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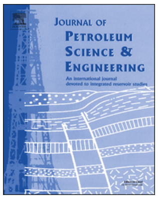

Improving sweep efficiency of edge-water drive reservoirs using induced formation damage

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ABSTRACT

A common problem in edge-water drive reservoirs is oil bypassing by aquifer water. The encroaching water from the adjacent aquifer overtakes oil phase and leaves a significant volume of trapped residual oil behind. Early arrival of these water fingers causes pre-mature water production that leads to well abandonment. One solution to the problem is creating a barrier against the encroaching water. In current study the possibility of using induced formation damage caused by injecting a small volume of low salinity water into abandoned wells is investigated. Formation damage as a result of injection of low salinity water into the watered-up wells creates a low permeable barrier against the water fingers. The methodology of modeling this technique using a commercial reservoir simulator is presented. The modeling results show that injection of small volume of low salinity water results in prolongation of wells' life which results in ~3–5% incremental recovery if compared to normal depletion.

1. Introduction

On average, more than three barrels of water is produced for each barrel of oil and it costs billions of dollars every year to dispose the unwanted water (Bailey et al., 2000). Many oil reservoirs derive their natural producing energy from adjacent aquifers. Oil bypassing due to water invasion is a major problem in edge-water drive reservoirs. In edge-water drive reservoirs, water tongue may underrun oil causing early water production at the well and low productivity of the oil with considerable unrecovered oil left behind (Hernandez and Wojtanowicz, 2006). Encroachment of edge-water results in pre-mature water production from wells low on structure and early termination of wells' life. The water production continues to increase until the economic limit of WOR of the well is reached. At the time of abandonment, there may be considerable unswept oil still trapped behind the water front. Depending on the reservoir heterogeneity, the residual oil saturation may reach 60% (Kumar, 1977; Braedley, 1987; Hernandez et al., 2006). Hence, it is of a great interest to ascertain ways to retard the water encroachment and control early water production and bypassed oil in edge-water drive reservoirs. Many different methods are used to slow down the water tongue including: production rate control, management of the total oil production pattern and injection of barrier fluids. Most commonly used barriers fluids are cement, gels, resins, foams and polymers (Karp et al., 1962; Seright et al., 2001; Zaitoun and Pichery, 2001). A large treatment volume is required to divert water away from the area that has been already swept by water, which is generally uneconomic (Bailey et al., 2000).

Reduction of rock permeability due to low salinity water injection has been observed in several laboratory and field studies (Mungan, 1965; Khilar et al., 1983; Lever and Dawe, 1984). It is explained by mobilization of in-situ fines and subsequent plugging of pore throats. Naturally in-situ fine particles are initially in mechanical equilibrium of drag, lifting, electrostatic and gravitational forces. Injection of low salinity water weakens the electrostatic force and perturbs the equilibrium of the particle on pore wall. As a result the fine particles are dragged with the flowing water and block narrow pore throats (Khilar and Fogler, 1998; Ochi and Vernoux, 1998; Bedrikovetsky et al., 2012; Hussein et al., 2012). Mobilization of fine particles and subsequent pore plugging results in permeability reduction when low salinity water is injected. Bedrikovetsky et al. (2012) introduced maximum retention function for modeling of fines migration in porous media. The proposed approach allows applying the torque balance of forces on single particle to calculate the maximum concentration of particles that can remain in a porous medium. The validity of this approach was confirmed by comparison with serious of directly measure core data (Lemon et al., 2011; Zeinijahromi et al., 2011; Hussein et al., 2012). The permeability reduction values of 40–100 times has reported in various laboratory experiments (Mungan, 1965; Khilar et al., 1983; Lever and Dawe, 1984; Sarkar and Sharma, 1990;

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Nomenclature

Latin letters

c	concentration of suspended particles
c_a	polymer adsorption concentration
c_p	polymer concentrations in the aqueous phase
c_p^0	polymer concentrations in the injected water
F_d	drag force, MLT^{-2}, N
F_e	electrostatic force, MLT^{-2}, N
F_g	gravitational force, MLT^{-2}, N
F_l	lifting force, MLT^{-2}, N
k	absolute permeability, L^2, mD
k_o	initial absolute permeability, L^2, mD
k_{ro}	oil relative permeability
k_{rw}	water relative permeability
l_d	lever for drag force, L, m
l_n	lever for normal force, L, m
p	pressure, $ML^{-1}T^{-2}$, Pa
R_k	resistance factor
S	water saturatin
U	overall flow velocity, LT^{-1}, m/s

