Modeling pressure-sensitive effect of shale gas wells based on history matching

Zhanke Li, Anfeng Shi, Xiaohong Wang, Zhifeng Liu*, Zhifan Liu

University of Science and Technology of China, Hefei, China
Both Zhanke Li and Anfeng Shi are joint first authors, contributing equally to this work.

*Corresponding author e-mail: lzf123@ustc.edu.cn

Abstract. Based on the measured data of gas production and backflow flux in Sichuan Province of China, pressure-sensitive effect is studied based on history matching in this article. When the shale gas development is on-going, the reservoir pressure declines and micro-fracture network may be partially closed in the stimulated reservoir volume (SRV). The closure of micro-fracture network not only leads to the decrease of absolute permeability, but also to the variation of relative permeability curve. The pressure-sensitive effect coefficient of relative permeability is introduced in this article to characterize this effect.

1. Introduction

The application of hydraulic fracturing technique is critical for improving shale gas recovery. The area induced by hydraulic fracturing can be approximated as stimulated reservoir volume (SRV). For tight oil or gas reservoirs, through scanning the energy released from the crushing of reservoir rocks and combining with the engineering fracturing curve, microseismic monitoring provides a feasible way to determine the space distribution of SRV. One effective way to obtain these important geological parameters is through history matching.

During shale-gas production, pressure declining will cause proppant crushing and narrow the flow channels in fractures, which results in the declining of permeability [1]. The closure of micro-fractures not only results in the decrease of absolute permeability, but also results in the variation of relative permeability. With the increase of overburden pressure or the decrease of pore pressure, the flow channel of the micro-fracture network becomes narrower, causing a general shift in the pore throat diameter distribution towards smaller values. It leads to the decrease of relative permeability of the non-wetting phase, and the increase of irreducible water saturation of the wetting phase [2, 5].

In this paper, history matching is performed to estimate the relevant geological and flow parameters for shale gas wells in Sichuan, China. The dynamic features of SRV are investigated, and pressure-sensitive effect is studied. This paper is organized as follows. In Section 2, the employed mathematical models are illustrated. History matching algorithm is sketched in Section 3. In Section 4, the simulation result of history matching is provided, and pressure-sensitive effect is studied for a real shale-gas wells in Sichuan Province of China. Conclusions are drawn in Section 5.
2. Mathematical models

2.1. Governing equations

For shale gas reservoir after hydraulic fracturing, the whole simulation domain can be divided into two parts: outside SRV and inside SRV. Outside SRV, the original reservoir is described by the dual porosity model where only the single gas flow is considered. Inside SRV, the reservoir is also described by the dual porosity model with gas-liquid two phase flow in it. The EDFM is employed to describe conductive fractures. The governing equations are:

For the single gas phase flow outside SRV,

\[
\left\{ \frac{\partial}{\partial t} \left[ \phi \rho_g + (1 - \phi) q_{\text{ads}} \right] \right\}^m = -q_g^{(mf)}
\]

\[
\left\{ \frac{\partial}{\partial t} (\phi \rho_a S_a) + \nabla \cdot (\rho_a \mathbf{V}) \right\}^f = q_a^{(mf)}
\]

For the two phase gas-liquid flow inside SRV,

\[
\left\{ \frac{\partial}{\partial t} \left[ \phi \rho_g + (1 - \phi) q_{\text{ads}} \right] \right\}^m = -q_g^{(mf)}
\]

\[
\left\{ \frac{\partial}{\partial t} (\phi \rho_a S_a) + \nabla \cdot (\rho_a \mathbf{V}) \right\}^f = q_a^{(mf)} - q_a^{(f)} \delta(r - r^{(f)})
\]

In these equations, superscripts \(m\), \(f\), \(F\) denote matrix system, fracture system and conductive fractures respectively. Subscript \(w\), \(g\) denotes liquid and gas phase, respectively. \(S_a\) is the \(a\) phase saturation. \(\delta(r)\) is the Dirac function and \(r^{(f)}\) represents the position of conductive fracture. \(q_a^{(mf)}\) represents the exchange flow rate of \(a\) phase between matrix and the micro-fracture network. \(q_a^{(f)}\) denotes the exchange mass flow rate of \(a\) phase between the conductive fracture and the artificial micro-fracture network. \(\mathbf{V}_a\) is the seepage velocity for \(a\) phase in artificial fracture system.

