The application of numerical simulation coupled flow and geomechanics in the study of geology-engineering integration

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Abstract. The low-permeability reservoir is mainly featured by small reservoir pore, tight, fine throat, high filtration resistance, and low oil productivity. After several years of working to recover hydrocarbons from these reservoirs effectively, it has been proven that creating complex fracture networks by multi-stage fracturing is one of the most efficient ways to enhance production. However, several factors affect the development of the complex fracture networks, and the in-situ stress is the most significant one. Low in-situ stress anisotropy \cite{1} increases the possibility of creating complex fracture networks with hydraulic fracturing. In order to compensate for the in-situ stress anisotropy, based on the application of a numerical model coupled flow and geomechanics, this research analyzes the variation of in-situ stress and suggests arranging a sequence of horizontal well deployment. In addition, the research predicts the dynamic productivity coupled flow and geomechanics. From the results, this research concludes the dynamic change regularity of in-situ stress and the impact of difference well deployment, which is beneficial to optimize horizontal well deployment and fracturing design \cite{2}.

1. Introduction

Conventional numerical simulation technology is adopted to simulate multi-stage fracturing in horizontal wells, which considers many factors such as the heterogeneity of geological conditions, the fractures simulation with differential grids, and the artificial fracture parameters obtained by historical data fitting. The problem with this technique is that the impact of geomechanics on hydraulic fracturing and post-fracturing production cannot be calculated. As the stress field is unstable and varies, the initiation and expansion of hydraulic fractures and their geometric morphology are mainly affected by the distribution regularities of stress. The accurate description of stress is necessary for the development of tight oil and gas fields. In the actual seepage process, the stress in porous media varies with the pore fluid pressure, thus lead to the change of permeability and porosity, and the changes in turn influence the distribution of the pore fluid pressure, therefore and seepage field coupling effect should be considered in the porous medium stress field. In this paper, based on finite element technique, combined with the distribution regularities of stress field, rock mechanical parameters, reservoir properties, pressure, temperature and other characteristics, the three-dimensional seepage stress coupling model was established \cite{3}. Seepage and can be calculated by the finite element
method. As a result, the variation of stress caused by exploitation and production can be calculated quantitatively.

2. Numerical simulation coupled flow and geomechanics

When the conventional numerical simulation technique is used to simulate the multi-stage fracturing of horizontal wells, as the traditional method cannot consider the influence of geomechanics on the hydraulic fracturing process, the traditional method simulates the process of fracture propagation inaccurately. It is not feasible to use the traditional method to optimize the fracturing design. There are many limitations exist in the traditional numerical simulation method.

Numerical simulation coupled flow and geomechanics is one of the new direction of numerical simulation technology development. Different from conventional numerical simulation, new model is composed of geostress model and geologic model with the application of REVEAL numerical simulation software developed by Petroleum Experts Company. The most important feature of this simulator is that it can simulate the propagation process of artificial fractures by considering petrophysical and geostresses, and the dynamic finite element grid is used to characterize the dynamic artificial fractures. The basic principles have been published in the relevant literature.

The volume variation of formation rock leads to the change of in-situ stress. Changes in the following physical aspects are included in the simulator to calculate the stress changes inside the reservoir. First of all, the rock poto-elastic coefficient relates the increase in the rock stress with an increase in fluid pressure. Second, the rock thermos-elastic coefficient relates an increase in the rock stress with the increase in fluid temperature. At last, additional terms such as rock movement may also be included in the calculation of stress [4].

The stress distribution underground is calculated by a displacement potential formulation about the pressure and temperature as follows:

$$\nabla^2 x = -\left(1 + \nu\right) \frac{E}{E} \left(A_P \Delta P + A_T \Delta T\right)$$

$$\sigma_{yy} = \sigma_{\text{in situ}} - \frac{E}{(1 + \nu)} \left(A_P \Delta P - A_T \Delta T\right)$$

$AP=$Poro-elastic coefficient, psi/psi
$T=$Temperature,°F
$E=$Young’s modulus, psi
$AT=$Thermo-elastic coefficient, psi/F
$\sigma=$Principal total stress, psi