Greek letters

γ	brine ionic strength, $molL^{-3}$, mol/l
γ^0	ionic strength of the injected brine, $molL^{-3}$, mol/l
γ_i	reservoir initial brine ionic strength, $molL^{-3}$, mol/l
μ_o	oil dynamic viscosity, $ML^{-1}T^{-1}$, cp
μ_w	water dynamic viscosity, $ML^{-1}T^{-1}$, cp
β	formation damage coefficient
ε	torque ratio (erosion number)
σ	volumetric concentration of captured particles
σ_a	volumetric concentration of attached particles
σ_{ao}	initial volumetric concentration of attached particles
σ_{cr}	maximum volumetric concentration of captured particles
σ_s	volumetric concentration of strained particles

Abbreviations

LSW	low salinity water

Hussein et al., 2012); that motivates application of low salinity water injection as a possible method to create a barrier against water tongue in edge-water reservoirs (Nguyen et al., 2013).

Modeling results by Nguyen et al. (2013) have shown that injection of small volume low salinity water (LSW) into abandoned wells can reduce the encroaching water velocity and enhances the ultimate sweep efficiency by 15–18%. The current study follows on from the method of applying low salinity water injection to control water encroachment by Nguyen et al. (2013). Whilst this earlier work has studied the method of creating barrier against aquifer water tongue, it assumed a simplified two dimensional reservoir model. The current paper extends the previous work (Nguyen et al., 2013) addressing 3D five spot pattern which is commonly used in field developments to increase the areal sweep efficiency.

The current work follows Bedrikovetsky et al. (2012) in modeling particle detachment during low salinity water injection. Thus the maximum retention function is applied to model the fines detachment due to injection of alternating brine salinity when non-swelling mobile clay fines are present. In current paper the approach by Zeinijahromi et al. (2013) is applied to implemented Eclipse black oil simulator (Schlumberger, 2013) in order to model low salinity water flow with induced fines migration. Zeinijahromi et al. (2013) developed a new method for implementing commercial reservoir simulators to model water injection with induced fines migration. From practical point of view, the advantage of the method is that it can be readily incorporated into the existing polymer simulator to model low salinity water injection without the need for developing new software or modifying the current simulators.

2. Induced formation damage method to decelerate edge-water encroachment

In this section the concept of using permeability decline by low salinity water injection to create low permeability barrier against the encroaching edge-water is discussed. Fig. 1a shows a schematic for encroachment of edge-water during oil production with full or partial pressure maintenance by the aquifer at different stages of the field development. The light blue and red colors represent water and oil respectively and black line shows aquifer water front. Water from the adjacent aquifer (purple arrows) encroaches into the oil reservoir due to pressure drop between the aquifer and the production wells. At the moment t_1, minimum pressure during water-driven production is reached near to production wells; hence the stream lines from the aquifer cross the location points for wells low on structure. Thus, the central lines of the water tongues also cross the location points for structurally low wells. The low structure wells are abounded at some high water-cut value, when the cost of water production and disposal exceeds the economical limit. Pressure builds up near the low structure producers after their closure; thus, minimum pressures over the area are reached near the high structure producing wells (moment t_2). Water tongues continue to move towards the wells high on structure and leave a significant volume of residual oil behind. Fig. 1b shows the similar scenario of oil production with the short-term LSW injection in the abandoned wells. Similar to the 'normal' production scenario, at the moment t_1 minimum pressure reaches near to wells low on structure and the pressure gradients from the aquifer cross the location points for wells low on structure causing water tongues to cross these wells. A small volume of low salinity water is injected into structurally low wells after they have reached the economical limit of water production. It induces permeability reduction due to fines migration and creates a low permeable zone in well vicinity (dark blue area around structurally low wells). The created low permeable zone can slow down the water fingers from moving towards up-structure producers. It homogenizes movement of water front and prolongs water-free production period of wells high on structure that leads to the ultimate recovery improvement.

3. Physic mechanisms of induced formation damage

Several studies have shown that low salinity water injection into reservoirs rocks can cause reduction of rock permeability. The phenomenon is explained by mobilization of reservoir fines which plug the narrow pore constriction (Khilar and Fogler, 1998; Ochi and Vernoux, 1998; Bedrikovetsky et al., 2011). The mechanical equilibrium of an attached particle is determined by torque balance of four major forces; drag force, lifting force, gravitational force and total electrostatic forces (Fig. 2).

$$F_d(U)l_d + F_l(U)l_n = (F_e(\gamma) + F_g)l_n \tag{1}$$