Study on Effect of Rock Interface on Hydraulic Fracture in W9 Offshore Gas Field

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Abstract. In-situ principal stresses in ZH formation of W9 offshore gas field are measured by Kaiser effect method, and the horizontal minimum stress profile is interpreted by logging information. Static Young's modulus and Poisson's ratio of rock are measured by tri-axial loading experimental system, and cohesion and internal friction angle of rock are calculated by empirical formula based on logging data. Failure mode discrimination equation of hydraulic fracture at the rock interface is established applying stress analysis of hydraulic fracture tips at rock interface combined with tensile failure criterion and shear failure criterion. In-situ stresses and strength parameters in ZH formation are used to calculate and analyze the control effect of interface on hydraulic fracture propagation. The calculation results show it is necessary to control fracture height growth in ZH formation of W9 offshore gas field, which is of great significance on guiding the optimization of fracturing parameters in this field.

1. Introduction

Hydraulic fracturing is essential for economic development of low permeability reservoir. Offshore hydraulic fracturing practices in Bohai Sea and East China Sea have significantly increased oil and gas production [1-3]. The results of field evaluations have proven that production after fracturing is lower with too high fracture height. So, it is necessary to control such height growth to prevent fracture penetration into undesirable zones. Usually, low viscosity of fracturing fluid and low pump injection rate can effectively reduce height extension of hydraulic fractures[4]. Nguyen[5] put forward “an artificial barrier” technique to prevent fracture height growth in hydraulic fracturing, that is, an artificial barrier at crack tip was created by injecting a heavier/lighter non-reaction diverter into fracture. Barree[6], Mack[7], Garcia[8] explored design guidelines for artificial barrier placement and reasonable pumping procedures for hydraulic fracturing with an artificial barrier controlling fracture height. Hu Yongquan[9,10] carried out an experimental study on the characterization of artificial interlayer and its influence on fracture height growth, and main controlling factors of fracture height propagation were determined on basis of theoretical simulation.

It has been realized that whether hydraulic fracture crosses rock interface depends on material properties and stress load. Warpiniski[11] discussed the effect of in-situ stress on crack height propagation in hydraulic fracturing. Ben-Naceur[12] investigated the influence of mechanical properties(elastic modulus and Poisson's ratio) differences in multi-layer media on fracture height growth, established mechanical criteria about fractures tip passing through the interface for controlling the height of cracks in multi-layer media. Danishy[13] pointed out that the shear strength of interface
also plays an important role. Warpinski & Clark[14] studied the influence of vertical stress contrast on fracture height extension, but its experimental stress condition is different from that in W9 field, so it cannot be directly used in hydraulic fracturing design.

ZH low-permeability gas formation in W9 offshore block, whose buried (vertical) depth is nearly 4000m, has been selected as a potential candidate for hydraulic fracturing stimulation. Considering its bottom water layer, it is necessary to control fracture height communication with water layer. Therefore, it is very important to research the control effect of the payzone-barrier interface on hydraulic fracture height growth.

2. In-situ Stress and Rock Mechanics Properties

2.1. In-situ Stress Analysis

In this research, acoustic emission Kaiser Effect experiment is chosen to measure in-situ stress of ZH formation, and in-situ stress profile is obtained by logging data interpretation.

(1) Kaiser effect experiment

Experimental core: Ф25×50mm core from the target layer

Firstly, the principal stress direction was tested by wave velocity anisotropy by acoustic emission instrument ultrasonic probe and digital oscilloscope. Experiment curve is displayed in Figure 1.

![Figure 1. Test results of wave velocity anisotropy](image1)

Then, Kaiser effect test was completed at principal stress direction by MTS (Material Test System) electro-hydraulic servo system and Locan AT-14ch acoustic emission instrument. The test curve is shown in Figure 2. The maximum and minimum horizontal principal stress gradients are 18.6KPa/m and 15.6KPa/m.

(2) in-situ stress profile

The vertical component of in-situ stress can be calculated by density logging data, and the horizontal in-situ stress[15] can be calculated by Terzaghi model, Anderson model, Newberry model, Huang’s model and combined spring mode. Selecting a best in-situ stress calculation model, then the in-situ stress distribution at ZH zone of W9 offshore gas field is obtained by the logging data of Well A, and stress profile is demonstrated in Figure 3.

![Figure 3. Rock strength parameter profile](image3)

![Figure 4. Stress-strain curves of triaxial compression tests](image4)
The principal stress of this formation from logging data interpretation is demonstrated in Fig. 3. The vertical stress gradient is 24.2 kPa/m, the horizontal maximum stress gradient is 16.76-21.78 kPa/m, and the horizontal minimum principal stress gradient is 13.41-17.42 kPa/m.

2.2. Rock Mechanics Parameters

According to test specifications and methods [16], rock mechanics properties are experimentally tested on φ 25mm×50 mm rock cores from payzone, and it was shown in Figure 4.

Rock cohesion and internal friction angle profile is determined by following empirical formula [17] as well as logging data.

\[
C = A(1 - 2\mu) \left(1 + \mu_d \mu \right) \frac{1}{1 - \mu_d} \rho^2 V_p^4 \left(1 + 0.78V_c \right) \tag{1}
\]

\[
\phi = 36.545 - 0.4952C \tag{2}
\]

Rock mechanics properties from logging data are determined as figure 5, rock cohesion force is 22-25 MPa, the internal friction angle is 30°, and the tensile strength is 5 MPa.