According to the previous assumption, we have \(q_w^{(mf)} = 0\). The exchange flow rate \(q_g^{(mf)}\) can be calculated by the following formula [6]:

\[
q_g^{(mf)} = D \sigma^m \left[ \rho_g^{(m)} - \rho_g^{(f)} \right]
\]

The mass of adsorbed gas per unit volume in shale matrix \(q_{\text{ads}}\) is calculated according to the Langmuir's adsorption formula [7].

It is assumed that pressures in conductive fractures equal the bottom hole pressure. Thus, \(q_a^{(f)}\) can be approximated numerically by using quasi Peaceman formula in the EDFM [8].

2.2. Pressure-sensitive effect

During the production process, reservoir pressure declines and fracturing fluid flows back to the well, resulting in closure of micro-fractures. Then the absolute permeability and relative permeability will also decrease apparently. The pressure-sensitive effect of absolute permeability in the micro-fracture network in SRV can be approximated as [9, 10]:

\[
K = K_0 e^{-ap(P - P_b)}
\]
where $K_0$ and $P_0$ denote the initial absolute permeability and initial pressure respectively. The parameter $a$ denotes the pressure-sensitive coefficient of the absolute permeability.

The closure of the fracture network also leads to the variation of the relative permeability curve. Brooks [11] proposed a semi-empirical model which has been widely used for modeling two-phase relative permeability. Because maximum relative gas permeability. $K_{rg\max}$ and irreducible water saturation $S_{wc}$ is pressure-sensitive, the pressure sensitive effect of the relative permeability is considered in this article:

$$K_{rg\max} = K_{rg\max}^0 \left[1 + b(P - P_0)\right]$$

$$S_{wc} = S_{wc}^0 \left[1 + c(P - P_0)\right]$$

where $K_{rg\max}^0$ and $S_{wc}^0$ are the initial maximum relative gas permeability and the initial irreducible water saturation, respectively. The parameters $b$ and $c$ are the pressure-sensitive effect coefficients of relative permeability to be fitted.

3. History matching algorithm

In history matching algorithm, we denote parameters to be fitted as a vector $x$, and the objective function as $y_0$. The aim of history matching is to assign the specific value for vector $x$, so that $y = y(x)$ calculated from numerical simulation is consistent with the target vector $y_0$ as closely as possible. Considering that the fitting parameters will be used to forecast the future production, long-term production behavior is matched preferentially. For this purpose, the error function is designed with increased weight for the later period of exploitation. The weighted error function $E$ is thus designed as:

$$E = \left(\sum_{n=1}^{N_t} \left\| y^n(x) - y^n_0 \right\| / \sum_{n=1}^{N_t} y^n_0^2 \right)^{1/2}$$

where $N_t$ is the total production days; $y^n$ is the corresponding production data for the $n$th day obtained from numerical simulation; and $y^n_0$ is the target data for the $n$th day. The specific value for the unknown vector $x$, denoted as $x_{\min}$, needs to be found satisfying $E(x_{\min}) = \inf_x E(x)$. The algorithm of getting $x_{\min}$ is just the classical gradient method [12].

4. History matching examples

In this section, history matching example is provided to estimate geological and flow parameters of SRV in shale gas reservoir in Sichuan Province, China. By analyzing pressure-sensitive effect coefficients of SRV, pressure-sensitive effect is studied.

There are 19 conductive fractures and one horizontal well in it. The depth of the horizontal well is 3140 meters. Some parameters of shale gas reservoir are provided by reservoir engineering (See Table 1).
Table 1. The known parameters.

| Parameters | $P_0$ | $T$ | $V_L$ | $P_L$ | $\phi^m$ |
|------------|-------|-----|-------|-------|---------|
| value      | 61.3MPa | 391.8K | 2200m$^3$/kg | 8.5MPa | 0.056   |

Figure 1 shows the fitting results for the cumulative gas production and the cumulative backflow fluid flux. These three tests imply that it is necessary to take the pressure-sensitive effect of both the absolute and the relative permeability into consideration when performing history matching.

To indicate the pressure sensitive effect, the variations of the average pressure and the average permeability with time. When its pressure decreases from 61.50 MPa to 33.54 MPa, its permeability will decrease greatly from 0.12 mD to 0.0013 mD. Correspondingly, $K_{r_{max}}$ will decrease greatly from 0.99 to 0.66, and $S_{w}$ will increase from 0.15 to 0.25.

