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Well control optimization considering formation damage caused by suspended particles in injected water

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ABSTRACT

Water flooding is one of the most important technologies to enhance oil recovery. An important task in water flooding is to determine optimal well control. Caused by suspended particles in injected water, formation damage always occurs during water flooding, thus leading to injectivity decline. Higher injection pressures, which may over the maximum injection pressure the surface facilities can provide, are needed to realize well control strategy. However, little attention has been paid to formation damage during well control optimization.

In this work, we develop a method to optimize well control considering formation damage caused by suspended particles in injected water. We predicted the effect of formation damage on the well production performance by coupling an analytical model with a reservoir numerical simulator. Then a well control optimization model subjected to injection pressure constraint is built and solved by the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) algorithm. The applications of our method in a five-spot model and an Egg Model justify its effectiveness.

Results demonstrate that the formation damage caused by suspended particles in injected water cannot be ignored during well control optimization. The method developed here provides a more practical well control strategy by considering formation damage during the process of optimization.

1. Introduction

Water flooding is a commonly used method to enhance the recovery in oil field development (Wang et al., 2015a,b). Injecting certain amount of water makes the reservoir maintain high pressure to sweep oil towards producers (Stenger et al., 2008). An important task of water flooding is to determine the optimal well control for individual wells (Wen et al., 2014; Wang et al., 2015a,b). By optimizing well rates or bottom hole pressures at different time, a higher net present value (NPV) or cumulative oil production can be achieved (Feng et al., 2015a; Humphries et al., 2014; Jansen and Durlofsky, 2016). The current well control optimizations mainly concentrate on deliverability of the pipeline, facilities operational ability (Wang, 2003), the reservoir uncertainty (Sarma et al., 2005), market uncertainty (Lund, 2000), or a combination of these considerations. However, the formation damage, caused by the existence of suspended particles in injected water, has seldom been taken into account in well control optimization.

When water is injected into the formation, these suspended particles in injected water migrate in the rock (You et al., 2016b). The suspended particles with size larger than pore throats gather on the well bore surface and then form the external cake, while these fines with size smaller than pore throats penetrate in formation and then are captured in pores forming internal filter cake (Sacramento et al., 2015; Kalantariasl et al., 2015; Yang et al., 2016; Yuan et al., 2016a,b). The fines migration, retention and cake formation lead to the permeability near the wellbore decline and formation damage gradually occurs (Barkman and Davidson, 1972; Feng et al., 2015b; Yuan et al., 2015, 2016a,b). The formation damage degree is related to the characteristics of particles, the reservoir properties, and the interaction between the suspended particles and reservoir materials (Fallah and Sheydai, 2013). A particle-filtration test conducted by Vetter et al. (1987), in which the sizes of all particles range from 0.05 to 7 μm, illustrates that larger particles lead to a more

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rapid decline in permeability. Even though the scope perturbed by the formation damage is very small, it can result in a tremendous decline of the injectivity (Pang and Sharma, 1997; Shi et al., 2013). Some models have been established to predict the declined injectivity. van Oort et al. (1993) only considered internal filter cake and purposed a simplified model to predict injectivity decline, in which the damage factor and the volume filter coefficient were introduced. Deep bed filtration model is usually used to describe the mechanism of internal filter cake (You et al., 2016b). However, both the internal and external filter cakes form in the actual formation damage. By using the transition time, mathematical models are established to describe the formation of the internal and external filter cakes (Herzig et al., 1970; Khatib, 1994; Wennberg and Sharma, 1997; Sacramento et al., 2015). On the basis of these models and injection histories, Bedrikovetsky et al. (2005, 2007) developed a method to estimate four injectivity damage parameters, which can be used to predict the injectivity decline.

Formation damage is neglected in these traditional well control optimizations. In the actual oilfield development, formation damage occurs which results in additional hydraulic resistance to the injected water (Kalantariasl et al., 2015). Therefore, in order to realize the optimal well control strategy in actual oilfield development, a higher injection pressure is needed which may beyond the maximum injection pressure that the surface facilities can provide. As a result, these traditional optimal well control strategies may not be realized in reality and they can lead to a poor development. Therefore, it is vital to take into account formation damage caused by injected water during well control optimization.