![Figure 5. Profile of rock Cohesion and internal friction Angle](image)

3. Control Effect of Layers Interface on Fracture Height

Assuming that rock is homogeneous, isotropic and linearly elastic. Figure 6 shows the orthogonal schematic diagram of vertical hydraulic fracture and rock stratum interface.

![Figure 6. Schematic diagram of interaction between hydraulic fracture and interface](image)

According to fracture mechanics theory, fracture tip stress in polar coordinates (r,θ) system under the action of far- effective stress field is calculated.
\[
\sigma_x = -\sigma_x' + \sigma_x^c (r, \theta) = -\sigma_x' + \frac{K_l}{\sqrt{r}} \times \cos \left( \frac{\theta}{2} \right) \left( 1 + \sin \left( \frac{\theta}{2} \right) \sin \frac{3\theta}{2} \right) \]  
(3)

\[
\sigma_y = -\sigma_y' + \sigma_y^c (r, \theta) = -\sigma_y' + \frac{K_l}{\sqrt{r}} \times \cos \left( \frac{\theta}{2} \right) \left( 1 - \sin \left( \frac{\theta}{2} \right) \sin \frac{3\theta}{2} \right) \]  
(4)

\[
\tau = \tau' + \tau^c (r, \theta) = \tau' + \frac{K_l}{\sqrt{r}} \times \sin \left( \frac{\theta}{2} \right) \cos \left( \frac{\theta}{2} \right) \cos \frac{3\theta}{2} \]  
(5)

1) When the stress at the end of the fracture reaches the tensile strength of materials on both sides of the interface, the hydraulic fracture crosses the rock interface. That is:
\[
\sigma_x^{(\text{max})} = -T \]  
(6)

2) If shear failure occurs at the fracture interface, the fracture will slip. That is:
\[
\left| \tau^{(\text{max})} \right| \geq C + \mu \sigma_y^{(\text{max})} \]  
(7)

Considering the critical conditions, the following criteria are obtained [18].
\[
\frac{C / \mu + \sigma_y'}{T + \sigma_x'} > \frac{1 + \mu}{3\mu} \]  
(8)

Where:
\[
\lambda_{cr} = \frac{1 + \mu}{3\mu} \quad \lambda = \frac{C / \mu + \sigma_y'}{T + \sigma_x'} \]

When \( \lambda > \lambda_{cr} \), the hydraulic fracture will cross the rock interface; on the contrary, when \( \lambda < \lambda_{cr} \), the hydraulic fracture will slip at the interface.

According to the in-situ stress profile and experimental test and analysis results of rock mechanics parameters obtained above, the calculation results are shown in Figure 7. The simulation results demonstrate that the hydraulic fracture always passes through the interface when it encounters the rock interface. Therefore, hydraulic fracture in ZH gas formation of W9 block will pass through the interface and enter the bottom shielding layer, which may communicate with the bottom water and reduce production. Therefore, it is necessary to control fracture height extension in fracturing design.

![Discrimination results of hydraulic fracture crossing and sliding at rock interface](image)

**Figure 7.** Discrimination results of hydraulic fracture crossing and sliding at rock interface

### 4. Conclusions

1) Kaiser effect test shows that the maximum and minimum principal stress gradients of ZH formation of W9 offshore gas field are 18.6KPa/m and 15.6KPa/m respectively. The vertical stress gradient is 24.2KPa/m, the horizontal maximum stress gradient is 16.76-21.78KPa/m, and the horizontal minimum...
principal stress gradient is 13.41-17.42KPa/m by interpretation of logging from well A of W9 gas reservoir

(2) The rock mechanics parameters are determined by empirical formula based on logging information. The cohesion is 22-25MPa, the internal friction angle is 30°, and the tensile strength is 5MPa.

(3) Whether under average or minimum stress gradient, the hydraulic fracture encounters the rock layer interface, the fracture propagation model is always passing mode, so the hydraulic fracture easily enters the bottom shielding layer and communicates with the bottom water.

(4) Since hydraulic fracture height is easy to pass though bottom water layer, it is necessary for controlling hydraulic fracture height cross interface in W9 offshore gas field fracturing.

Symbol description

\( A \) — constant, depending on unit system
\( C \) — cohesion force, MPa
\( K_I \) — stress intensity factor, MPa
\( T \) — tensile strength, MPa.
\( V_p \) — compressional wave velocity, m/s.
\( V_d \) — shale content of sandstone, decimal.
\( (r, \theta) \) — refers to the polar coordinates (polar radius r, polar angle) at the crack end.
\( \rho \) — rock density, Kg/m³
\( \mu \) — refers to the friction coefficient of rock interface.
\( \mu_d \) — dynamic Poisson's ratio, dimensionless
\( \sigma_i \) — effective stress at crack tip \((i=x,y)\), MPa
\( \tau_i \) — effective shear stress at crack tip, MPa
\( \tau_i^r \) — refers to the far-field effective shear stress, MPa
\( \lambda \) — stress ratio
\( \lambda_c \) — critical crossing stress ratio

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