Research and Application of Numerical Simulation of Hydraulic Fracturing in Low Permeability Fracture Reservoirs

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Abstract. Based on FuYu formation of DaQing oil field, built the geology, 3D rock mechanics and 3D stress field models with core and logging data, and obtained the properties of any point between wellbores. With the fracturing principle, the actual geometry of the fractures can be calculated, and the asymmetry fractures model can be built, including the length, height, width and the direction of the fractures. With the analysis of production history, the residual oil distribution can be obtained, and the multiple fracturing procedure can be designed. With the guidance of the asymmetric fracture models, the daily increase of production is more than 4 ton.

Keyword: Hydraulic fracturing; Full-length; Ultra-low permeability; DaQing oil field.

1. Introduction
The key issue for the effective development of ultra-low permeability reservoirs is to identify the spatial distribution of artificial fractures after fracturing and to properly match the well networks to build an effective drive system. Hydraulic fracturing technology is one of the most important and basic process measures to improve single well production.

Therefore, it is of great significance to accurately describe the geometry of cracks generated by hydraulic fracturing. Since the 1950s, scholars at home and abroad have developed various models to describe the geometry and extension laws of pressure cracks. In 1955, Khristianovich et al. proposed the KGD model. The PKN model established by Perkin et al. in 1961 is a two-dimensional model. Cleary improved KGD and PKN and built a pseudo-three-dimensional model. Clifton et al. derived the governing equations for the crack morphology of the full three-dimensional model. Bouteca has established a practical full 3D fracture morphology prediction model in the laboratory. In 1996, Sun Juchen and others carried out a full three-dimensional hydraulic fracturing program design based on the vertical extension of hydraulic fracturing cracks, and developed a full three-dimensional hydraulic fracturing software. The application of the full three-dimensional fracturing simulation program provides tools for crack extension control and fracture conductivity control. On the basis of the full three-dimensional fracturing simulator, domestic and foreign scholars in the hydraulic fracturing simulation assume that the ground stress and rock mechanics parameters near the two wings and the wellbore are homogeneous, and the simulation results are all semi-slit. The actual geological body is...
obvious. The heterogeneity, therefore, the use of full seam length to describe the crack generated by hydraulic fracturing is more realistic.

In this study, a numerical model of anisotropic mesh nodes closely related to fracturing at any point in the three-dimensional space of the geological body is considered. The three-dimensional numerical simulation of the full-seam length of the artificial fracture is carried out to quantitatively calculate the actual occurrence of the crack outside the well point. The ground characterizes the distribution of underground cracks.

2. Full-seam long fracturing numerical simulation basis

2.1. Rock mechanics model
The mechanical properties of rock refer to the performance of rock against external forces, including the deformation characteristics and strength of rock. Rock mechanics properties are generally characterized by rock mechanics parameters (Poisson's ratio, Young's modulus, compressive strength, etc.). The Young's modulus is a sign of the elastic deformation of the rock, and the Poisson's ratio is the ratio of the lateral relative compression of the rock to the longitudinal relative elongation. Due to the different mechanical properties of different rocks, the geometry of the cracks is significantly different under the same construction conditions. Therefore, it is necessary to study the spatial shape of the cracks.

At present, the researches on rock mechanics parameters at home and abroad mainly include: laboratory simulation of rock in the underground environment, determination of static rock mechanics parameters; use of logging curves for back calculation, determination of dynamic parameters. In the case of array acoustic logging data, the rock mechanics parameters of the formation can be calculated from the longitudinal and transverse wave time differences as well as the lithology and density. However, due to the high cost of such special logging, it is difficult to carry out on a large scale. Therefore, this study carried out core-scale array acoustic logging, established the relationship between array acoustic logging response, conventional logging response and rock mechanics parameters, and then obtained regional empirical formula through correlation analysis and multiple regression, using conventional logging calculation. The rock mechanics parameters, and the three-dimensional rock mechanics model under the constraints of wellbore parameters, reservoir space and physical anisotropy model, solve the problem that the previous fracturing uses only single well logging data, and the rock mechanics field changes outside the wellbore cannot be obtained.

![Figure 1. Analysis of 3D Model of Rock Mechanics](image)

2.2. Three-dimensional stress model
The ground stress associated with the reservoir is mainly composed of the coupling of gravity stress, tectonic stress, pore pressure and thermal stress. Traditional methods of field stress research are generally divided into four categories: mine stress measurement, qualitative analysis using geological and seismic data, core measurement, and geostress calculation. These traditional geostress research methods cannot obtain a heterogeneous stress field model with spatially continuous changes, which
limits the real simulation of underground artificial fracture morphology. Based on the established three-dimensional rock mechanics model as a constraint, based on the stress calculation formula, the gravity stress, tectonic stress, pore pressure and thermal stress of each node in the three-dimensional space are superimposed by coupling vector to obtain heterogeneous orientation. Any mass point stress in the three-dimensional space of the heterogeneous reservoir, thus establishing a three-dimensional stress field mesh model. The total stress calculation formula is as follows:

\[
P_c = \frac{\nu}{(1-\nu)} \left[ D_{tt} \gamma_{ob} - \alpha_v \left( D_{tv} \gamma_p + P_{off} \right) \right] + \alpha_h \left( D_{tv} \gamma_p + P_{off} \right) + \varepsilon_x E + \sigma_t
\]

