Journal of Petroleum Science and Engineering 78 (2011) 288–303

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

# Taking advantage of injectivity decline for improved recovery during waterflood with horizontal wells

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ARTICLE INFO

*Article history:*
Received 3 November 2009
Accepted 23 May 2011
Available online 30 May 2011

*Keywords:*
Injectivity
Raw water
PWRI
Waterflooding
Sweep efficiency
Waterflood simulation

ABSTRACT

Injectivity formation damage with waterflooding using sea/produced water has been widely reported in the North Sea, the Gulf of Mexico and the Campos Basin in Brazil. The damage is due to the capture of solid and/or liquid particles by reservoir rock that consequently leads to the permeability decline. Another reason for the permeability decline is the formation of a low permeable external filter cake.

However, moderate injectivity decline is not too damaging for a waterflood project with long horizontal injectors, where the initial injectivity index is high. In this case, the injection of raw or poorly treated water may significantly reduce the cost of water treatment, which is a cumbersome and expensive procedure in offshore projects.

In this paper we investigate the effects of injected water quality on waterflooding using horizontal wells. An analytical model for injectivity decline, which accounts for particle capture and a low permeable external filter cake formation, has been implemented into black oil reservoir simulator. It was found that induced injectivity damage results in a noticeable reduction of water cut and in increased (although delayed) sweep efficiency.



## 1. Introduction

Injectivity decline is a widely spread phenomenon in waterflood projects. Usually it occurs due to the injected water containing solid and liquid particles. Particle capture by the rock decreases the permeability and the formation of an external filter cake on the well surface increases the hydraulic resistivity of the system (Pang and Sharma, 1997; Ochi et al., 1999; Al-Abduwani et al., 2005a). Both phenomena result in the decline of well index. The injectivity decline occurs during seawater injection, re-injection of produced water (PWRI) and injection of any poor quality water (Nabzar et al., 1996, 1997; Chauveteau et al., 1998; Rousseau et al., 2007).

The injectivity damage can be prevented or mitigated by injected water treatment, which is an extremely expensive operation under offshore conditions. Water treatment costs remain high even with the relocation of treatment facilities onto the sea floor. The subject of cost reduction for injected water treatment is becoming of extreme importance worldwide due to increasing oil production by waterflooding, especially from offshore deep-water oil fields.

The formation damage, induced by the captured particles and filter cake, leads to the homogenisation of the injectivity profile (Khambharatana et al., 1997, 1998) and decreases residual oil saturation (Soo and Radke, 1986a,b). Yet, it was found that the particle retention phenomena take place within a close vicinity of injection wells. In the case of vertical injectors used in thin layer-cake reservoir, the injected water bypasses the damaged zone near to the vertical injector by moving vertically along a short distance from low permeability to high permeability layer. The perturbation of the stream line system due to the induced formation damage is minimal. So, the un-uniformly distributed skin, induced along the vertical well, almost do not affect the oil-water flow away from the injector. Therefore, the injectivity profile homogenization has a little effect on sweep efficiency for the case of vertical wells in layer-cake reservoirs. For long horizontal wells, where the well length have the same order of magnitude as the inter-well distance, it would take much longer for water to bypass the damaged zone by moving "parallel" to the injector in order to enter the faster flow path. So, it is expected that the injectivity profile homogenization may result in more significant sweep increase in a

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doi:10.1016/j.petrol.2011.05.020

system of long horizontal wells. Nevertheless, the corresponding studies are not available in the literature.

The effects of near-well formation damage on waterflood performance have long been recognised (Civan, 2007). Skin factor in injection wells grows with time due to reservoir clogging and cake formation (Pang and Sharma, 1997; Wennberg and Sharma, 1997; Mojarad and Settari, 2007). Despite this, to the best of our knowledge, the formation damage options in modern reservoir simulators are designed for a constant skin factor throughout the field life.

In the current paper we investigate the effects of injectivity skin in a system of horizontal wells, induced from the injection of poorly treated water, in order to create incremental oil recovery. The waterflood black-oil reservoir simulator (ECLIPSE 100) was coupled with the analytical model for injectivity decline (Pang and Sharma, 1997; Wennberg and Sharma, 1997; Ochi et al., 1999; Bedrikovetsky et al., 2005; Paiva et al., 2007). The simulation results show the noticeable effect of injectivity decline provoked by the injection of poor quality water on the water cut history and the reservoir sweep by waterflooding.

The structure of the paper is as follows. Firstly, the reservoir physical factors leading to incremental recovery due to low quality water injection are discussed. Then, we describe the analytical model for injectivity index decline due to deep bed filtration of injected particles and low permeable external cake formation. Finally, the implementation of the analytical model into the black-oil ECLIPSE 100 reservoir simulator is discussed followed by the results of waterflood modelling.

