Finite element analysis of damage region of CBM well based on underbalance reconstruction technology

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Abstract. The reserves of coalbed methane (CBM) in China are very high. But the characteristics of "three low" (low pressure, low permeability, low porosity), thin formation and shallow burial depth for the CBM reservoirs may cause problems of long production cycle and slow increase in production. For above problems, a new reconstruction method for coal bed methane formation named underbalance reconstruction was introduced. By this method, a jet generator was lowered to perforated interval. Then, with the nitrogen injected and blowout, reconstruction results of coalbed reservoir can be achieved. Considered the process of underbalance reconstruction, coalbed reservoir properties and mechanical properties of coalbed, mechanical model of coalbed methane well was built and analyzed by finite element method. Afterwards, damage area of different nitrogen injecting cycle can be characterized. And the effect of underbalance reconstruction for coal bed methane formation can be obtained. Then, parameters of reconstruction technology can be optimized and optimization scheme can be supplied for the underbalance reconstruction for coal bed methane formation.

1. Introduction

In recent years, natural environmental stress increases with the rapid development of economy. As an efficient clean energy and an unconventional resource with high interest (Supartono 2013, Shan et al 2005), development of coalbed methane (CBM) receives more and more attention. Commonly, hydraulic fracturing is the main technical mean for the development of coalbed methane (Shan et al 2005, Wu et al 2006, Luo et al 2008, Chen 2008). By hydraulic fracturing method, the connectivity between cleats and well can be improved. And the gas channel and flow conductivity in gas channel can be improved at the same time. Then, the pressure of CBM producing layer is released. And the pressure of gas in the producing layer is reduced at the same time. After that, CBM adsorbed in reservoir becomes free state and flows into wellbore through the gas channel that has been improved by hydraulic fracturing. The aim of increasing production of CBM well can be achieved finally. However, in CBM reservoir, there are characteristics of cleats development, shallow burial depth, low temperature and et al. These characteristics may cause many problems in process of hydraulic fracturing. The flowing time of fracturing fluid in wellbore is short. And this leads to the short crosslinking time of crosslinked fracturing fluid and linear gel fluid in wellbore. The activity of tackifier in fracturing fluid may be low. Gel breaking incompletely, filter cake and residue of fracturing fluid would produce formation contamination. In order to avoid the above problems in the process of fracturing, from the perspective...
of underbalanced drilling and using the principle of underbalanced drilling (Xian et al 2008, Ma et al 2000, Salehi et al 2010, Zhao et al 2001), a new reconstruction method named underbalance reconstruction was used to reconstruct CBM formation. After drilling and completion, a jet generator was lowered to slotted screen located in perforated interval. Then, five cycles of nitrogen injection were performed. Based on the constitutive model of coalbed, mechanical parameters of coalbed and pump injection parameters, the stress state and ranges of plastic zones around wellbore under five cycles of nitrogen injection can be analyzed. Thus, the effect of underbalanced reconstruction can be demonstrated. According to the analysis results, optimization scheme can be provided for underbalanced reconstruction while applied on site operation.

2. Damage characteristics of coalbed surrounding CBM well

The drilling of borehole will disturb the initial in-situ stress field and redistribute the stress distribution of coalbed surrounding CBM well. And at the same time, there is stress concentration of far field stress on the borehole wall coalbed that can cause the deformation damage or even failure of the coalbed around the wellbore.

There are a large number of joints and fractures in the coalbed mass around the wellbore, which are potential damage development sources. The strength of the weak joint surface is far less than the tensile strength of the coalbed. Due to the influence of high in-situ stress and drilling construction, when the coalbed itself does not break, it can only cause the fracture of the weak joint and crack, and the fracture length of these weak surfaces is very short without connection.

In the damage range of coalbed surrounding coalbed, the damage does not mean the deterioration of the coalbed mass caused by single fracture growth, but refers to a coalbed mass environment formed by a large number of fracture growth that complies with the statistical law. There is a regional characteristic for the damage coalbed surrounding coalbed. And with only a few fractures, this regional characteristic cannot be produced. The generation of these fractures is caused by the original defects or weak plane with fracture initiation and propagation due to the action of the in-situ stress. When the number of such fractures in the coalbed mass reaches a certain extent, the properties of coalbed mass will change obviously. Thus, the surrounding coalbed failure damage zone is formed.

Bui elastoplastic damage constitutive model can be used to analyze the damage in the coalbed mass around the wellbore. In the one-dimensional case, the damage evolution equation is given as follows:

\[ D = 0 \quad (\varepsilon \leq \varepsilon_a) \]  
\[ D = \frac{\lambda}{E} \left( \frac{\varepsilon}{\varepsilon_a} \right) \quad (\varepsilon \geq \varepsilon_a) \]  

where $\lambda$ is reduced modulus, $E$ is elasticity modulus, $\varepsilon$ is the strain and $\varepsilon_a$ is the strain under the condition of peak strength. In the triaxial case, let the principal strain be $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$, and equivalent strain can be given as follows:

\[ \varepsilon = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_a)^2 + (\varepsilon_2 - \varepsilon_a)^2 + (\varepsilon_3 - \varepsilon_a)^2}. \]  

Replace the strain of $\varepsilon$ in one-dimensional case with the equivalent strain of and the damage evolution equation in triaxial case can be obtained as follows:

\[ D = \frac{\lambda}{E} \left( \frac{\varepsilon}{\varepsilon_a} - 1 \right). \]  

By the damage evolution equation of coalbed surrounded wellbore, the stress near wellbore formation can be calculated and the stress distribution can be obtained thereby.
3. Probability statistics of mechanical properties of coalbed

Before the numerical simulation of coalbed damage in the near wellbore area by using the damage model, probability statistics of mechanical properties of coalbed surrounded wellbore were carried out based on logging and mechanical test data of CBM Wells in block W of China, as shown in table 1. And the probability distribution and the fitting curve correspondingly for coalbed surrounded wellbore can be shown in Figures 1-4.