PC represents the total stress (MPa), \(\nu\) represents the Poisson's ratio, \(D_{tt}\) represents the vertical depth (m), \(\gamma_{ob}\) represents the stress gradient of the overburden (MPa/m), \(\gamma_p\) represents the pore pressure gradient (MPa/m), \(\alpha_v\) represents the vertical To Biot's constant, \(\alpha_h\) represents the horizontal Biot's constant, \(P_{off}\) represents the compensated pore pressure (MPa), \(\varepsilon_x\) represents the horizontal strain, \(E\) represents the Young's modulus (104 MPa), and \(\sigma_t\) represents the horizontal tectonic stress (MPa).

3. Full-slit 3D fracturing dynamic numerical simulation implementation process

Fracturing numerical simulation of the fracturing design and post-pressure evaluation at home and abroad is based on the wellbore data and cannot obtain the parameters of the well. The low-permeability reservoirs in the underground are highly heterogeneous. If the construction design does not match the geological characteristics, the actual distribution of the cracks after fracture will be unclear. Therefore, the calculation of crack parameters by semi-seam length simulation is very different from the distribution pattern of underground actual cracks, which directly affects the formulation of development technology policies and the development of reservoirs.

Based on the theory of rock failure and the theory of full three-dimensional fracture numerical simulation, this paper combines the reservoir geological model with the three-dimensional rock mechanics parameter model and the stress field model to carry out three-dimensional numerical simulation of the full length of the artificial fracture and quantitatively calculate the actual crack outside the well point. Occurrence.

**Figure 2.** Dynamic numerical simulation of full seam long three-dimensional fracturing

The fracturing software developed in this study was developed by STIM-LAB, USA, and is equipped with a comprehensive database of fracturing fluids and proppants. The software considers multi-dimensional fluid flow and proppant transport conditions simultaneously, using grid structure calculation method, based on rock mechanics data, using the full three-dimensional crack propagation
model to predict the fracture crack geometry under various formation conditions, the obtained crack profile is more realistic.

In hydraulic fracturing, the crack extends simultaneously in three directions of length, height and width. In this study, a three-dimensional crack model is used to simulate the assumption that the crack is a plane joint, and the crack maintains a plane during the extension process; the rock anisotropy, the formation is linear elastic and layered; and the non-Newtonian power law flow equation is satisfied. The calculation model for establishing the three-dimensional extension according to the linear elastic fracture theory and fluid mechanics is as follows.

1) Continuity equation: According to the principle of material balance, there is

\[
\frac{\partial q}{\partial x} + \frac{2CH}{\sqrt{t-\tau}} + \frac{\partial A}{\partial t} = 0
\]

2) Pressure drop equation: The pressure gradient of the fracturing fluid flowing along the length of the slit is

\[
\frac{dp}{dx} = -\frac{16}{3\pi} C \left( \frac{2n+1}{2n} \right)^n q^n \frac{x^n}{h^w w^{n+1}}
\]

3) Crack opening width:

\[
W = \frac{2(1-\nu)ph}{E} \left[ 1 - \frac{2\sigma_2 - \sigma_1}{\pi pf_1} \left( \arccos \frac{1 + \sqrt{1-f_1^2}}{f_1} \right) \right]
\]

4) Crack extension height: For linear elastic fractures, the extension criterion can be derived:

\[
\frac{dh}{dx} = -h / \left[ \frac{Kc}{\sqrt{2\pi h}} \frac{2f_1 \sigma_2 - \sigma_1}{\pi \sqrt{1-h_{ij}^2}} \right] \frac{dp}{dx}
\]

Where A represents the fracture cross-sectional area (m²) perpendicular to the length of the crack, C represents the fracturing fluid comprehensive fluid loss coefficient (m/min 1/2), p represents the net pressure (MPa), and W represents the fracture crack width (m), x is the crack length (m), h is the fracture crack height (m), H is the effective thickness of the pay zone (m), n is the fracturing fluid flow index (negative number), and K is the fracturing fluid consistency coefficient (MPa · sn), Kc represents the rock fracture toughness value (MPa), f1 represents the number of non-causes (f1 = H/h), q represents the fracturing fluid flow rate within the fracture (m³/min), and \( \sigma_1 \) represents the minimum horizontal principal stress of the pay zone (MPa), \( \sigma_2 \) represents the minimum horizontal principal stress (MPa) of the occlusion layer, t represents the construction time (min), \( \tau \) represents the time in which the crack length is exposed to the fracturing fluid (min), \( \nu \) represents the rock Poisson's ratio, and E represents the Yang model. the amount.

