The world’s oil reserves are overwhelmingly held in carbonate reservoirs - their recovery has been the subject of many investigations. This type of oil reservoir is characterized by two types of porous medium namely i) matrix blocks and ii) natural fractures. EOR methods for fractured reservoirs are usually designed to facilitate the transmission between matrix and fractures. One such method for enhanced oil recovery from carbonate reservoirs is low salinity water imbibition which is aimed at altering wettability from oil-wet to neutral or water-wet conditions. Should a block matrix be surrounded by water that exists in the fractures then two types of imbibition are expected to occur. 1) co-current and 2) counter-current imbibition. When water enters the carbonate block matrix, oil can be produced either in the same direction (co-current) or opposite direction (counter-current) (see Figures 1 and 2). The amount of oil production due to these

mechanisms would depend on block matrix length, oil/water viscosity ratio, type of ions that exist in the brine, crude oil chemistry, and reservoir pressure and temperature conditions.

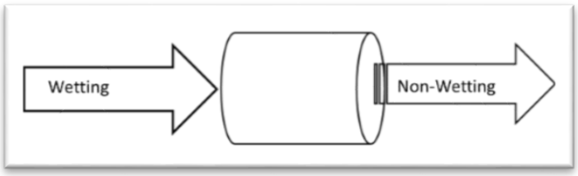

Figure 1: Co-current imbibition

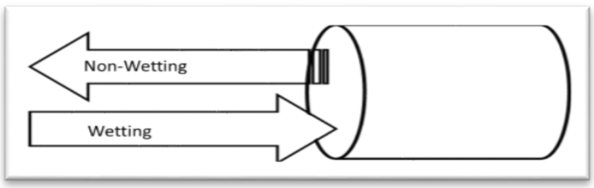

Figure 2: Counter-current imbibition

Many factors such as wettability, viscosity [1], interfacial tension [2], oil composition, injection fluids properties are known to influence counter-current imbibition [3]. In addition, the interaction between fluid and porous media depends on pore shape, matrix permeability, relative permeability and boundary conditions, which would, in turn, determine the rate of imbibition and oil recovery [4]. At the beginning of the imbibition process, the counter-current imbibition always prevails. The oil/water mobility ratio determines how counter-current continues which, in turn, depends on wetting phase viscosity. If brine mobility is high, then the counter-current continues, otherwise it stops and instead co-current imbibition begins to produce oil [5]. The surfaces where oil is produced as droplets determine the capillary back pressure (CBP) at the open face. CBP was mentioned by Parsons and Chaney (1966), but it is usually ignored in co- and counter-imbibition [6]. During the imbibition process large oil droplets would usually stick to the open face of the core. In this process if the radius of curvature of oil droplets is much higher than pore radius, then they would only produce small back pressures. Snap off phenomenon could also happen for strongly water wet conditions near the faces that are in contact with the wetting phase, resulting in coalescence of large droplets on the outside of the core [7].

The present study investigates the ability of brine composition to increase the amount of counter-current and co-current produced oil, which feeds into the fractures and is expected to increase oil recovery.

EXPERIMENTAL SET UP AND PROCEDURE

In an imbibition process, two important parameters, interfacial tension and wettability, can be profoundly affected and controlled by the composition of the injecting fluid. Low salinity water and smart water (containing $SO4^{2-}$, Ca^{2+} and Mg^{2+} ions) at the oil/brine and rock/brine interfaces, cause low interfacial tension and more water wetness, respectively. Accordingly, in the present investigation, 5-times diluted seawater and also seawater with manipulated sulfate, calcium and magnesium ions were used. 5-times diluted sea water showed to perform the best among dilution experiments and the IFT and contact angle are represented in figure 3. For ion concentration manipulation EOR the one with 3 times sulfate, calcium and 6 times magnesium was the best and the results are shown in figure 4.

A B

Figure 3: 5 diluted seawater A) change of contact angle in a calcite thin section (from 125 to 78) B) pendant drop IFT measurement (11.1 mN/m)

A B

Figure4**:** SW-3S-C-6M A) change of contact angle in a calcite thin section (from 129 to 30) B) pendant drop IFT measurement (8.3 mN/m)

After determining the best wettability and IFT between diluted sea water samples and optimum salinity of seawater as smart seawater (SSW), their effects on the amount of produced oil during co-current and counter-current imbibition were investigated.

Core preparation

The outcrop block of a carbonate formation has been considered and many plugs were taken from it, thereafter among all cores, six cores with similar permeability and porosity selected. The carbonate cores' petrophysical properties are provided in Table 1.

Table 1: Petrophysical properties of investigated carbonate cores.

