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Research on Fracture Initiation Pressure in Deviated Well of WCH9 Block

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Abstract: Highly-deviated well are applied for effectively developing WCH9 gas field with deep buried and low permeability, and the payzone are candidates for hydraulic fracturing by evaluation of gas reservoir. Therefore, fracture initiation pressure is a key parameter for design of hydraulic fracturing treatment. Firstly, a series of experiments were completed by core sample from target formation, Young's modulus is about 13GPa and Poisson's ratio is 0.286 at a confining pressure of 40MPa, horizontal principal stress is 78 MPa and 63 MPa, and in-situ stress profiles were interpreted by logging data. Then, the formation rock is regarded as isotropic linear elastic material, thus total stresses distribution on the deviated wellbore wall was determined by stress superposition principle, in which in-situ stress redistribution around the deviated wellbore, fluid pressure acted on the borehole wall and filtration stress are taken into account when fracturing fluid was injected into wellbore. Further, prediction model of fracture initiation pressure was established by applying criterion of maximum tensile stress and effective stress transformation. Lastly, according to the borehole trajectory, in-situ stress and other parameters from payzone of WCH9 block, fracturing initiation pressure varied with *Deviation angle and azimuth angle* were computed by numerical simulation method, these results provide a basis for optimization design of hydraulic fracturing technology parameters.

Keywords: Deviated Well, In-situ Stress, Fracture Initiation Pressure, Hydraulic Fracturing

1. Introduction

Hydraulic fracturing is a widely used stimulation technique in petroleum and gas industry for enhanced hydrocarbon production and recovery from low-permeability oil/gas reservoirs. Fracture initiation pressure (FIP) was required in order to perform an efficient hydraulic fracture stimulation treatment. Location of initial fractures and the breakdown pressure of these hydraulically fractures in inclined wellbores are important in many other operations such as sand-control and production optimization. A lot of research has proven that FIP and path is closely related to in-situ stresses and well bore hole trajectory.

Hubbert first considered that the hydraulic fracture will be created by increasing wellbore fluid pressure when tensile tangential stresses exceed tensile strength of the formation [1]. Yew pointed out that rock tensile strength and formation fluid pressure have an important influence on rock breakdown pressure, and simplified the FIP prediction model according to the first strength theory [2]. Wan summarized the previous formulas on FIP prediction for vertical open-hole wells [3]. Daneshy raised the issue for the first time by performing theoretical and experimental investigation on inclined hydraulic fractures [4].

Yu and Zhou presented the model of stress distribution on the wall of arbitrary inclined well, calculation method on FIP and breakdown location in base of maximum tensile strength criteria [5, 6]. Considering formation fluid pressure, operating conditions, fracturing fluid leak effect, and so on, Chen proposed the calculation method of FIP of deviated well [7]. Hossain discussed the influence of wellbore trajectory, perforation and stress range under arbitrary deviation or azimuth angle on initiation and extension during hydraulic fracture job [8].

Weng displayed the results of an analytical study of fracture initiation and propagation from inclined wellbores. He presented a criterion that correlates fracture link-up to wellbore parameters and investigated the impact of the horizontal stress anisotropy and multiple fracture formation [9]. Shi believes that the porous elastic inclined well model is more appropriate for arbitrary deviated wells by calculating and analyzing the influences of relating parameters on FIP [10]. Zeng established a simulation model of FIP of open-hole well by applying the maximum tensile stress theory according to effective stress, and analyzed the influence of infiltration effect on FIP of open holes [11].

Zhu believes reservoir damage has an important influence on the FIP in hydraulic fracturing, a new prediction model of FIP was established for a random inclined well by considering an additional fracturing fluid infiltration pressure according to the empirical relationship of permeability and porosity combined with Darcy's law of fracturing fluid in poro-elastic media [12].

Roostaei proposed a new analytical model for hydraulic fracture initiation in deviated wellbores, the results displayed that the in-situ stresses state depended on the reverse, strike-slip or normal faulting regime, has a significant impact on the effect of azimuth and inclination on the FIP [13].