Where the AP and AT coefficients are calculated from Biot’s coefficient and the coefficient of linear thermal expansion.

$$A_P = \left(1 - \frac{c_g}{c_b}\right) \frac{\left(1 - 2\nu\right)}{\left(1 - \nu\right)}$$

$$A_T = \alpha_T \frac{E}{(1 - \nu)}$$

$cg=$Grain compressibility, psi-1
$\nu=$Poisson’s ratio
$\alpha_T=$Coefficient of linear thermal expansion,F-1

3. The application of numerical simulation coupled flow and geomechanics

The new numerical simulation calculations for stress, predicting flow rates and oil saturations are performed using standard principles of reservoir simulation in REVEAL [5]. Moreover, the geomechanics model allows the calculation of directional stress inside the reservoir grid. This allows further application such as :1) Stress related fracturing changes, 2) Dynamic productivity prediction, 3) Horizontal well deployment.
3.1. Stress related fracturing changes

For conventional numerical simulation technique, it is difficult to simulate the stress variation induced by the interaction of the previous fractures with analytical solutions. Therefore, numerical simulation coupled flow and geomechanics is needed to predict the stress contrasts and optimize the fracture stages. Based on the three-dimensional geological model and the mathematical model of stress, take geology, rock mechanics and characteristics of fracture into consideration to simulate the changes of rock physical properties and stress after treatment. Meanwhile, combined with the actual field fracturing data, dynamic finite element mesh [6] [7] was used to characterize the three-dimensional initiation of fractures, to develop a more nuanced understanding of the fracture parameters and variation of in-situ stress field during the treatment. In the simulation process of fracturing, the propagation of artificial fractures is closely combined with wellbore and formation, and the finite element mesh representing fractures is dynamically coupled with the mesh representing strata. Fractures initiated in one lateral at each step is comprehensively calculated by material balance equation, rock physical balance equation and fracture propagation equation.

The geostress field is an unstable field that varies with space and time [8]. Based on the integrated numerical model and the dynamic simulation of production, the characteristics of stress field during the treatment and the production are described, the variation of in-situ stress are predicted accurately.

Take M tight reservoir as an example. The reservoir with the low original dissolved gas-oil ratio is a lithological-structural reservoir, with porosity varies from 0.5% to 12.5% and permeability in the range of 0.011 to 102 md, which belongs to ultra-low porosity, ultra-low permeability reservoir. The maximum horizontal stress direction is nearly east-west, the maximum horizontal stress of the main target layer is 65 ~ 80Mpa, and the minimum horizontal stress is 45 ~ 60Mpa.

![Figure 1](image1.png)

Figure 1. Variation curves of formation pressure and minimum horizontal stress.

![Figure 2](image2.png)

Figure 2. Comparison of stress field changes in the target layer.
Since September 2013, 7 horizontal wells have been deployed in this area for fracturing. According to the simulation results of M reservoir, the formation pressure and minimum horizontal stress rise rapidly with the injection of fracturing fluid, and gradually decrease at the early stage of well opening and then reaches stability (Figure 1). The stress diffusion radius is about 200m, and the stress near the wellbore changed greatly. Because of different injection and production volume, the variation of minimum horizontal stress around each well is different. The minimum horizontal stress around wells with low injection volume and high production volume decreased significantly, from the initial minimum horizontal stress of 52 ~ 47MPa, which decreased by about 5MPa (Figure 2).

3.2. Dynamic productivity prediction

In the preliminary stage of production [9], because of the high pressure gradient of reservoir, the oil and gas production is high. With the increase of production time, the pressure gradient becomes lower, the pressure in the reservoir gradually decreases, which lead to decrease of production rate. Compared with the non-coupling rigid model, the porosity and permeability of the reservoir decrease in the model coupled flow and geomechanics. On the basis of traditional seepage theory, considering the influence of stress field on fluid flow in pores, as well as the impact on porosity and permeability, a mathematical model coupled flow and geomechanics was established. For unconventional reservoirs, the grid direction should be carefully considered with the direction of crack, and the mesh accuracy needs to meet the requirements of fine simulation of cracks. Meshing size along the horizontal well trajectory direction matches the fractures spacing, and the mesh vertical horizontal well trajectory direction is appropriate to describe the reservoir heterogeneity. The consolidation and division of vertical mesh should fully consider the vertical distribution characteristics of the reservoir, and usually adopt the unequal mesh division to refine the main target layer as much as possible.