Brine-condition-core NO	Porosity %	Permeability (mD)	Length (mm)	Diameter (mm)
SSW- OOF-1	17.4	32	67	38.1
SSW-TOF-2	18.3	31	67	38.1
SSW-OOCO-3	19.0	33	67	38.1
5dSW-OOF-4	16.9	29	67	38.1
5dSW-TOF-5	17.9	32	67	38.1
5dSW-OOCO-6	18.0	30	67	38.1

As a first step, these cores were saturated with formation brine, then initially maintained for 14 days at 75°C to achieve original positive carbonate surface charge as it would exist at the reservoir conditions. Then oil flooding was started until the saturation of formation brine in cores reached to about 0.2 cc for which the fluid saturation is given in Table 2. Once this is done then the saturated cores were further maintained for 40 days at 2500 psi and 75°C. After the accomplishment of this aging process, the matured cores were categorized in two groups

1) 5dSW is mutual wetting phase imbibition brine and three cores were coated with tubes and epoxy resin as: i) first core-one open face (OOF) ii) second core-two open faces (TOF) iii) third core-one open face and another face isolated from brine with a special tube that would be able to collect the co-current produced oil during imbibition test (OOCO) as depicted in figure 5.
2) SSW is mutual wetting phase imbibition brine and three cores as: i) first core-one open face (OOF) ii) second core-two open faces (TOF) iii) third core-one open face and another face isolated from brine with a special tube that would be able to collect the co-current produced oil during imbibition test (OOCO) as depicted in figure 5.

Table 2: Fluid saturation volume

Core NO	pore volume (cc)	FW Volume (cc)	Oil Volume (cc)
1	13.28	2.6	10.68
2	13.97	2.7	11.27
3	14.50	2.9	11.60
4	12.90	2.6	10.30
5	13.66	2.7	10.96
6	13.74	2.8	10.94

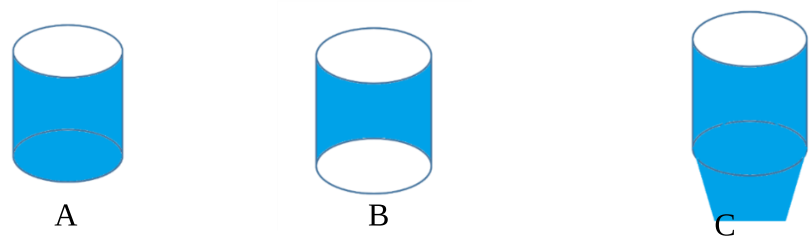

Figure 5: blue color shows the lateral surfaces and faces that coated with epoxy resin.
A) OOF B) TOF C) OOCO

Table 3: recovery factor during SSW and 5dSW imbibition.

%RF(Brine) / Time (hrs.)	$RF_{(SSW-OOF-1)}$	$RF_{(SSW-TOF-2)}$	$RF_{(SSW-OOCO-3)}$	$RF_{(5dSW-OOF-4)}$	$RF_{(5dSW-TOF-5)}$	$RF_{(5dSW-OOCO-6)}$
4	14.98	22.18	7.76	5.48	9.12	2.91
12	18.73	24.84	9.48	8.23	16.42	4.85
48	21.54	29.28	12.07	11.88	26.46	6.80
72	25.28	32.83	12.93	14.63	23.72	8.74
96	29.03	37.27	14.66	14.63	27.37	8.74
120	29.03	38.15	14.66	14.63	27.37	8.74
144	29.03	38.15	14.66	14.63	27.37	8.74
168	29.03	38.15	14.66	14.63	27.37	8.74
192	29.03	38.15	14.66	14.63	27.37	8.74
216	29.03	38.15	14.66	14.63	27.37	8.74
240	29.03	38.15	14.66	14.63	27.37	8.74
264	29.03	38.15	14.66	14.63	27.37	8.74
288	29.03	38.15	14.66	14.63	27.37	8.74
312	29.03	38.15	14.66	14.63	27.37	8.74

RESULTS AND DISCUSSION

Two groups of cores were submerged in Amott cells. The cells were filled with the synthetic brines to the same level to eliminate gravity effects and were kept at a constant temperature of 75°C. Then, at specified time intervals, the amount of produced oil was recorded. Table3 presents the oil recovery versus time for SSW and 5dSW for co- and counter-current imbibition.

For all brines that were used in these experiments, viscosity was almost equal to distilled water due to the low level of total dissolved solids (TDS). Thus all resistances against entrance of the brines into the cores were in the oil phase, and all flow was due to capillary pressures. Due to optimum wettability alteration in SSW, capillary pressure is stronger than what was in 5dSW imbibition.

More oil recovery in TOF cores was due to the existence of co-current and counter-current imbibition at two faces simultaneously (Figures 6 and 7). By entrance prevention of brine from one face (OOF) co-current imbibition will be eliminated and hence oil will be produced by a