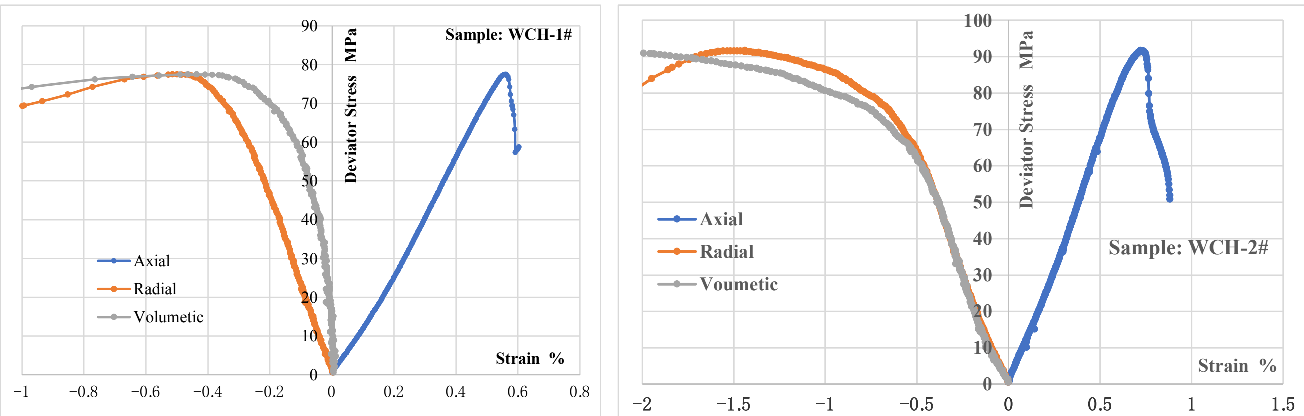
The target formation of WCH9 gas field has a buried depth of 3800-4000m, reservoir temperature is approximately 160℃, and effective permeability is about 0.02-0.46mD. In order to effectively enhance hydrocarbon production in the block, highly-deviated well are used and the payzone are candidates for hydraulic fracturing. Obviously, fracture initiation pressure is an important parameter for reasonable scheme design of hydraulic fracturing treatment.

In this study, a series of experiments, such as rock modulus (YM) and Poisson's ratio (PR) as well as in-situ stress, were completed. Then, the prediction model of FIP in arbitrarily oriented wellbore was established according to effective stress principle and maximum tensile stress criterion. So, FIP and its variation law was obtained according to parameters from the payzone of WCH9 block.

2. Experimental Study on Rock Mechanics Parameters

Rock core sample drilled from target formation of WCH9 block, and experiment instrument is RTR-1000 high temperature and high pressure tri-axial mechanics testing system (MTS).

According to recommended standard practice, Young's elastic modulus and Poisson's ratio of core sample are calculated by stress-strain curve of rock sample. The experiment curves were shown in Figure 1. YM and PR experimental results of the samples were shown in Table 1.



(a) Sample: WCH-1# (b) Sample: WCH-2#

Figure 1. *Strains and axial deviator stress curve of triaxial experiment.*

Table 1. *Triaxial mechanical test results of core samples.*

Sample No.	WCH -1	WCH -2
Length (mm)	35.115	43.175
Dia. (mm)	24.8	24.955
Density (Kg/m^3)	2406	2571
Conf. pressure (MPa)	40	40
Comp. strength (MPa)	77.5	91.7
Elastic modulus (MPa)	13018	2713
PR	0.286	—

3. In-situ Stress Field in WCH9 Block

Usually, in-situ stress field mainly includes gravity stress, tectonic stress, formation fluid pressure and thermal stress. The vertical component of the initial in-situ stress is induced by the gravity of the overlying strata and can be calculated by density log integral.