Relevant parameters are obtained through history matching. The initial permeability of SRV is 0.12mD, while the permeability of the naturally micro-fracture network outside SRV is only 0.00038mD. After hydraulic fracturing, the permeability of micro-fracture networks $K_0$ in SRV increases greatly, which is the main reason of gaining high gas production, especially at the initial exploitation period.

The pressure-sensitive coefficients of absolute permeability is 0.08, indicating that the decrease of the conductivity in SRV. The pressure-sensitive coefficients $b$ of relative permeability is 0.024, also indicating that the decrease of the conductivity in SRV. The pressure-sensitive coefficients $c$ of relative permeability is 0.012, showing $S_{w}$ is pressure-sensitive.

5. Conclusion

In this article, history matching is performed to estimate the relevant geological and flow parameters for shale gas wells in Sichuan, China. Based on the fitting results, pressure-sensitive effect is studied. Conclusions are drawn as following:

When The initial permeability of micro-fracture networks in SRV is a key parameter of determining the gas production, especially at the initial exploitation period. The higher the permeability is, the better the fracturing effect is and the higher the gas production is. On the other side, pressure declining will lead to production declining due to the pressure sensitive effect.

With the shale gas exploitation on-going, reservoir pressure declines and micro-fracture network may be partially closed. The pressure-sensitive effect not only leads to the variation of absolute permeability, but also the variation of relative permeability curve. The relevant parameters $b$ and $c$ characterizing pressure sensitive effect of relative permeability is introduced (see formula (5) and (6)).
Acknowledgments
This work was supported by National Science and Technology Major Project of China (No.2017ZX05072-005) and the CNPC-CAS Science and Technology Cooperation Project (Grant Number No.2015A-4812).

References
[1] Wang, J., Jia, A., Wei, Y., Qi, Y.. Approximate semi-analytical modeling of transient behavior of horizontal well intercepted by multiple pressure-dependent conductivity fractures in pressure-sensitive reservoir, Journal of Petroleum Science and Engineering 153 (2017) 157-177.
[2] Ali, H.S., Al-Marhoun, M.A., Abu-Khamsin, S.A., Celik, M.S.. The Effect of Overburden Pressure on Relative Permeability, SPE (1987) 1–6.
[3] Jones, C., Al-Quraishi, A.A., Somerville, J.M., Hamilton, S.A.. Stress sensitivity of saturation and end-point relative, International Symposium of the Society of Core Analysts (2011) 1-12..
[4] Lei, G., Dong, P., Wu, Z., Mo, S., Gai, S., Zhao, C., Liu, Z.K.. A fractal model for the stress dependent permeability and relative permeability in tight sandstones, Journal of Canadian Petroleum Technology 54 (2015) 36–48.
[5] Xiong, Y., Xua, H., Wang, Y., Zhou, W., Wang, L., Feng, K.. The variation mechanism of petrophysical properties and the effect of compaction on the relative permeability of an unconsolidated sandstone Reservoir, Marine and Petroleum Geology 92 (2018) 754-763.
[6] Wu, K., Li, X., Wang, C., Yu, W., Chen, Z.. Model for Surface Diffusion of Adsorbed Gas in Nanopores of Shale Gas Reservoirs, Industrial & Engineering Chemistry Research 54 (2015) 3225-3236.
[7] Langmuir, I.. The adsorption of gases on plane surfaces of glass, mica and platinum, J. Am. Chem. Soc. 40 (1918) 1361-1370.
[8] Li, L., Lee, S.H.. Efficient field-scale simulation of black oil in a naturally fractured reservoir through discrete fracture networks and homogenized media, SPE 11 (2008) 750-758.
[9] Kikani, J., Pedrosa Jr., O.A.. Perturbation analysis of stress-sensitive reservoirs, SPE (1991) 6,379–386.
[10] Pedrosa Jr., O.A.. Pressure transient response in stress-sensitive formations. SPE (1986) 203-208.
[11] Brooks, R.H., Properties of porous media affecting fluid flow, Journal of Irrigation and Drainage Engineering 92 (1966) 61-88.
[12] Polak, E.. Optimization:Algorithms and Consistent Approximations, (1997) 56-70.