Table 1 Statistics of coalbed mechanical parameters of W block in China

| Parameters                        | Elasticity modulus/GPa | Poisson’s ratio  | Tensile strength/MPa | Shear strength/MPa |
|-----------------------------------|------------------------|------------------|----------------------|--------------------|
| Minimum                           | 0.241                  | 0.162            | 0.054                | 0.065              |
| Maximum                           | 5.703                  | 0.431            | 0.651                | 0.693              |
| Average                           | 2.981                  | 0.292            | 0.361                | 0.354              |
| Standard deviation                | 1.126                  | 0.063            | 0.142                | 0.147              |
| The lower limit of 95%            | 2.751                  | 0.276            | 0.312                | 0.309              |
| confidence interval for the mean  |                        |                  |                      |                    |
| The upper limit of 95%            | 3.202                  | 0.303            | 0.411                | 0.398              |
| confidence interval for the mean  |                        |                  |                      |                    |
| Coefficient of variation          | 0.379                  | 0.218            | 0.392                | 0.415              |
4. Analysis of stress damage zone of coalbed surrounded wellbore under unbalanced transformation

Based on the principle of underbalanced drilling (Xian et al 2008, Ma et al 2000, Salehi et al 2010, Zhao et al 2001), after the completion of CBM drilling, slotted screen with certain specifications is lowered to perforated interval. Then, nitrogen is injected with certain pump injection pressure. And coalbed surrounded wellbore is damaged. After that, the CBM is discharged and there is an underbalanced environment for coalbed surrounded wellbore. And exfoliated pulverized coal particles in the damage zone flows into wellbore through screens and goes upwards with air current recirculation at last. So far, the first cycle of unbalanced transformation has been finished. After five cycles of unbalanced transformation, the transformation of CBM formation will be achieved finally. For the damage of coalbed surrounded wellbore, a finite element model with parameters: wellbore diameter with 0.1524m, screen fractured width with 12mm, number of circumference screens with 6, density of coalbed with 1400kg/m³, shear strength of coalbed with 2.6MPa and pump injection pressure with 14MPa is built up. Take five cycles of unbalanced transformation and colored stress patterns applied to analyze the radial extension of the damage of coalbed surrounded wellbore can be obtained as follows:
As the shear strength of 2.6 MPa and the pump injection pressure of 14MPa, the relationship of shear stress and the distance from damage zone edge to the axle center of wellbore with five cycles of injection can be obtained in Figure 6. As shown in Figure 6, the stress decreases with the increase of distance in the single injection process. Around the wellbore, the stress of the next injection is less than that of the last injection. But the action region of the next pump injection pressure is wider than condition of the last pump injection pressure.
Figure 6. Relationship between axial radius and shear stress with 5 injection cycles

As shown in Figure 7, as the shear strength of 2.6 MPa and after the first injection, damage region with the radius of 18cm was formed. After the second injection, the radius of the damage region increased 8cm. And the radius of the damage region increased 6cm further after third injection. The radius of the damage region increased 5cm after the fourth injection and 5cm after the final injection. Increase the injection pressure to 16.3 MPa, 18.6 MPa and 21 MPa correspondingly, the extension of the damage region can be seen Figure 7. And The extension of the damage region through the whole process of injection conforms to exponential decay law. The fitting formula can be seen in Table 2.

Table 2. Fitting formula of axial radius of the damage region under different pump injection pressure

| Pump injection pressure | Fitting formula | Correlation coefficients | Reduced Chi-Sqr |
|-------------------------|----------------|--------------------------|----------------|
| 14MPa                   | $R = -55.81572 \times \exp(-p/5.67629) + 64.93243$ | 0.99923 | 0.13596 |
| 16.3MPa                 | $R = -60.34962 \times \exp(-p/5.12622) + 68.70652$ | 0.99992 | 0.019 |
| 18.6MPa                 | $R = -61.85799 \times \exp(-p/4.91001) + 73.38633$ | 0.99981 | 0.04705 |
| 21MPa                   | $R = -56.5705 \times \exp(-p/2.37077) + 61.39579$ | 0.99959 | 0.11906 |

Under five cycles of pump injection, the damage region increases during five cycles of pump injection. And the increasing degree conforms to exponential attenuation law. The total axial radius of the damage region increases with the increasing of pump injection pressure. And the degree of attenuation increases with the increasing of pump injection pressure.

5. Conclusions

(1) Based on the principle of underbalance reconstruction, properties of coalbed reservoir and damage characteristics of coalbed surrounding CBM well, a finite element model was built to analyze the extension of the damage region for the CBM well.

(2) With the increasing of pump injection pressure, the damage region was enlarged. And the enlarged degree conforms to exponential attenuation law.

(3) As the effect of pump injection pressure on the damage region, the underbalance reconstruction technology can be optimized to maximize CBM well productivity.
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