3.1. Experiment Measure

Kaiser effect test is chosen to measure formation in-situ stress by Φ25×50mm core from the target layer. Firstly, the principal stress direction was tested by wave velocity anisotropy. The experiment curve is displayed in Figure 2.

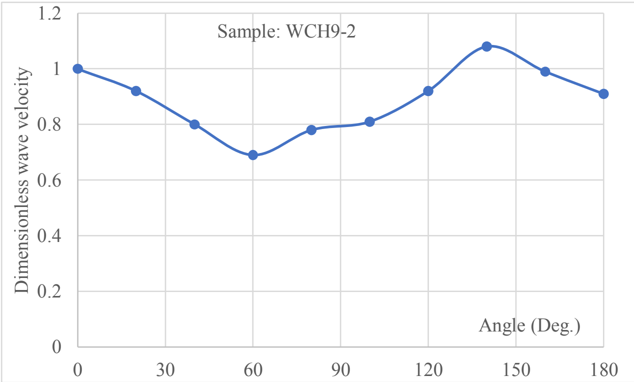


Figure 2. *Test results of wave velocity anisotropy.*

Then, rock sample were drilled at principal stress direction, and Kaiser effect test of the sample was completed by MTS and Locan AT acoustic emission instrument. An example test curve is shown in Figure 3. The maximum and minimum horizontal principal stresses are 78MPa and 63MPa.

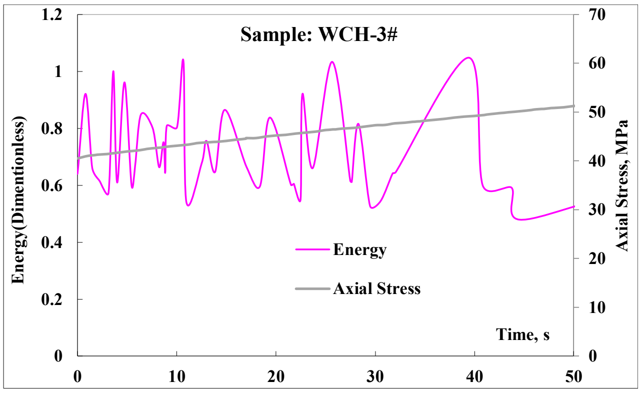


Figure 3. *Test results of Kaiser effect test.*

3.2. In-Situ Stress Profile

The in-situ stresses profiles were obtained by logging interpretation software, and the logging data comes from well WCH931. The vertical component of in-situ stress can be calculated by density logging data, the horizontal principal stress can be interpreted by Newberry model and corrected by experimental results [14]. In-situ stress distribution of WCH9 block is displayed in Figure 4.

