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Practical Analysis of Injection/Falloff Data of Horizontal Wells

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Abstract

We have constructed new approximate analytical solutions for injection and falloff pressure response which include thermal effects that arise when flooding a reservoir with water having a temperature considerably below of that of the reservoir. We have developed an optimization code based on the Levenberg-Marquardt algorithm and coupled it with our new approximate analytical solutions to obtain a procedure for data analysis where our approximate analytical solutions are used as the forward model in the non-linear regression. We demonstrate that we can generate estimates of absolute permeabilities, the well skin factor, the length of the well and relative premeabilities by matching data to analytical solutions by minimization of a weighted least squares objective function. The relative permeability curves are constructed assuming a power law parametrization. In the horizontal well case, we show that the absolute permeabilities in the three principal directions can be resolved separately provided the duration of the test is sufficiently long.

Introduction

Heat transfer must occur whenever there exists a temperature difference in a medium or between media. When cold water is injected into a hot reservoir, the formation around the water injector will cool down to the temperature of the injected water. This creates a cold water bank around the injector which expands with time into the reservoir. Similar to the saturation front, the temperature front will also propagate in the reservoir. Both the solid and fluid phases contribute to the heat transfer. The heat exchange in the reservoir occurs mainly through three processes: convective heat transfer between injected fluid and solid matrix, heat conduction (vertical and horizontal conduction) and heat transfer by radiation. The last mechanism is not considered to be important in porous media and therefore is usually neglected when the gas phase is not involved.

There exist numerous articles in the literature which provide insight and a general understanding of the injection and falloff pressures for one-dimensional radial flow when cold waterflooding a hot reservoir. We cite for example Woodward and Thambynayagam (1983) who presented an analytical solution for the pressure response based on the Verigin model (Verigin (1952)) which assumes that the injected fluid displaces the formation fluid in a piston-like manner (two-bank system). Their study indicated that the effect of temperature variations during injection are found to behave as skin effects. Despite the fact that their analytical solutions were validated by comparison with results obtained from a numerical simulation, the authors did not provide a formal derivation for the Verigin generalization to nonisothermal conditions. Similarly to Woodward and Thambynayagam (1983), Barkve (1989a) considered the displacement to be piston-like. By decoupling the mass and energy equations, the author was able to analytically solve the system for temperature and pressure in the reservoir during injection providing, therefore, a formal derivation of the results presented by Woodward and Thambynayagam (1983).

Platenkamp (1985) conducted a numerical study in order to show the relative importance of the heat exchange processes involved when injecting cold water into a hot reservoir, that is convection, vertical and horizontal conduction. From his results, he concluded that heat transfer from conduction is negligible compared to that from convection during an injection period as long as the duration of the test is not too long and the injection rate is sufficiently high.

Bratvold and Horne (1990) derived an analytical solution for injectivity tests which accounts for the saturation profile behind the front. Based on the study of Platenkamp (1985), these authors assumed the temperature distribution to be completely dominated by convective heat transfer during the injection period leading to a quasilinear hyperbolic system for water saturation and temperature that they solved using the method of characteristics. They, then, directly solved a moving boundary problem where the boundary corresponds to the location of the front as predicted from the nonisothermal Buckley-