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Full Length Article

Effects of ions and dissolved carbon dioxide in brine on wettability alteration, contact angle and oil production in smart water and carbonated smart water injection processes in carbonate oil reservoirs

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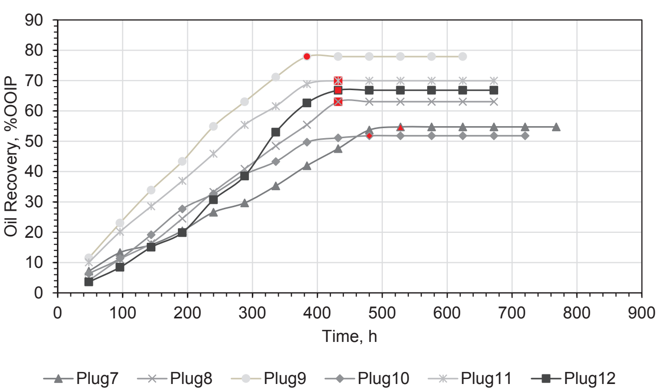
GRAPHICAL ABSTRACT



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ABSTRACT

Imbibition is one of main production mechanisms in fractured carbonate reservoirs. This mechanism is very dependent on hydrophilicity of reservoir rock and somehow is controlled by it. The contact angle tests, due to the test conditions, i.e, a polished rock section-crude oil droplet system, do not easily indicate the wettability of the porous medium but generally, are accepted to expression of rock wettability. Imbibition tests with a strong dependence on wettability can generalize contact angle tests to wettability of porous medium. Carbonated smart water injection can active water imbibition mechanism and increase production in fractured carbonate reservoirs by wettability alteration to hydrophilic. In this study, the optimal concentration of saline water used with oil in Karanj and Gachsaran reservoirs in Iran was determined by calculating the contact angle in different concentrations and dilutions. Then, the optimal solutions were carbonated by adding carbon dioxide at various temperatures and pressures. The effect of carbon dioxide on wettability of pre-hydrophobized sections was investigated by contact angle experiments.

The results show the efficiency of carbonated smart water in wettability alteration as compared with smart water. Then, oil-saturated carbonate plugs were exposed to spontaneous imbibition by optimal solutions in the

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presence and absence of carbon dioxide. The experiments reveal an increase in oil recovery by imbibition with carbonated smart water. The results of these experiments indicate the water alteration efficiency of carbonated smart water compared with the smart water. A minimum contact angle of 18.75° was obtained by adding carbon dioxide to a smart solution at a concentration of 1000 ppm of different salts and at 10.34 MPa and 75 °C. Then, oil-saturated carbonate plugs were exposed to imbibition process with optimal solutions in the presence and absence of carbon dioxide. According to the results of these experiments, oil recovery increased by 78% of the initial oil in place by imbibition in the presence of carbonated smart water.