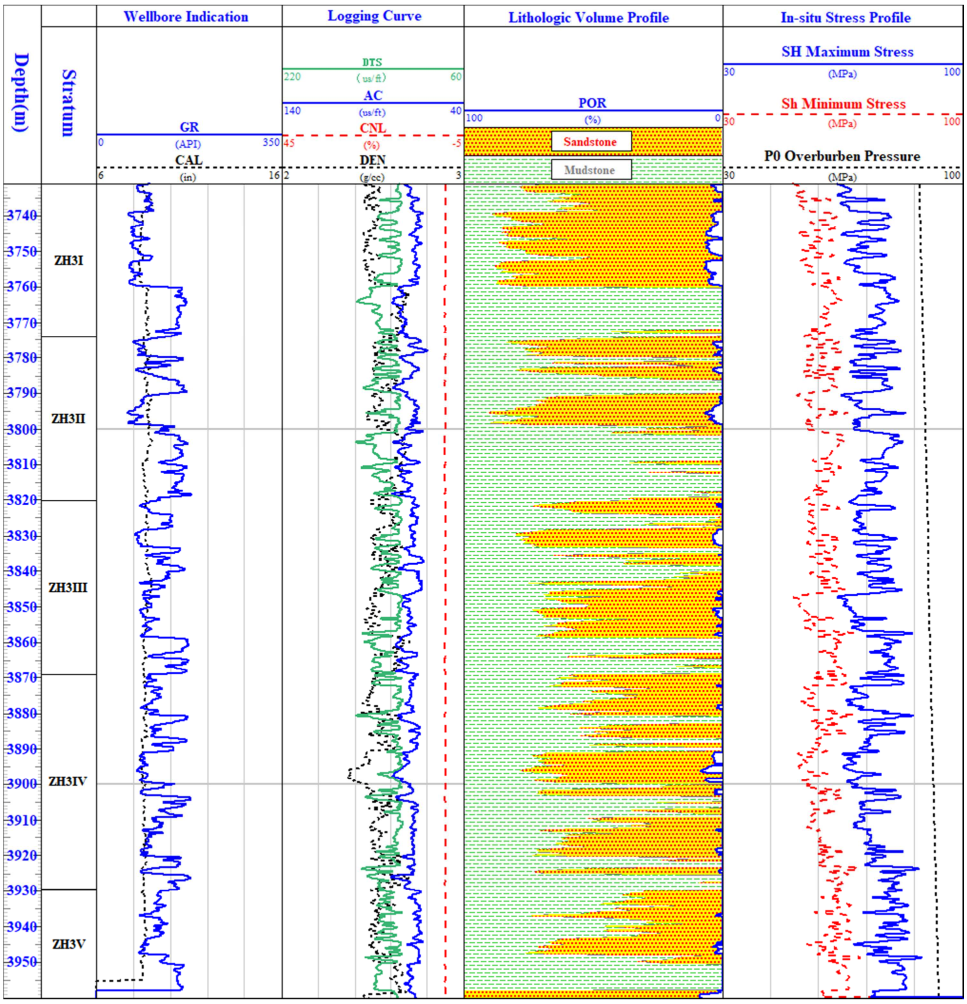


Figure 4. *In-situ stress profile of the ZH formation in WCH9 block.*

The vertical stress gradient is 24.2KPa/m, the horizontal stress gradient is 16.76-21.78KPa/m and 13.41-17.42kpa/m

4. Prediction Model of Fracture Initiation Pressure

Generally, formation rock is assumed as a homogeneous isotropic linear elastic medium. Three orthogonal stresses define the stress system in the underground formations, one of them can be taken along vertical direction, which is designated as σ_v, and the other two along horizontal directions, which are σH and σh. Hydraulic fracturing in deviated well is taken into account in current stress distribution from stress redistribution around the wellbore, injection fluid pressure and fracturing fluid filtration [15, 16], and an appropriate rock failure criterion was chosen.

4.1. Stress Redistribution Around the Deviated Wellbore

For any deviated well as shown in Figure 5, the well inclination angle is ψ and the azimuth angle β. After the wellbore is drilled in the formation, there will be stress redistribution around the wellbore due to the stressed solid material removal and the fact that the fluid pressure in the wellbore does not match the original stresses of the formation.

Bradley generalized Kirsch formulas to the case of an arbitrarily oriented borehole with non-uniform far-field stresses [17].

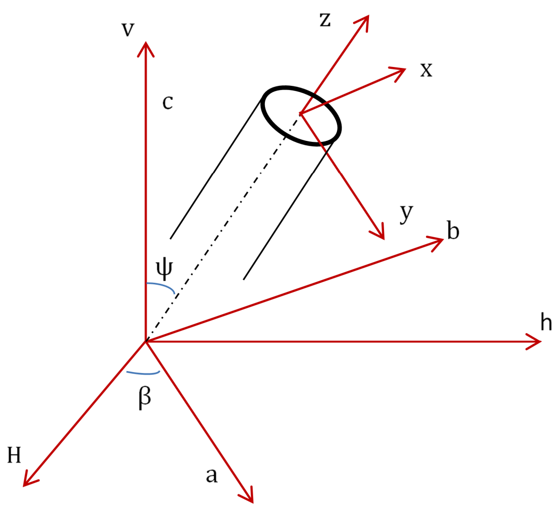


Figure 5. *In-situ stress system around an inclined wellbore.*

The in-situ stress distribution in coordinate system (X, Y, Z) is translated from original in-situ stress coordinate system (H, h, V).