## 2. Reservoir physics of interaction between the injectivity and waterflooding

Let us discuss why the injection of water with particles induces formation damage that may result in sweep efficiency increase and in reduction of the amount of injected water.

Heterogeneity of oil bearing formations is a major factor controlling the oil recovery during waterflooding. Water enters mostly in high permeability zones. The breakthrough of low viscosity water fingers forms a high conductivity channel between the injection and production wells. This leads to the 'recirculation' of a significant fraction of injected water without further displacement of any significant oil volumes.

Several Enhanced Oil Recovery (EOR) methods are based on the plugging of swept areas and redirection of the injected water into unswept zones (Lake, 1989; Bedrikovetsky, 1993). The possibility of poor quality water injection, where the particles are captured by the rock causing the permeability decrease in the waterflooded zones and the consequent sweep increase, has been discussed in the literature (Khambharatana et al., 1997, 1998). The particles, which are captured in pores where water has already entered, decrease the amount of residual oil (Soo and Radke, 1986a, b). These phenomena encouraged the considerations of the injection of particulated water for improved oil recovery. The mass of retained particles is a monotonically increasing function of injected water volume (Herzig et al., 1970). So, the induced skin is high 'in front' of high permeability zones or 'at the beginning' of high-velocity streamlines. The possibility of preferential plugging of swept zones by the 'captured' particles was discussed for vertical injectors (Khambharatana et al., 1997, 1998). Yet, it was found that the injectivity damage is induced by the particles which are captured near to injection wells; the damaged zone radius rarely exceeds 1–2 m (Nunes et al., 2010). So, the injected water by-passes the damaged zone and enters the highly permeable zone or the high-velocity stream lines close to the injector. Therefore, the incremental sweep efficiency due to the induced formation damage is small and the reservoir simulations show a negligible sweep increase due to the induced injectivity damage in system of vertical wells.

Let us consider the application of poorly treated water in reservoirs with long horizontal injectors for both horizontal and vertical producers. Preferential deposition of particles 'in front' of the high-speed streamlines causes an increase of 'flight' times. High variation of streamline sizes and speeds for long horizontal wells may result in the preferential plugging of highly swept zones and in the significant increase of sweep efficiency.

Fig. 1 shows a displacement schematic in a horizontal two-permeability-zone reservoir with two horizontal wells. Water enters preferably in the high permeability zone. Therefore, the main portion of the injected water passes via the well sections in the highly permeable zone. So, the particles deposit mainly in the highly permeable zone which then creates an additional resistance to the flow of water. It slows down the displacement front in the high permeability zone and delays the water breakthrough. The continuous line in Fig. 1 corresponds to the reservoir sweep by 'clean' water in a damage-free case. The injected suspension is redirected into the low permeability zone resulting in increased reservoir sweep.

The final conclusion of the importance of the sweep increase effect must be based on results of reservoir simulations that account for injectivity damage.

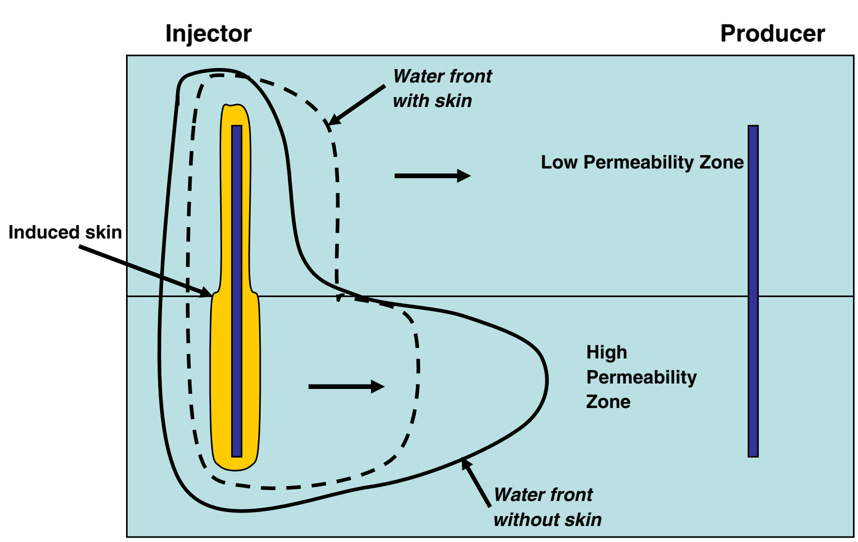


**Fig. 1.** Schematic for improved sweep of low permeability zone due to skin, induced by injectivity of low quality water, in a two-permeability-zone reservoir.