1. Introduction

Water injection into oil reservoirs is a common practice in the world. This method has been associated with successful field and research experiences in both carbonate and sandstone reservoirs. It can be argued that water injection has been the most successful way to enhance oil recovery so far [1]. Smart water and carbonated smart water methods are among improved chemical water injection methods. Ion management is of great importance in smart water injection. In fact, smart water injection is a control method, meaning that the most important point is to control and manage the ions in the injection phase to pave the way for activating the mechanisms of this procedure, especially wettability alteration of rock from hydrophobic to hydrophilic. Thus, before implementing this method in the field, an ion in the injection phase may be completely removed or the strength of another ion should be increased by increasing concentration based on experimental data. For example, Strand et al. introduced SO_4^{2-} and Ca^{2+} as key ions in wettability alteration of limestone rocks [2]. In addition, the concentration of some ions may be in the useful range. The injection temperature and pressure may also change to increase the temperature of injected smart solution. In low-temperature reservoirs, the chemical mechanisms involved in wettability alteration may not be activated. The injection pressure is of special importance especially when carbon dioxide is injected with a smart solution. Although smart water may reduce interfacial tension between oil and water, the main mechanism to increase the efficiency of smart water injection is wettability alteration of reservoir rock from hydrophobic to medium and hydrophilic wettability [3,4]. Hence, it can be said that interactions between ions in the smart water and carbonate reservoir rocks can be strengthened by adjusting the concentration of injected water and the type of ions as well as temperature and pressure. Understanding the optimum values of these parameters is a technique for more targeted implementation of this method. In addition, knowing the optimum and controllable conditions of the reservoir and the injection fluid may reduce the costs of operations. Another point in the implementation of a water injection operation, especially in case studies, is supply of saline water needed to meet the volume required for injection. In reservoirs close to sea, seawater can be a good choice. Diversity of ions in seawater makes it a good candidate for use as smart water. According to literature, seawater can be used as smart water at high temperatures without changing its concentration [5,6]. In reservoirs where access to water is difficult or impossible, the use of water extracted from the reservoir formation can be evaluated. Although the concentration of ions in the formation water is usually much higher than that in seawater, cost estimation may reveal that the treatment and control of ion concentration will be more affordable than transfer of water with lower salinity to the field. According to the above discussion, the optimal conditions for injection of seawater and formation water extracted from two reservoirs along with dissolved carbon dioxide were investigated with regard to the composition and properties of oil in these reservoirs. Injection of carbon dioxide both separately or dissolved in water and/or periodically with saline water is common. The aim of carbon dioxide injection, regardless of the method used, is to enhance oil recovery or the storage of carbon dioxide in reservoirs. It can be argued that carbonated water injection is a modified carbon dioxide injection operation. Poor efficiency of CO_2 injection is increased by injection of carbonated water. Carbon dioxide dissolved in smart water is used to change the chemical composition of saline water. When carbonated water is in the vicinity of oil, the carbon dioxide dissolved in water is transferred to oil. As a result, the properties of oil and reservoir rock are changed during transportation of chemicals migrating from water to oil. This reduces the viscosity and swelling of oil as well as water-oil interfacial tension. A decrease of more than 20% in interfacial tension has been reported [3,7].

Furthermore, carbonated water alters wettability by influencing the reservoir rock [8]. In this study, contact angle tests were conducted on hydrophobic sections aged in smart and carbonated smart solutions. The optimal solutions were identified in terms of reducing the contact angle and wettability alteration to hydrophilicity. The reservoirs studied in this investigation are of fractured carbonate type. The mechanism of production in fractured reservoirs include: Free-fall gravity drainage, which happens when the gravity force is the only crude oil drainer power from the reservoir rock system, molecular diffusion, solution gas drive or expansion of oil in under-saturated area and capillary imbibition. The capillary and gravity forces are effective on oil recovery processes. In gravity drainage process gas phase (in the fractures) replaces oil phase (in the matrixes) and the capillary pressure is an obstacle for displacement of wet phase (oil) via non-wet phase (gas). Thus, the matrix height should be higher than a critical value to overcome the non-wet phase on the capillary pressure and enter the matrix to active the gravity drainage process [9–11].

Imbibition is one of the most important processes occurring in fractured reservoirs during oil production. Webb et al. studied spontaneous imbibition at reservoir conditions using the gypsum core with seawater and saline water of the same reservoir. They found 40% improvement in oil production by imbibition with seawater as compared with primary saline water [12]. Due to high permeability of fractures in fractured reservoirs and non-wettability of carbon dioxide, it is better to use carbonated water instead of carbon dioxide injection, since the density of carbonated water (even in supercritical state) is higher than that of carbon dioxide and tap water [13,14], consequently causing its penetration down the formation. In addition, carbonated water is capable of changing the wettability of reservoir rock to hydrophilic due to

Table 1
Analysis of Gachsaran crude oil.

Component	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}^+	Total
Molar Percent	0.00	0.08	0.73	0.72	2.22	1.10	1.10	8.66	9.32	6.60	7.14	5.36	5.01	51.96	100.00

Molecular weight = 247.
Molecular weight of C_{12}^+ = 380.
Specific gravity of C_{12}^+ @ 15.55 °C = 0.9369.
Saturation pressure of reservoir fluid @ 60.6 °C = 14.04 MPa.

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