$$\begin{bmatrix} \sigma_x & \sigma_{xy} & \sigma_{xz} \\ \sigma_{zy} & \sigma_z & \sigma_{zx} \\ \sigma_{yz} & \sigma_{yx} & \sigma_y \end{bmatrix} = T \begin{bmatrix} \sigma_H & 0 & 0 \\ 0 & \sigma_h & 0 \\ 0 & 0 & \sigma_v \end{bmatrix} T^T \tag{1}$$

where,

$$T = \begin{bmatrix} \cos\beta\cos\psi & \sin\beta\cos\psi & -\sin\psi \\ -\sin\beta & \cos\beta & 0 \\ \sin\psi\cos\beta & \sin\beta\sin\psi & \cos\psi \end{bmatrix} \tag{2}$$

$$\sigma_{xy}=\sigma_{yx}\ \sigma_{yz}=\sigma_{zy}\ \sigma_{zx}=\sigma_{xz}$$

Therefore

$$\begin{cases} \sigma_x = (\sigma_H \cos^2\beta + \sigma_h \sin^2\beta)\cos^2\psi + \sigma_v \sin^2\psi \\ \sigma_y = \sigma_H \sin^2\beta + \sigma_h \cos^2\beta \\ \sigma_z = (\sigma_H \cos^2\beta + \sigma_h \sin^2\beta)\sin^2\psi + \sigma_v \cos^2\psi \\ \tau_{xy} = 0.5\times(\sigma_h - \sigma_H)\sin 2\beta \cos\psi \\ \tau_{zx} = 0.5\times(\sigma_H \cos^2\beta + \sigma_h \sin^2\beta - \sigma_v)\sin 2\psi \\ \tau_{yz} = 0.5\times(\sigma_h - \sigma_H)\sin 2\beta \sin 2\psi \end{cases} \tag{3}$$

In polar coordinates system, the stress components on the borehole wall were expressed as follows:

$$\begin{cases} \sigma_r = 0 \\ \sigma_\theta = (\sigma_x + \sigma_y) + 2(\sigma_x - \sigma_y)\cos2\theta\text{-}4\tau_{xy}\sin2\theta \\ \sigma_{zz} = \sigma_z\text{-}2v(\sigma_x - \sigma_y)\cos2\theta\text{-}4v\tau_{xy}\sin2\theta \\ \tau_{r\theta} = 0 \\ \tau_{rz} = 0 \\ \tau_{\theta z} = 2(-\tau_{xz}\sin\theta + \tau_{yz}\cos\theta) \end{cases} \tag{4}$$

4.2. Wellbore Inner Pressure and Filtration Stress by Injection Fracturing Fluid

The high rate fluid injection of hydraulic fracturing is regarded as a static process, and the expression of radial and circum-axial stress components under column coordinates (r,θ,z) is calculated by elastic mechanics theory as follows [17]

$$\begin{cases} \sigma_r = p_{in} \\ \sigma_\theta = -p_{in} \\ \sigma_{zz} = cp_{in} \end{cases} \tag{5}$$

According to Lubinski's results [18], the additional stress generated by fracturing fluid filtration in porous elastic media near the well was established.

