Numerical Simulation for the Flow Characteristics of Shale Oil in Fractured Shale Reservoirs

Fei Peng, Zhaqin Huang *
School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, China
*Corresponding author e-mail: s18020051@s.upc.edu.cn

Abstract. Compared to conventional reservoirs, shale reservoirs are characterized by the extraordinary low porosity and permeability, which contribute to the large-scale application of the technology of hydraulic fracturing in the development. The flow characteristics of shale oil is quite complicated in the hydraulic and natural fractures and the flow characteristics of shale oil in fractures is vital significant to oilfield development. In this paper, a model is developed to simulate the flow characteristics in fractured shale reservoirs, which fully coupling the geomechanics and fluid flow. Specifically, an embedded discrete fracture model is adopted to characterize the hydraulic fractures and the flow between natural and hydraulic fractures. Correspondingly, the Multiple Interacting Continua model is adopted to characterize the flow between matrix and natural fractures. The influence on production caused by the stress sensitivity of two kinds of fractures is considered. Then, the sequential iterative solution method is adopted to solve the model which coupled the geomechanics and fluid flow, and the finite volume method and the finite element method are applied to solve the fluid-governing equations and geomechanics-governing equations, respectively.

1. Introduction
The technology of horizontal drilling [1] and hydraulic fracturing [2-6] contribute a lot to improving economic effects during the process of production of shale reservoirs. Correspondingly, the complicated fractures network is formed, which provides the channel for flow. A model is developed in our paper to simulate the flow characteristics of shale oil in fractured shale reservoirs, which fully coupling geomechanics and fluid flow, and to examine its main factor of influence.

2. Mathematical model descriptions
2.1. Fluid-governing equations
In our paper, it is assumed that oil and water are stored in the reservoir, and a model is adopted to simulate the flow of fluid, which can be obtained from law of conservation of mass and is shown as follows:

\[ F_i + q_i = \frac{\partial N_i}{\partial t} \]  

(1)
Where \( i = o, w \), and \( o \) represents oil, and \( w \) represents water. \( N \) is the accumulation term of mass, \( F \) is the flux term of mass and \( q \) is the source term of mass.

2.2. Governing equations of mechanics

In this study, the equations of mechanics for matrix of shale reservoir deformation is given as [7],

\[
\nabla \cdot \sigma + \rho_b g = 0
\]

The sign convention of continuum mechanics is adopted. In this model, \( \sigma \) is the total stress tensor and is given as:

\[
\sigma u = C_{up} \varepsilon + \sum K_{ij} h_j \rho_i \mathbf{I}
\]

Where \( \rho_b \) is the bulk density. \( \varepsilon \) is the strain tensor, which is given as follow:

\[
\varepsilon = \frac{1}{2} \left( \nabla u + \nabla^T u \right)
\]

For the solving of the geomechanics-governing equations, the boundary condition is given as follows:

\[
\sigma \cdot n = \dot{t} \text{ on } \Gamma_t, \quad \mathbf{u} = \dot{\mathbf{u}} \text{ on } \Gamma_u
\]

2.3. Constitutive relations

The relationship between matrix porosity and strain, fluid pressure and temperature can be derived as follows:

\[
\phi_m = \phi_{m0} + \frac{(\alpha - \phi_{m0})(1 - \alpha)}{K_d}(p_0 - p_m) + \alpha(\varepsilon_v - \varepsilon_v^0)
\]

Where 0 is the reference status, and \( \varepsilon_v \) is the strain of the volume. The permeability of matrix can be derived as:

\[
k_m = k_{m0} \left( \frac{\phi_m}{\phi_{m0}} \right)^3 \left( \frac{1 - \phi_{m0}}{1 - \phi_m} \right)^2
\]

In particularly, Equation (10) is based on Kozeny-Carman model [8, 9]. Considering the influence of natural fractures and roughness of surface, the Barton-Bandis model [10] is adopted to describe the change of fracture aperture, which is as follows:

\[
\Delta d_{nf} = \frac{\Delta d_{nf_{max}} \sigma_n}{k_n \Delta d_{nf_{max}} + \sigma_n}
\]

Where \( \sigma_n \), \( \Delta d_{nf_{max}} \) and \( k_n \) are the normal stress, the maximum allowable fracture closure and the initial normal stiffness of fractures respectively. \( k_n \) and \( \Delta d_{nf_{max}} \) can be obtained as follows:

\[
k_n = -7.15 + 1.75JRC + 0.02^{\frac{JCS}{d_{m0}}}\]

\[
\Delta d_{nf_{max}} = -0.1032 - 0.0074JRC + 1.1350^{\left( \frac{JCS}{d_{m0}} \right)^{-0.2510}}
\]
3. Flow Characteristics in fractures
As shown in Figure 1, a model in 3D which is built to simulate the flow characteristics of shale oil in fractured shale reservoirs. It is assumed that this shale reservoir is a dual-porosity and single-permeability medium for simplifying the calculation. The well for production is situated at the center of the shale reservoir. The schematic of mesh for the physical model are showed in Figure 1. The parameters of reservoir for model are listed in Table 1.

