Journal of Petroleum Science and Engineering 78 (2011) 609–617

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

Effects of induced fines migration on water cut during waterflooding

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ARTICLE INFO

Article history:
Received 13 February 2011
Accepted 8 August 2011
Available online 19 August 2011

Keywords:
IOR
Fines migration
Mobility control
Low salinity waterflooding
Water cut

ABSTRACT

Permeability decline during corefloods with varying water composition, especially with low salinity water, has been widely reported in the literature. It has often been explained by the lifting, migration and subsequent plugging of pores by fine particles, which has been observed in numerous core flood tests with altered water composition (salinity, pH) and temperature. This effect can be considered to provide a relatively simple method for mobility control during waterflooding. In previous research, the Dietz model for waterflooding in a layer-cake reservoir with a constant injection and production rate was combined with a particle detachment model to investigate the effect of fines migration and induced permeability decline on reservoir sweep efficiency. In this work, the analytical model was extended to waterflooding with a given pressure drop between injection and production wells. The modelling showed that permeability decline in the water swept zone, caused by the alteration of the injected water composition and induced fines migration, may be able to improve waterflood performance by delaying water breakthrough and reducing the water cut.

1. Introduction

Fines migration and subsequent reduction in permeability occur during core flood experiments due to decreased water salinity, increased flow velocity and altered water pH or temperature (Mungan, 1965; Bernard, 1967; Lever and Dawe, 1984; Valdya and Fogler, 1992; Khilar and Fogler, 1998; Civan, 2010). The traditional view of fines migration is that it should be avoided because of its detrimental effect on reservoir permeability. However, during waterflooding, an induced reduction in the effective permeability to water in the water swept zone, caused by fines migration, may be used to provide mobility control to improve the performance of the waterflood. This effect is similar to that of other EOR mobility control techniques such as polymer flooding. Reducing the salinity of the injected water is the most practical method to implement mobility control by induced fines migration as the other parameters that control the release of fines (pH, temperature, velocity) are not easily changed. Low salinity water is also often readily available and inexpensive compared to other alternatives.

Low salinity waterflooding, which is presently considered as a very promising EOR method, has been extensively studied (Yildiz and Morrow, 1996; Tang and Morrow, 1999; Pu et al., 2010). These investigations have largely focused on the effects of water composition on wettability, relative permeability, capillary pressure and residual oil saturation (Tang and Morrow, 1999; Jerauld et al., 2008; Takahashi and Kovcsek, 2010). These effects appear to be separate phenomena from fines migration but may occur simultaneously with fines migration. Some low salinity core flood studies have reported the release of significant amounts of fines (Bernard, 1967; Morrow et al., 1998; Tang and Morrow, 1999; Pu et al., 2010), while others have reported no evidence of fines migration (Lager et al., 2008; Jerauld et al., 2008; Rivet et al., 2010) even though additional oil was recovered. Bernard(1967) observed the residual oil reduction during low salinity coreflooding and explained it by fines migration. This paper only considers the effects of fines migration to provide mobility control and does not consider changes to the residual oil saturation or relative permeability curves as a result of injecting low salinity water.

Several models describing the release and capture of particles were developed. Kinetics-based approaches describing particle release (Shapiro and Stenby, 2000, 2002; Tufenkji, 2007; Rousseau et al., 2008) were found to exhibit a delayed response to an abrupt velocity rise or salinity decrease, which did not agree with the near instantaneous response seen in laboratory experiments (Ochi and Vernoux, 1998). Hence the maximum retention function model (Bedrikovetsky et al., 2011a,b), which exhibits the core response without delay, was chosen for the current investigation.

The induced formation damage, as a result of fines migration in the water swept zone, can be used for mobility control during waterflooding. Introduction of the maximum retention function allowed the effects of fines migration and permeability decline to be integrated into the quasi 2D Dietz model for waterflooding in layer cake reservoir (Lemon et al., 2011). The Dietz model was used because it provided a relatively simple and transparent analytical solution. However, the analytical model was derived assuming a constant injection/production

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doi:10.1016/j.petrol.2011.08.005

rate. The practical application of this solution was limited since most waterfloods are controlled by the reservoir fracture pressure and the injection/production rates vary with time.

The current paper extends the previous work (Lemon et al., 2011) addressing the problem of modelling a waterflood with fines migration for a given pressure drop across the reservoir. First, the maximum retention function as a function of water salinity is introduced and the concepts behind the use of induced fines migration for mobility control are explained. Secondly an analytical model for normal waterflooding in layer cake reservoir under a given pressure drop across the reservoir is derived and then adapted to include the effects of fines migration. Finally, an example application of the model is presented. The injection of low salinity water with fines lifting under a given pressure drop between the injection and production wells was found to increase the time until water breakthrough, decrease the water cut at the producing well and decrease the volume of injected water required while having a negligible effect on oil recovery.