$$\begin{cases} \sigma_r = -\delta\varphi p_{in} \\ \sigma_\theta = \delta(A-\varphi)(p_{in} - p_p) \\ \sigma_{zz} = \delta(A/2-\varphi)(p_{in} - p_p) \end{cases} \tag{6}$$

where,

$$A = \frac{\alpha(1-2\nu)}{1-\nu}$$

4.3. Total Stress Distribution Around Borehole Wall

Considering the current in-situ stress to inject fluid into the well and fracturing fluid filtration, the mathematical model of stress field at arbitrarily oriented wellbore borehole wall is presented based on the principle of stress superposition as follows:

$$\begin{cases}\sigma_r = p_{in} - \delta\phi p_{in} \\ \sigma_\theta = -p_{in} + \sigma_x + \sigma_y + 2(\sigma_x - \sigma_y)\cos2\theta \\ -4\tau_{xy}\sin2\theta - \delta[A - \phi](p_{in} - p_p) \\ \sigma_{zz} = cp_{in} + \sigma_z - 2v(\sigma_x - \sigma_y)\cos2\theta \\ -4v\tau_{xy}\sin2\theta + \delta\left[\frac{A}{2} - \phi\right](p_{in} - p_p) \\ \tau_{r\theta} = 0 \\ \tau_{rz} = 0 \\ \tau_{\theta z} = 2(-\tau_{xz}\sin\theta + \tau_{yz}\cos\theta)\end{cases} \quad (7)$$

4.4. Fracture Initiation Pressure Prediction Model

Early studies have proven that maximum tensile stress criterion is the most accurate and widely used to predict FIP. Based on the composite stress theory, the three-dimensional stress field transformation on the borehole wall with arbitrary well inclination and azimuth angle is the main stress.

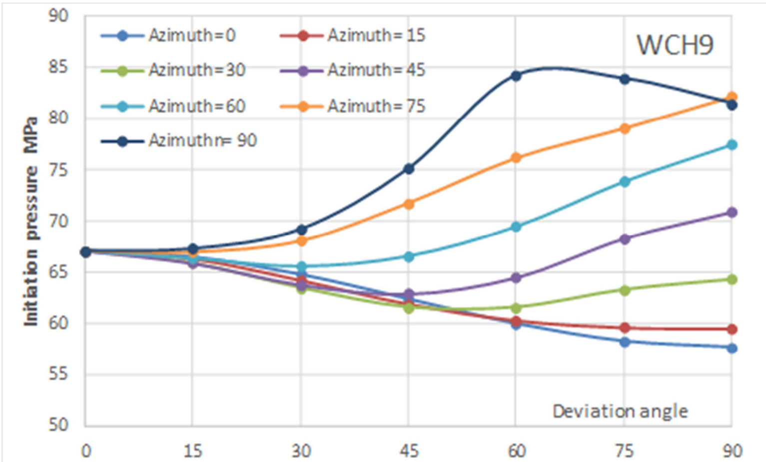
$$\begin{cases}\sigma_1 = \sigma_r \\ \sigma_2 = \frac{1}{2}\left[(\sigma_\theta + \sigma_{zz}) + \sqrt{(\sigma_\theta - \sigma_{zz})^2 + 4\tau^2_{\theta z}}\right] \\ \sigma_3 = \frac{1}{2}\left[(\sigma_\theta + \sigma_{zz}) - \sqrt{(\sigma_\theta - \sigma_{zz})^2 + 4\tau^2_{\theta z}}\right]\end{cases} \quad (8)$$

According to principle of effective stress and the first strength theory, the fracture initial pressure criterion is expressed as follows:

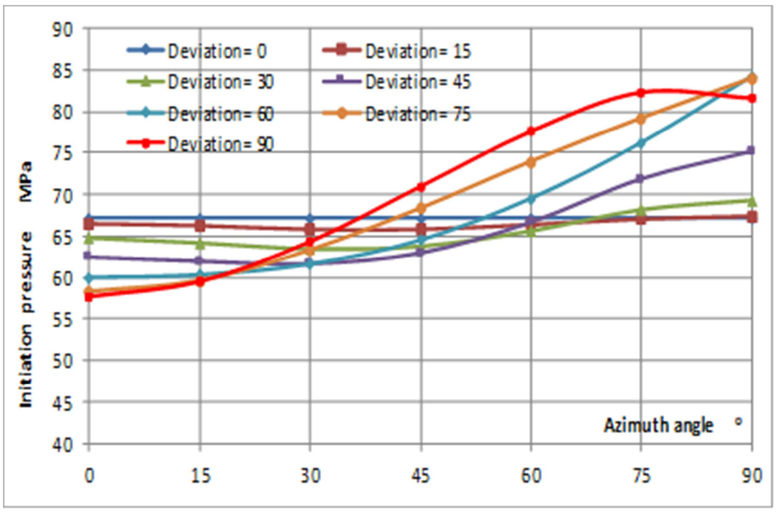
$$\sigma_3 - \eta p_{in} \le -\sigma_t \quad (9)$$

