



A systematic and comprehensive approach in analyzing produced water re-injection

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ABSTRACT

This paper addresses the issues related to the injectivity maintenance during the process of produced water re-injection. This primary process can be attributed to a particle transport process where the particle clogging on the pore throats near the injection appears to be the dominant mechanism. In this paper, the impacts from all other processes (i.e. mechanical, hydraulic, and thermal influences) on the transport process are also evaluated. Additional processes may be envisioned as secondary, but the preliminary example indeed shows the noticeable impacts from these secondary processes on the primary process. Theoretical formulation of all related processes is general, and can be applied to other petroleum engineering applications besides the issue of produced water re-injection (e.g. sand control, reservoir stimulation, and wellbore stability analysis, etc.). Formulation, solution, interaction, and application of these coupled processes at various levels are detailed in this paper.

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1. Introduction

In oil production using water flooding drive mechanism, significant amount of contaminated water, frequently mixed with oil residues, must be disposed after the production. However, disposal of oily water becomes an issue of environmental remediation, which is subjected to not only numerous restrictions by the environmental protection agencies, but also substantial incidental costs for the disposal. Injecting the contaminated water back to the injection wells has been considered as an economically and environmentally viable means to dispose the water while re-using it to flood the oil in the formations. However, one of the disadvantages for this alternative approach is that contaminated water frequently contains residual oil and other chemical solute, together with fine grains, minerals, clays, and other solid particles, which may significantly reduce the available porous spaces and degrade the formation permeability, thus reduce the injection efficiencies. Such a degradation is reflected on the difficulties in maintaining the stable injection rate even though the injection pressure is kept at a constant level. Furthermore, a number of field observations have already indicated that the injectivity decline occurs mainly in the near-well regions (e.g., a few feet from the well). A normal hydraulic fracturing job may be just an overkill to a rather localized problem. Majority of operations have adopted limited stimulation methods such as acidizing, changing filters, and temporary back flow, etc. Nevertheless, the injection rates in these sites continue to decline, eventually leading to the abandonment of the injection wells.

Before a more cost-effective method can be identified to improve the injection rate, it is crucial to understand the actual physical phenomena related to the re-injection, and to be able to replicate the responses using analytical and numerical tools. The review of existing literature indicates that most people choose a mechanism before examining the re-injection issues. For example, if the issue of injectivity decline is believed to be caused by the near-well formation failure, the mechanical impact becomes a primary factor, while other mechanisms may be neglected. Similarly, if the permeability degradation is considered as the primary scapegoat for the injectivity decline, fluid flow may be the only mechanism chosen for the further analysis. This is a persistent trend, as demonstrated in the following literature review. Later it will show that such an approach can be biased on certain preferred mechanism as a result of individual background. However, it may not be a cost-effective method since the issue shows that the causes can be multiple and combined from numerous mechanisms.

1.1. Mechanical impact

As a matter of fact, the causes of injectivity decline and sand production may be similar, i.e., both are due to solid particle migration and deposition, except that the flow directions are opposite. However, resistance to the flow can be quite significant for the injection cases but much less for the sanding cases even though the magnitudes of pressure gradients are similar. Such a difference in the resistance to the flow merely leads to different flow rates. Excluding the cases with excessive sand production (e.g., fill up in the well), it may be permissible to consider the injectivity decline and sanding due to same reason but reversed flow directions. People from rock mechanics field believe that formation of plastic and elastoplastic zones around

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the well contributes directly to the rock failure in the region. [Dusseault and Santarelli \(1989\)](#) stated that near-well rock failure was attributed to the broken bonds of the solid materials after yielding. In other words, the rock is transformed from the intact state at the pre-yielding load to the discrete state when it fails. [Morita et al. \(1987a, 1987b\)](#) applied numerical tool using elastoplastic theory that incorporated plastic hardening to study the possible rock failure near a well. Using an elastic perfectly-plastic constitutive law, [Bratli and Risnes \(1981\)](#) and [Risnes et al. \(1982\)](#) studied rock yielding around well perforations subjected to steady-state fluid flow. Based on the similar flow conditions, [Wang and Dusseault \(1991\)](#) and [McLellan and Wang \(1994\)](#) conducted modeling of rock yielding around a well using elastic–brittle–plastic relation with strain softening. Based on the shear yielding and tensile failure criteria, [Ong et al. \(2000\)](#) assessed possible wellbore failure subjected to non-Darcy flow. [Addis et al. \(1996\)](#) provided a simplified poroelastic analytical model to assess the variations of reservoir pore pressure on the changes of in-situ stresses that may generate a non-hydrostatic stress field near a well, causing elastic property anisotropy. [Zhang et al. \(2000\)](#) studied rock failure near a wellbore in a naturally fractured formation using the theory of dual-porosity poroelasticity.