Despite its immediate relevance to the applications, there is no study to probe such a significant topic. Well control optimization always takes into account pipeline and facilities operational abilities (Wang, 2003). They influence the well control strategy by adding the constraints such as the maximum and minimum injection rates, the maximum and minimum production rates and the total injection rate (Forouzanfar et al., 2013; Wen et al., 2014; Humphries et al., 2014; Feng et al., 2015a). Besides, reservoir uncertainty, market uncertainty, or a combination of these considerations are studied in well control optimization (Lund, 2000; Wang, 2003; Sarma et al., 2005). van Essen et al. (2009) developed a robust optimization method to deal with the geological uncertainty which affected the well control strategy. The robust optimization procedure, which took geological uncertainty into consideration, was performed on a set of 100 realizations. Wen (2014) defined a monetary measure to represent the risk of a long-term optimal control strategy which was associated with the market uncertainty. It reflected the potential loss of the objective function caused by the lack of knowledge of market.

Although these works considerably improve the technique to optimize waterflooding performance, the influence of formation damage, which is caused by the existence of suspended particles in injected water, has seldom been taken into account in well control optimization. The present work develops a method to optimize well control considering formation damage caused by suspended particles in injected water. This method is obtained by coupling a derivative-free algorithm and a reservoir numerical simulator, which incorporates formation damage during water flooding. To the best of our knowledge, this work is the first study to optimize well control considering formation damage due to suspended particles in injected water.

2. Reservoir simulation considering formation damage

2.1. Formation damage prediction model

The injectivity decline process caused by injected water can be divided into two stages: firstly the injected particles are captured by the porous media (also termed deep-bed filtration) and then, after the transition time between the deep bed filtration and external filter cake formation (Sacramento et al., 2015), the external filter cake forms (see Fig. 1).

The model for deep bed filtration is (Bedrikovetsky et al., 2007; You et al., 2014, 2015):

$$\phi\frac{\partial c}{\partial t}+\frac{q}{2\pi r}\frac{\partial c}{\partial x}=-\frac{\partial \sigma}{\partial t} \tag{1}$$

$$\frac{\partial \sigma}{\partial t}=\lambda' Uc \tag{2}$$

$$U=-\frac{k_o k_{rwor}}{(1+\beta\sigma)\mu}\frac{\partial p}{\partial r} \tag{3}$$

whereφ is formation porosity; λ' is filtration coefficient denoting the ability of particles captured by porous media, m^{-1}; β is the formation damage coefficient; c represents the concentration of suspended particles, particle volume per unit fluid volume; σ is the deposited particle concentration, volume per unit filter volume; U is total flow velocity, m/s; μ is viscosity, Pa·s; k_o is the permeability before the injection, m^2; k_{rwor} is relative permeability for water at the presence of residual oil; p is pressure, Pa; r is radius distance, m. Eq. (1) describes mass balance of the suspended and deposited particles, Eq. (2) is the equation of particles capture kinetics, and Eq. (3) is Darcy's flow equation considering formation damage.

Assuming that external cake forms instantly after the deep-bed filtration stage, the dimensionless transition time T_{tr} between the deep bed filtration and the external filter cake can be calculated by (Pang and Sharma, 1997; Wennberg and Sharma, 1997; You et al., 2016a):

$$T_{tr}=\frac{2\alpha r_w}{\lambda' c^o R_e^2} \tag{4}$$

where α is the critical porosity; c^o is the injected suspended particle volume concentration, particle volume per injected volume; R_e is drainage radius, m; r_w is well radius, m.

The volume balance equation of particles forming external filter cake is given by (Bedrikovetsky et al., 2005):

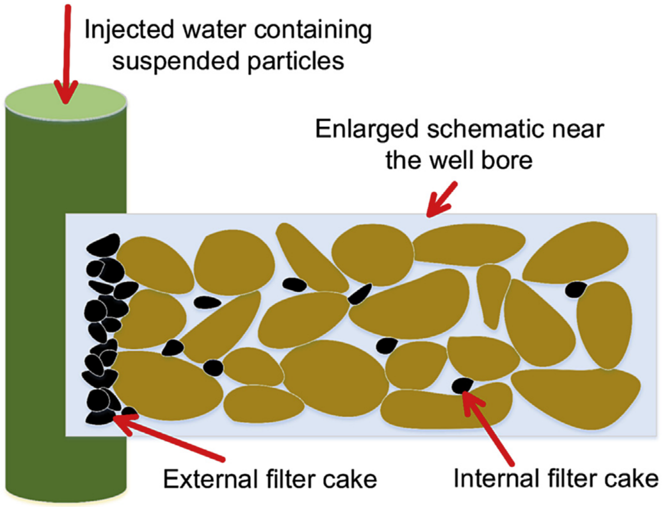

Fig. 1. Sketch of formation damage caused by suspended particles in injected water.