5. Fracture Initiation Pressure of Inclined Well in WCH9 Block

The payzone is mainly concentrated in ZH formation, with a vertical depth of nearly 4000m. The porosity is 15%. YM is 12.8GPa and PR is 0.286. The vertical stress is 94MPa, the horizontal principal stress is 78MPa and 63MPa, and FIP change curves with the well trajectory is shown in Figure 6.



(a)



(b)

Figure 6. *Fracture initiation pressure for wellbore deviation and azimuth angle.*

FIP of vertical wells in the gas field is 67MPa. FIP in deviated well generally increases with wellbore azimuth angle, and its variation with well inclination is more complicated and related to azimuth.

FIP increase with the growth of inclination when azimuth angle is greater 30°. It goes down if azimuth angle is less 30°.

The maximum FIP mainly appears when the well inclination angle is greater than 60° and the azimuth angle is 60°.

The azimuth angle is about 40 °-70°from statistics information in horizontal well in WCH9 gas field. Therefore, the FIP can reach 71MPa and 81.5MPa and is much higher than 67MPa in vertical well.

6. Conclusion

Based on the study results of experiment and numerical simulation in payzone in WCH9, the conclusions are obtained as following:

(1) The static Young's elastic modulus and Poisson's ratio of the reservoir are 12-13GPa and 0.286.

(2) In the payzone of WCH9 block, the vertical stress is 94MPa, and the maximum and minimum horizontal stresses are 78MP and 63MPa.

(3) FIP in vertical wells is 67MPa. The FIP generally goes up with the increase of inclination angle. And its variation with well inclination is more complicated and related to azimuth. FIP increases with growth of inclination angle when azimuth angle is greater than 30°, it goes down if azimuth angle is less than 30°.

(4) The maximum FIP mainly appears when the well inclination angle is greater than 60° and the azimuth angle is 60°. The azimuth angle is about 40°-70 °of horizontal well in WCH9 block, and FIP can reach 71MPa and 81.5MPa and is much higher than 67MPa in vertical well.

Nomenclature

c— Operation impact factor, Decimal;

p_{in}—Hydraulic fracturing or fracture initiation pressure is injected into the wellbore, MPa;

p_p—Formation fluid pressure, MPa;

α—Biot factor, Dimensionless;

β—Azimuth angle of inclined wellbore, degree;

δ—Permeability coefficient, Dimensionless;

φ—Formation porosity, Decimal;

ν—Poisson's ratio, Decimal;

ψ—Deviation angle of inclined wellbore, degree;

θ—Angular position around wellbore circumference, degree.

η—Pore pressure contribution coefficient, Decimal;

σ_t —Rock tensile strength, MPa;

σ_H, σ_h, σ_v —Maximum horizontal principal stress and the minimum principal stress in situ and the vertical principal stress, MPa;

σ_x, σ_y, σ_z — Normal stresses of three directions in the XYZ coordinate system, MPa;

σ_r,σ_θ, σ_{zz} —Wellbore radial, tangential and axial stresses, respectively, MPa;

σ_1, σ_2, σ_3 — Maximum, intermediate and minimum principal stresses, MPa;

τ_{xy}, τ_{yz}, τ_{zx} — The shear stresses in the coordinate system XYZ, MPa;

$\tau_{r\theta}$, τ_{rz}, $\tau_{\theta z}$ — Cylindrical wellbore shear stresses in the coordinate system (r,θ, z), MPa.

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