Based on the integrated numerical model, the pressure, water cut and daily production indexes of the fractured well are fitted [10]. Many types of parameters including geological parameters, stress parameters, petrophysical parameters, fracture parameters, fluid parameters are needed to be considered in order to avoid the randomness of parameters. Sensitivity analysis of parameters is needed to master the sensitivity of various parameters. Production history fitting is a process of modifying, make the model closer to the actual reservoir conditions, which improve the reliability of the model prediction results greatly.

![Figure 3. Production forecast of well 1.](image-url)
Table 1. Fracture parameters of M black.

| Black | Well | Layer | Cluster | Length (m) | Height (m) | Width (cm) | Fracture conductivity (md.m) |
|-------|------|-------|---------|------------|------------|------------|-----------------------------|
| M     | 1    | T₁₁₂₂  | 41      | 77-143     | 35-41      | 0.4-0.65   | 160-318                     |
|       | 2    | T₁₁₂₂  | 40      | 96-124     | 39-43      | 0.35-0.6   | 175-347                     |
|       | 3    | T₁₁₂₂  | 37      | 102-145    | 36-49      | 0.41-0.64  | 162-349                     |
|       | 4    | T₁₁₂₂  | 37      | 109-145    | 36-49      | 0.36-0.67  | 169-367                     |
|       | 5    | T₁₁₂₂  | 78      | 83-150     | 36-42      | 0.29-0.63  | 142-327                     |
|       | 6    | T₁₁₂₂  | 66      | 108-147    | 36-43      | 0.34-0.62  | 139-316                     |
|       | 7    | T₁₁₂₂  | 12      | 75-125     | 36-42      | 0.33-0.61  | 123-308                     |

According to the 3D geological model, 3D stress model and fracture parameters obtained from fracturing simulation in the experimental area (Table 1), an integrated numerical model was established, and numerical simulation coupled flow and geomechanics was adopted to conduct the historical fitting of production. The simulated result is basically consistent with the actual output, reflecting the reliability of reservoir and fracture parameters (Figure 3).

3.3. Horizontal well deployment

Through the numerical simulation coupled flow and geomechanics, the distribution of the in-situ stress field and oil saturation field in the experimental area is intuitively presented, which greatly enhance the rationality of the new well deployment and fracturing design [11][12]. According to the simulation results, the deployment of the new well was carefully designed, aim at reducing the interference of stress between wells and finding the rich areas to enhanced oil recovery. At the same time, different horizontal well trajectory schemes are designed according to the direction of maximum horizontal
stress, and productivity prediction is carried out to optimize the design of horizontal well trajectory. A total of four plans have been designed for the horizontal well trajectory to be at an angle of 20°, 30°, 40° and 50° with the direction of maximum horizontal stress (Figure 4). With different included angles, the number of fractures and fracture angles formed after fracturing are different, which affecting the productivity of horizontal wells greatly.

Figure 5. Comparison of production forecast with different angles.

According to production prediction, while the horizontal well trajectory is at an angle of 40° with the direction of maximum horizontal stress, the productivity is the highest, it is preferred to design the horizontal well trajectory at an angle of 40° (Figure 5).

4. Conclusions
(1) The establishment of the 3D percolation-stress integrated numerical model coupled flow and geomechanics stimulation has been proved to be one of the most effective methods for multi-stage fracturing stimulation in horizontal wells, which consider the influence of geomechanics and post-press production.

(2) Dynamic production simulation calculated the variation of in-situ stress and oil saturation caused by the change of reservoir percolation in the production process of horizontal wells, and describes the distribution of in-situ stress and oil saturation of reservoirs, which is beneficial to optimize horizontal well deployment and fracturing design.

(3) The results presented are specific to the parameters used and cannot be generalized, however, the significant effects of stress and geological are still obvious and it is important to be considered when determining horizontal well placement and performing well productivity calculations in low permeability reservoirs.

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