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An examination of the concept of apparent skin factor in modeling injectivity of non-Newtonian polymer solutions

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ABSTRACT

In a conventional reservoir simulation, analytical well models relate well block pressure, wellbore pressure, fluid mobility, and geometric factors such as wellbore radius and grid size. Basically, fluid viscosity is assumed to be Newtonian in these models. Commercial reservoir simulators using these well models often predict unrealistic well injectivity in simulation of processes involving non-Newtonian fluids such as polymer solutions. Apparent viscosity of a polymer solution is a complicated function of flow velocity, polymer properties, permeability, porosity, salinity, etc. As the distance away from an injection well increases, flow velocity decreases; meanwhile, the apparent polymer viscosity changes drastically. For shear-thinning polymers, the average flow velocity in a well block is several orders of magnitude smaller than the flow velocity near the wellbore, especially when grid size is large. Using the average flow velocity for apparent viscosity calculation leads to an underestimate of well injectivity. Thus it is crucial to consider non-Newtonian effects in simulation of injectivity of polymer solutions. UTCHEM, a general purpose chemical flooding simulator developed at the University of Texas, uses a semi-analytical polymer injectivity model based on an extension of Peaceman's well model to non-Newtonian fluids. This model corrects the apparent viscosity in well index calculation and gives a more realistic estimate of polymer injectivity. However, the model needs to be programmed and implemented in a code. It is not practical for users of commercial simulators which do not have semi-analytical polymer injectivity model. Compared with UTCHEM, CMG-STARS, the thermal and advanced processes reservoir simulator developed by Computer Modeling Group, uses an apparent skin factor to account for non-Newtonian effects of power law fluids. The apparent skin factor can be used as an input parameter to the simulator.

In this study, we revisited the analytical polymer injectivity model and proposed a general form for the calculation of apparent skin factor. The apparent skin factor is estimated using polymer rheological properties, grid size, wellbore radius, etc., and can apply to any polymer rheology. Simulation studies of polymer flooding cases were conducted to verify the concept of apparent skin factor. The results show that for shear-thinning polymers, the apparent skin factor can be estimated properly and correct the analytical well model to give close predictions compared to the semi-analytical polymer injectivity model and fine-grid simulation. The concept of apparent skin factor was proved to be useful for improving the accuracy of well injectivity calculations by commercial simulators. However, it is also worth pointing out that the apparent skin factor cannot be used for polymers which show shear-thickening behavior at high shear rates for cases of heterogeneous reservoir.

1. Introduction

Reservoir simulators are widely used to simulate chemical enhanced oil recovery processes (Goudarzi et al., 2013). One interesting topic in simulating chemical flooding is on modeling non-Newtonian behavior of a polymer solution (Carreau, 1968; Hirasaki and Pope, 1974; Masuda et al., 1992; Bird et al., 2007; Delshad et al., 2008; Stavland et al., 2010), which is important to polymer solution flow in the reservoir (Lake, 1989; Sorbie, 1991), and also polymer injectivity (Bondor et al., 1972; Sorbie et al., 1982; Li and Delshad, 2014). Sweep and displacement efficiencies are dependent on the rheological behaviors of polymer solution flow in the reservoir, while project life is dependent on the rheological behaviors of polymer solution flow near wellbore, which affect polymer injectivity.

For a specific type of polymer, apparent viscosity of its solution is a

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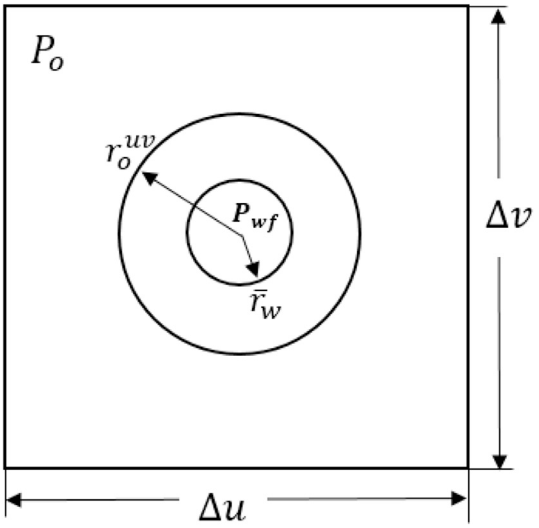

Fig. 1. Peaceman's well model where the well block has a Peaceman's radius of r_o^{uv}, and the well has a radius of $\bar{r}_w$ in transformed coordinates (u–v).