The fracturing crack extension process is controlled by the above equations, and the equations are solved by the fourth-order Runge-Kutta method.

4. Application examples and effect analysis

4.1. Geological characteristics of a block

A block is located in a anticline wing, controlling oil area of 2.43km², original formation pressure of 11.11MPa, saturation pressure of 7.43MPa, air permeability of 3.6×10⁻³ μm². In 1992, 300m×300m anti-nine-point area well network was put into development, with 21 base oil wells and 6 basic wells. In 2004, it was encrypted by "triangular center of gravity encryption, water well row offset 106 meters", 33 oil wells were encrypted, and 12 injection and production systems were adjusted.

The sedimentary environment of the Fuyu oil layer in this area is the facies sedimentation. The rock composition is unequal-grain hybrid elastic hard feldspar sandstone. The median particle size is between...
0.097 and 0.118 mm, the quartz in the debris accounts for 30.0%, and the feldspar accounts for 34.0%. Cuttings accounted for 25.0%. The sandstone is mainly composed of mud cement, and the mud content is 12.91% to 16.25%. The average effective porosity of the reservoir is 15.0%, the average air permeability is $3.56 \times 10^{-3} \mu m^2$, and the oil saturation is 49.0%.

Figure 3. Full three-dimensional numerical simulation of oil well cracks

4.2. Full three-dimensional numerical simulation of cracks in B-well
The rock mechanics properties and geostress are important factors influencing and controlling the shape of hydraulic fracturing artificial fractures. In this study, the rock mechanics and stress parameters at any point in the stratum are studied, and the three-dimensional rock mechanics field and stress field model are established by combining the actual field data. The three-dimensional numerical simulation of the full-slit length of the hydraulic fracturing is carried out, and the geometrical distribution of the fracture is finally obtained.

The data obtained by multi-pole array sonic logging can directly extract the longitudinal, shear and Stoneley slowness parameters in soft and hard formations. In this study, oil wells with multipole subarray sonic logging data are selected to establish conventional logging. The correlation between data characteristics and rock mechanics characteristics. After correction, correlation analysis and multiple linear regression analysis are performed, and the correlation between conventional logging data and special logging data is obtained. The rock mechanics parameters such as continuous Poisson's ratio and Young's modulus in the wellbore are obtained, and the parameters and storage in the wellbore are obtained. A three-dimensional rock mechanics model is constructed under the constraint of layer space and physical anisotropy model. Based on the established three-dimensional rock mechanics model, the stress value of each grid node is obtained according to formula (1). Figure 1 is the full three-dimensional numerical simulation result of the pressure crack. It can be seen that both the horizontal and vertical directions have obvious non-Homogenization. Under the same conditions of fracturing construction, the larger the Young's modulus value, the less easily the rock is deformed. The larger the rock Poisson's ratio, the smaller the elasticity and the more plastic, the more easily the rock breaks or fracturing.

Figure 4. Numerical simulation of crack propagation in hydraulic fracturing of Turning B well
Figure 5. Shows the production curve of the B well

4.3. Implementation effect
Taking the F-B well fracturing simulation results and field application as an example, the target interval is the 131 layer. The well has undergone the first hydraulic fracturing since it was put into production on January 12, 1995. The initial daily production liquid is 2.89 m$^3$, the water content is 7.3%, and the hydrodynamic surface depth is 719 m. After several years of production, the formation energy gradually decays. Two repeated fracturings were performed in 2001 and 2007 respectively. After the second fracturing, there is an increase in production. After the third fracturing, high water cut occurred and the water content quickly reached 100%. In November 2009, in the upper part of the perforating section, the numerical simulation study of the full-seam long-fracture shows that the upper part of the third section of the well has not been pressed for a long time. It is proposed to block the third layer of the perforated section (see Figure 1) and close the upper layer of the third layer. The programme was implemented in September 2011. Since the re-fracturing, the oil production capacity has been restored, and the daily oil production has risen to 3.79 t, and stable production has been maintained (Fig. 2).

5. Conclusion
In this study, we consider the heterogeneous mechanical parameters and the stress value grid joint numerical model which are closely related to fracturing at any point in the three-dimensional space of the geological body. The vertical section calculation is carried out by combining the porosity and permeability, and the full length of the artificial crack is three-dimensional. Numerical simulations are used to quantitatively calculate the distribution of cracks outside the well point. It is verified by the field field that it is close to the actual occurrence of artificial cracks in underground heterogeneous oil and gas reservoirs. The research results have a certain guiding significance for identifying the underground geometry of single well pressure cracks in ultra-low permeability oilfields and proposing single well reconstruction measures.

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