![Horizontal Well](image1)

**Figure 1.** Physical model and Schematic of mesh.

| Table 1. Parameters of the reservoir model. |
|--------------------------------------------|
| **Name**                                      | **Value**               |
| Size of the model, m                        | 302×62×50              |
| Number of grids                             | 151×31×10              |
| length of the horizontal well, m            | 50                     |
| Initial pressure and BHP, MPa               | 26.0, 12.0             |
| Production, m³/day                          | 22.0                   |
| Initial porosity of hydraulic fractures, matrix and natural fractures | 1.0, 0.06, 0.5         |
| Permeability of hydraulic fractures, matrix and natural fractures, mD | 0.1, 0.001, 0.01 |
| Temperature of the reservoir, K             | 353.17                 |
| Density of matrix, kg/m³                    | 2790                   |
| Radius of the well, m                       | 0.11                   |

This model consists of three flow systems, which are hydraulic fractures system adapting non-Darcy flow, natural fractures system and matrix system adapting with Darcy flow. The drop of pressure in double logarithmic coordinate is shown in Figure 2.

![Figure 2](image2)
According to the characteristics of pressure drop, the process of flow can be divided into three sections (Figure 3). In the fracture flow section, the production of fluid mainly comes from the fluid stored in the fracture system, where the flow is the non-Darcy flow. In the interaction flow section, the flow into the fractures from matrix. In the total system flow section, the flow between matrix and two kinds of fractures is stable, and the pressure of systems of the fracture and matrix decrease synchronously.

4. The influence of length of hydraulic fracture on flow

The production simulation for different length of hydraulic fracture is carried out. The model is shown in Figure 4 and the effect on flow is shown in Figure 5.
Figure 6. Pressure drop and derivative of pressure drop.

The pressure drop and derivative of pressure drop are shown in Figure 6. According to Figure 6, it can be concluded that the longer the length of the hydraulic fracture, the stronger the fluid supply capacity of the fracture and the slower the pressure drop during the fractures flow section. During the interaction flow section, the later section of overall flow, the matrix has a stronger ability to supply liquid to the fracture and the slower the pressure drop.

5. Conclusion

An hybrid model was developed in the paper to study the flow characteristics of complex fractures after fractures in shale oil reservoirs. According to simulation results, the process of flow can be divided into three sections, which are fracture flow section, interaction flow section and total system flow section. Based on analysis of flow characteristics under different parameters, the length of hydraulic fracture has of vital importance influences on the entire section of flow.

References

[1] Giger, F. M., L. H. Reiss, and A. P. Jourdan. "The reservoir engineering aspects of horizontal drilling." SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1984.
[2] Zeng, Qing-Dong, Jun Yao, and Jianfu Shao. "Numerical study of hydraulic fracture propagation accounting for rock anisotropy." Journal of Petroleum Science and Engineering 160 (2018): 422-432.
[3] Zeng, Qing-Dong, Jun Yao, and Jianfu Shao. "Study of hydraulic fracturing in an anisotropic poroelastic medium via a hybrid EDFM-XFEM approach." Computers and Geotechnics 105 (2019): 51-68.
[4] Hubbert, M. King, and David G. Willis. "Mechanics of hydraulic fracturing." (1972): 239-257.
[5] Memon, Khalil Rehman, et al. "Influence of Cryogenic Liquid Nitrogen on Petro-Physical Characteristics of Mancos Shale: An Experimental Investigation." Energy & Fuels 34.2 (2020): 2160-2168.
[6] Mahesar, Aftab Ahmed, et al. "Morphological and petro physical estimation of eocene tight carbonate formation cracking by cryogenic liquid nitrogen; a case study of Lower Indus basin, Pakistan." Journal of Petroleum Science and Engineering (2020): 107318.
[7] Zhang, Qi. "Hydromechanical modeling of solid deformation and fluid flow in the transversely isotropic fissured rocks." Computers and Geotechnics 128 (2020): 103812.
[8] Liu, Jishan, et al. "Interactions of multiple processes during CBM extraction: a critical review." International Journal of Coal Geology 87.3-4 (2011): 175-189.
[9] Zhang, Lei, et al. "The investigation of permeability calculation using digital core simulation technology." Energies 12.17 (2019): 3273.
[10] Kveldsvik, Vidar, et al. "Alternative approaches for analyses of a 100,000 m 3 rock slide based
on Barton–Bandis shear strength criterion." Landslides 5.2 (2008): 161-176.

[11] Kim, Jihoon, Eric L. Sonnenthal, and Jonny Rutqvist. "Formulation and sequential numerical algorithms of coupled fluid/heat flow and geomechanics for multiple porosity materials." International Journal for Numerical Methods in Engineering 92.5 (2012): 425-456.

[12] Kim, Jihoon, Hamdi A. Tchelepi, and Ruben Juanes. "Stability and convergence of sequential methods for coupled flow and geomechanics: Fixed-stress and fixed-strain splits." Computer Methods in Applied Mechanics and Engineering 200.13-16 (2011): 1591-1606.