strongly nonlinear function of fluid velocity, permeability, porosity, salinity, hardness, etc. The deformation and flow of polymer molecules are the focus of the study of polymer rheology. Polymer molecules, no matter if they are a biopolymer or a synthetic polymer (Delshad et al., 2008), show similar rheology in a bulk fluid. Generally a bulk polymer solution is shear-thinning, which means fluid viscosity decreases as shear rate increases (Sorbie, 1991). When a polymer solution flows through porous media, polymer rheology is affected by the existence of tortuous pore structures and also rock properties. Polymer molecules may get trapped by small pores and adsorb to the wall of the rock, which reduces polymer concentration and is called polymer retention. Besides, polymer molecules will stretch and contract during the flow through porous media. A biopolymer may show very different rheological behaviors from a synthetic polymer. When the flow velocity or shear rate is small, the biopolymer shows shear-thinning behavior and the synthetic polymer shows shear-thinning or nearly Newtonian behaviors (Sorbie, 1991). At a high flow velocity or shear rate, the biopolymer still shows shear-thinning behavior while the synthetic polymer shows shear-thickening behaviors, which means viscosity increases as shear rate increases (Delshad et al., 2008; Seright et al., 2009). This difference is due to the different polymer structures of these two types of polymers: the biopolymer has a more rigid structure while the synthetic polymer has a more flexible structure. The most commonly used polymer, hydrolyzed polyacrylamide (HPAM), is a synthetic polymer (Sheng, 2011). Although it is clear that polymer solution may experience shear-thickening regime at high shear rates near injection wells, it is commonly accepted that polymer solution is shear-thinning for most part of the reservoir far away from injection wells and therefore treated as a shear-thinning fluid in most commercial reservoir simulators such as ECLIPSE (Schlumberger, 2010), CMG-STARS (Computer Modeling Group Ltd, 2013), etc. Delshad et al. (2008) proposed a unified viscoelastic model to describe shear-thinning behaviors at low shear rates and shear-thickening behaviors at high shear rates.

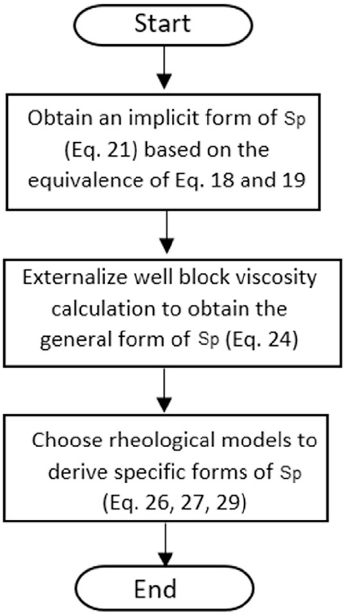

Fig. 2. Flow chart for the derivation of an apparent skin factor model.

Table 1
A summary of polymer injectivity correction methods.

Type	Equation	Authors
Empirical	$\lvert\vec{u}_w\rvert = \frac{q_w}{2\pi r_{weff} h}$	Sharma et al. (2011)
Empirical	$\lvert\vec{u}_w\rvert = \frac{q_w}{2\pi r_{weff} h} r_{weff} = \sqrt{r_a r_w}$	Schlumberger (2010)
Modified Peaceman's well model	$\bar{\mu}_w = \frac{\int_{\bar{r}_w}^{\bar{r}_o^{uv}} \frac{\mu_{app}(\bar{r})}{\bar{r}} d\bar{r}}{\ln\left(\frac{r_o^{uv}}{\bar{r}_w}\right)}$	Li and Delshad (2014)
Apparent skin factor model for power law fluids	$S_{cmg} = \left(\frac{1}{1-n}\right)\left[1 - \left(\frac{r_w}{r_{ec}}\right)^{1-n}\right] + \ln\left(\frac{r_w}{r_{ec}}\right)$	CMG STARS (2013)
Apparent skin factor model for power law fluids	$s_p = \frac{1}{1-n}\left[\left(\frac{r_o^{uv}}{r_A}\right)^{1-n} - \left(\frac{\bar{r}_w}{r_A}\right)^{1-n}\right] - \ln\left(\frac{r_o}{r_w}\right)$	This work
General form of apparent skin factor model	$s_p = \frac{\int_{\bar{r}_w}^{\bar{r}_o^{uv}} \frac{\mu_{app}(\bar{r})}{\bar{r}} d\bar{r}}{\mu_{app}(r_A)} - \ln\left(\frac{r_o}{r_w}\right)$	This work

When a polymer solution is injected into an injection well, the flow is nearly radial for a well located in a relatively homogeneous and isotropic area. For a radial flow, flow velocity decreases as the distance away from the wellbore increases. So the flow velocity is high near the wellbore and low in the reservoir. Therefore, a non-Newtonian polymer solution will experience a variation of apparent viscosity as the injection fluid travels from the wellbore to the reservoir. The most significant part of the viscosity variation occur in the vicinity of the well, where the flow velocity changes several fold (Bondor et al., 1972; Sorbie et al., 1982). This implies the variation of apparent viscosity needs to be considered in the well model in a reservoir simulation. However, commonly used analytical well models (e.g., Peaceman, 1983) was developed for Newtonian fluids. Simulation studies using Peaceman's well model (Yuan, 2012) confirm that neglecting the variation of apparent viscosity in the vicinity of the well causes a strong sensitivity of polymer flood simulation results to grid block size, because velocity calculation is averaged for a coarse grid block and the variation of apparent viscosity tends to be smeared out as the well block size increases. While a fine grid simulation may give accurate results, it is computationally expensive and commonly avoided in a field scale simulation.

To include non-Newtonian effects in the well model and avoid the grid effect, Bondor et al. (1972) modified their well model using an apparent skin factor determined by an integral of the non-Newtonian viscosity profile for radial flow around the wellbore. The polymer rheology was assumed to be shear-thinning and modelled using the Blake-Kozeny model modified from the power-law model. However, their well model was based on the assumption that the well block pressure should be equal to the areal average pressure (Van Poollen et al., 2007), which was proved to be incorrect by Peaceman (1978). Thus the predicted apparent skin factor based on this well model was questionable. However, this was the first attempt to capture non-Newtonian effects in simulating polymer injectivity using the apparent skin factor.