2. Fines mobilisation by alteration of injected water chemistry

The results of a typical core flood experiment with a natural sandstone sample are shown on a plot of permeability versus injected water salinity (Fig. 1), adapted from Lever and Dawe (1984). In this example, the core plug permeability continuously decreases from 140 mD to 12 mD as the water salinity decreases from 30 g/L sodium chloride to essentially zero (distilled water). Such permeability decline may be explained by fines migration, induced by a change in the chemistry of the injected water, in this case a decrease in salinity (Khilar and Fogler, 1998). The decrease in salinity of the injected water causes a reduction in the magnitude of the electrostatic force which attaches fine particles to surface of rock grains, resulting in release of fines. A released particle is transported until it encounters a small pore throat which it cannot pass. The particle lodges in this pore throat and is said to be strained (Fig. 2). The detachment of a particle from within a pore body causes a negligible increase in permeability; however, plugging of pore throats by strained particles causes a significant permeability reduction.

The modified particle detachment model (Bedrikovetsky et al., 2011a,b) uses a maximum (critical) retention function: if the retained concentration of particles is less than the maximum value, particle capture continues according to the classical model of deep bed filtration, otherwise, the concentration of retained particles is equal to the maximum. The maximum concentration of retained particles primarily depends on the flow velocity, brine ionic strength γ and pH. However,

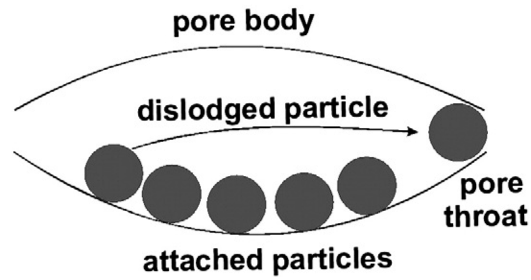

Fig. 2. Straining of detached particles in a single pore.

for the purposes of this investigation, it is assumed to only be a function of ionic strength, as it may be computed at the average velocity:

$$\sigma = \sigma_{cr}(\gamma) \tag{1}$$

The maximum retention concentration is determined by the condition of mechanical equilibrium of an attached particle, which is described by the torque balance of the electrostatic, drag, lifting and gravity forces acting on the particle. Fig. 3 presents the maximum retention concentration, as a function of water salinity, as obtained from the data by Lever and Dawe (1984). The details of the recalculation of permeability as a function of ionic strength, $k = k(\gamma)$ (Fig. 1), into the retained particle concentration, $\sigma = \sigma_{cr}$ (γ), are presented in Lemon et al. (2011). It was shown that the dependency (Eq. (1)) from Fig. 3 matched adequately with the maximum retention function as calculated from the mechanical equilibrium of a single fine particle on the wall of a cylindrical capillary.

The above observations are sufficient to warrant consideration of the effects of induced fines migration on waterflooding. During a waterflood, the rapid breakthrough of water can be a significant problem, leading to high water cut at producing wells and lower volumetric sweep efficiency for a given volume of injected water. The problem is particularly pronounced for a mobility ratio significantly greater than unity or where the variation of permeability across the reservoir is significant. Mobility control techniques, such as polymer flooding, may be employed to reduce a high mobility ratio by increasing the viscosity of the injection water or decreasing the effective permeability to water in the water swept zone behind the flood front (Lake, 1989). Such techniques decrease the fractional flow of water in the reservoir and hence decrease the water cut at the producing wells. The volumetric sweep efficiency for a given volume of injected water is also increased. Fines release, due to the alteration

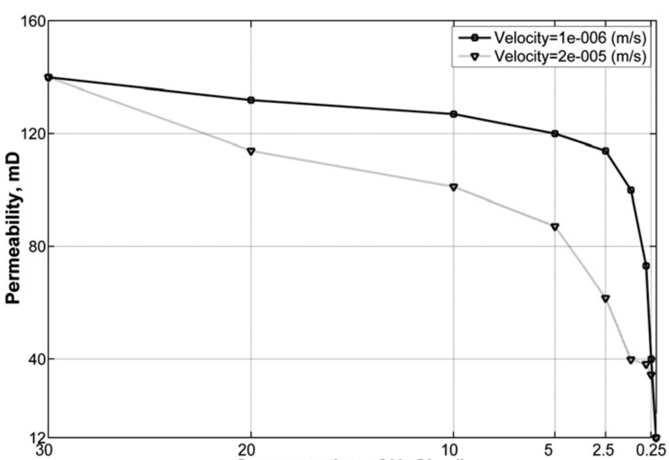

Fig. 1. Permeability change with salinity variation.

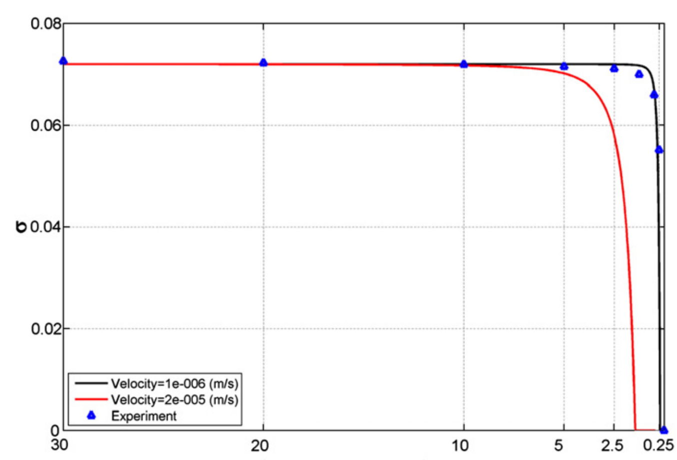

Fig. 3. Salinity dependency of retained concentration.