Except for some coupled analyses where both mechanical and flow mechanisms are examined, the study of mechanical impact alone (including those considering fluid flow as boundary load) focuses on the static system of force equilibrium where the changes in the material properties due to external loading may offer certain clues to the formation damage. However, the mechanical approach alone may overlook the important time factor and non-uniform pressure gradient in the transient fluid flow. In the meantime, it also neglects the important plugging mechanism of particle deposition during the transport process. Furthermore, the variations in material properties as a result of temperature changes may also be omitted.

1.2. Flow impact

Without making an analogy such as in the previous section between injectivity decline and sanding, most people in the field tend to contribute the issues of injectivity decline to the impact of fluid flow. This seems to be an easy solution since the permeability reduction in a flow system is easily claimed to be the primary scapegoat for formation plugging. Most permeability reduction models assume that clogging particles reduce both porosity and permeability ([Wennberg, 1998](#)).

[Herzig et al. \(1970\)](#) suggested the following relationship:

$$\frac{k}{k_0} = 1 - \omega(\phi - \phi_0) \quad (a)$$

where k is the permeability, ϕ is the porosity, subscript 0 denotes initial state, ω is an empirical constant ranging from 28 to 432 depending on the degree of specific deposition. The larger ω is, the more severe the deposition would be.

[Rumpf and Gupta \(1971\)](#) proposed the following equation:

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0} \right)^\omega \quad (b)$$

where ω is a constant, determined from the experiment.

[Rochon et al. \(1996\)](#) used the following equation to describe the permeability changes:

$$\ln \frac{k}{k_0} = \omega^*(\phi - \phi_0) \quad (c)$$

where ω^* is a constant, determined from examining the limiting conditions when k and ϕ approach to each respective initial values.

Without referring to the original states of k and ϕ , [Nelson \(1994\)](#) obtained the following relationship from experiment:

$$\log k = a + b\phi \quad (d)$$

where a and b are experimental constants, which are the functions of grain size, clay contents, and cementing conditions.

The expressions of Eqs. (a), (b), (c) and (d) can be viewed as the variations of the permeability–porosity relation originally postulated by Kozeny–Carman ([Bear, 1972](#)). The expressions may be simple. However, it is not straightforward to determine the actual porosity changes during the flow process.

For underbalanced perforation, [Walton \(2000\)](#) analyzed the surge flow through the perforation tunnel when subjected to instantaneous drawdown. Walton related the surge flow to the strength of the near-well formation and to the consequential permeability reduction.

The approaches from analyzing the flow impact may be correct to capture the permeability degradation as a major source for injectivity decline. However, the flow approach neglects the major difference between flow and transport. The re-injected contaminated water is different from the pure water in that the concentration variations are the primary catalyst for the former activities, while the changes in pore fluid pressure are the major factor for the latter responses. As a result, the plugging mechanism due to the deposition of suspended solids and oil in the water cannot be represented by a flow model alone. In addition, the fine grain generation as a result of mechanical crushing of originally intact rock needs to be considered, which can only be invoked from the study of mechanical impact, as described in the previous section.

1.3. Transport impact

The migration of oily water can be a simple transport problem. However, the migration of suspended solids within the water is a complex transport case. It may not be easy to represent the physical straining, size exclusion and bridging of moving particles at pore throats when subjected to high flow velocity. By the same token, it may be equally difficult to characterize the sedimentation, sorption/desorption, imbibition/drainage of migrating particles when subjected to relatively low flow velocity. In most cases, these responses have been approximated using the source/sink-like terms in the transport equations.

[Donaldson and Baker \(1977\)](#) proposed a hypothetical model for the particle transport system where the distribution of particle sizes was randomly selected, which was used as a threshold to determine the transport velocity of each particle passing through the porous rock idealized as a bundle of capillary tubes. Using the concept of random walk method, [Bai et al. \(1998\)](#) derived the solution of particle migration through gravel packs that matched the experimental results. [Liu and Civan \(1993\)](#) presented a model of particle transport with two-phase fluids, which revealed that formation damage due to particle invasion is strongly affected by the particle wettability. [Imdakm and Sahimi \(1993\)](#) developed a Monte Carlo model to simulate particle and molecule transport in 3D network of interconnected pores. The model could consider the effect of various phenomena that may change the morphology of the porous medium, such as pore plugging, particle deposition or macromolecular adsorption on the pore surface. Based on the stochastic model of the void structure and void size, [Aberg \(1992\)](#) presented a method to calculate the grain size distribution in relation to the effect of gravel packs. [Abboud and Corapcioglu \(1993\)](#) used numerical method (finite difference method) to determine the formation of filter cakes and associated permeability reduction.

In the analytical modeling of injectivity decline, [Herzig et al. \(1970\)](#) suggested to neglect the diffusion terms for particles larger than 1 μm . Since smaller particles are unlikely to clog the pore

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