counter-current imbibition process. On the contrary, when the other face is allowed to co-currently produce oil (in a special condition without contact with brine) the amount of counter-current oil production will be reduced. The reason is that when co-current imbibition is allowed (OOCO) to the cores, then the amount of fluid resistance between oil and brine for co-current imbibition is lower than OOF (when only counter-current happened). This is because after a while of counter-current imbibition, the fluid front will be displaced thus i) fluid volumes that have to be replaced and displaced will be increased and ii) capillary pressure would not have enough force to imbibe the brine and eject the oil outside the cores at the same face.
Movement of an oil-water front in imbibition process is known to be piston like. Important factors with positive and negative impacts on oil productions are trapping of oil drops in the water invaded zone due to porous nature of the medium, interlayer friction, mixed wettability conditions which are categorized as factors that hinder the upward movement of oil drops and decrease oil production; however, bouancy force and capillary pressure are those which facilitate oil production.
One important issue is the competition between the oil interlayer frictions as an obstacle against the oil flow and capillary pressure as a booster in progress of imbibition process. As the process goes forth and the front descends in the core, interlayer friction increases because of a longer path ahead of the oil droplet than before while capillary pressure increases duo to more water wetness condition behind the front; however, increase in these two opposing factors is unequal and capillary pressure which imbibes the brine and ejects the oil out of the core seems not to be high enough

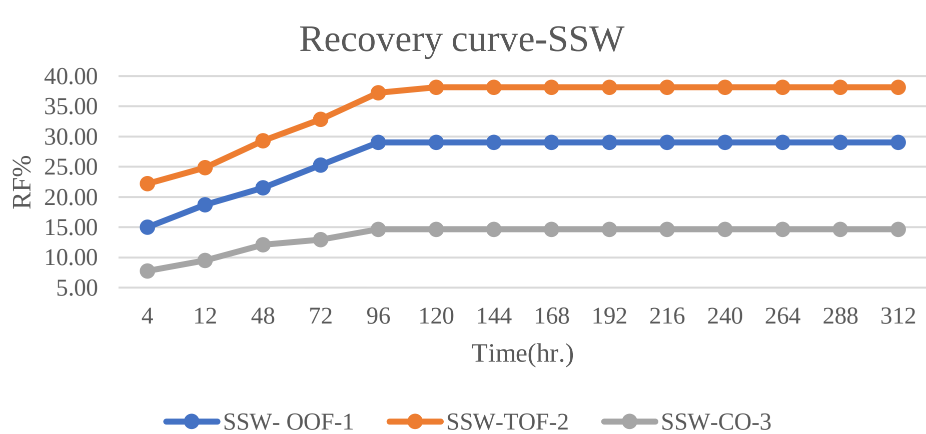

Figure 6: Recovery curve of SSW-OOF-1, SSW-TOF-2, SSW-CO-3

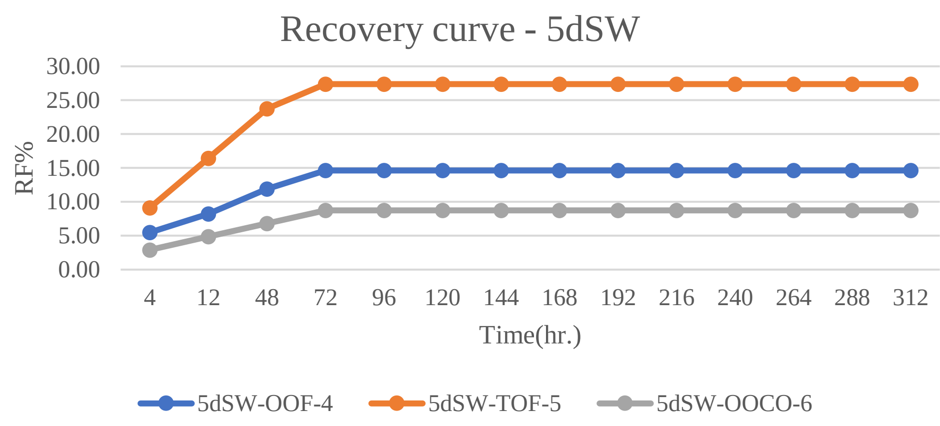

Figure7: Recovery curve of 5dSW-OOF-4, 5dSW-TOF-5, 5dSW-OOCO-6

CONCLUSIONS

- Generally speaking, for SSW with respect to 5dSW, the total recovery increased as optimum ions were used as a result of wettability alteration and IFT reduction.

- when lateral surface of cores is coated and
  i)One face is in contact with brine and the other face is isolated, only counter current will be happening. OOC
  ii)Two faces are in contact with brine, at two faces co-current and counter current will be happening. TOF
  iii)One open face is in contact with brine (Counter-current imbibition) and another face isolated from brine with a special tube that allows collection of the co-current produced oil during the imbibition test, co-current imbibition will weaken the counter current imbibition from the side that is in contact with brine. OOCO

- Wettability alteration to more water wetness increased capillary pressure and improved co- and counter-current imbibition processes.

- Fluids interlayer friction (Resistance against of flow) in competition with capillary pressure, determine whether co-current or counter-current imbibition or both will occur.

- Due to elimination of co-current flow in OOF, the amount of counter-current oil recovery increased but total production typically decreases.

- For OOCO though due to opening of one face without contact with brine, counter-current oil production was much lower at the open face.

- Based on the experimental findings, the oil production of the six cores in different types of brine can be ranked as follows:
  TOF-SSW > OOE-SSW > TOF-5dSW > OOF-5dSW = OOCO-SSW > OOCO-5dSW

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