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The Research on the Model of the Multi-Interval Fracturing of Horizontal Wells

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Abstract

Multi-interval fracturing technology in horizontal well are used more and more widely in the exploitation of unconventional hydrocarbon resources, to accurately determine the initiation pressure having an important significance to improve the fracturing effect. On the basis of the homogeneous and isotropic two-dimensional plane strain model, established the geometric model of two-dimensional vertical fractures induced stress field; Based on rock mechanics and elastic mechanics theory, taking multi-stage fracturing induced stress into consideration, established the calculation model of the initiation pressure of the multi-stage fracturing of horizontal wells' fracture. The calculation results showed that taking induced stress into consideration, the calculation result is consistent with the actual situation, compared with the actual construction pressure, and the average accuracy rate is 95.15%. It proved that this model can be used for calculating the initiation pressure of the multi-interval fracturing of horizontal wells' fracture.

Key words: Horizontal well; Multistage fracture; Initiation pressure; Induced stress

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INTRODUCTION

As the energy supply problems is increasingly tensing in the world, the development and utilization of unconventional hydrocarbon resources like shale gas, coal-bed gas has risen continued. The exploitation of unconventional hydrocarbon resources, the multistage fracture of horizontal well is a relative successful approach, and the approach is widely used. For the study of multistage fracturing model, C.H. Yew[1,2] based on the former models of the stress field distribution around the horizontal well bore, the calculation model of initiation pressure was established without regard to pore pressure, degree of porosity and rock tensile strength; Chen mian *et al*.[3] based on the elastic theory of porous medium, established the model of stress distribution around the inclined well bore taking into account pore fluid pressure, the filtration effect of fracturing fluid and etc., proposing a more reasonable new evidence of initiation pressure of inclined well, respectively analyzing the mechanism of fracture initiation in the inclined well's vertical fracture and fracture initiation in the horizontal well's vertical fracture. M.A. Emanuele etc. considering the situation of being multi-fracture, generated induced stress makes initiation pressure increase, and propose that by increasing injection and adjust perforating in order to avoid multi-fracture at the same time open as much as possible. D.G. Crasby *et al*. research that multiple fractures opening at the same time, two nearest fractures interfere with each other, and can guide effectively fracture of horizontal well; Lv zhikai *et al*. established the calculation model of initiation pressure of horizontal wells completed by perforation, and analyzing influencing factors and variation of failure pressure. But the fractured initiation pressure of multi-fracturing horizontal wells, previous studies have not analyzed theoretically and obtained very good influence of induced stress on impact the multistage hydraulic fracturing during the fracturing process, this paper theoretically explain this problem, and it is a supplement and perfect to the calculation model of initiation pressure of multistage fracturing horizontal wells' fractures.

1. THE CALCULATION MODEL OF INDUCED STRESS OF MULTISTAGE FRACTURING HORIZONTAL WELLS' FRACTURES

On the basis of the homogeneous and isotropic two-dimensional plane strain model, established the geometric model of two-dimensional vertical fractures induced stress field, among, taking the minimum principal stress direction as z axis, taking the overburden pressure direction as x axis, taking the maximum principal stress direction as y , borehole layout along the minimum principal stress direction, assuming that fracture longitudinal profile is oval, fracture height is h, perforated azimuth is α, the model assumes that the tensile stress is, positive and the compressive stress is negative. The diagram of model two-dimensional profile section is shown in Figure 1.

The induced component stress of any point (x, y, z) on the two-dimensional hydraulic fracture around the wellbore.

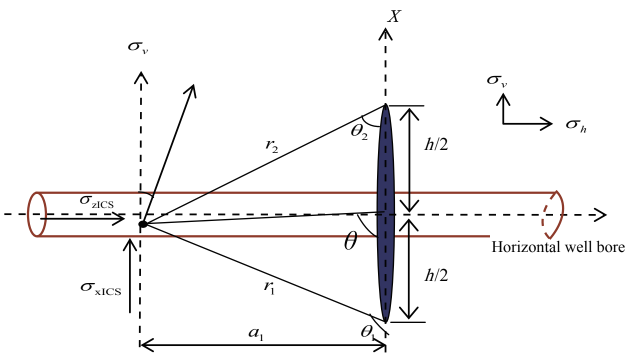

Figure 1
The Model of Induced Stress Under the Different Azimuth of Perforation

$$\begin{cases} \sigma_{zICS} = p\dfrac{r}{d}\left(\dfrac{d^2}{r_1 r_2}\right)^{\frac{3}{2}} \sin\theta \sin\dfrac{3}{2}(\theta_1+\theta_2) + p\left[\dfrac{r}{(r_1 r_2)^{\frac{1}{2}}}\cos\left(\theta-\dfrac{1}{2}\theta_1-\dfrac{1}{2}\theta_2\right)-1\right] \\ \sigma_{xICS} = -p\dfrac{r}{d}\left(\dfrac{d^2}{r_1 r_2}\right)^{\frac{3}{2}} \sin\theta \sin\dfrac{3}{2}(\theta_1+\theta_2) + p\left[\dfrac{r}{(r_1 r_2)^{\frac{1}{2}}}\cos\left(\theta-\dfrac{1}{2}\theta_1-\dfrac{1}{2}\theta_2\right)-1\right] \\ \sigma_{yICS} = v\left(\sigma_{az}+\sigma_{ax}\right) \\ \tau_{zxICS} = p\dfrac{r}{d}\left(\dfrac{d^2}{r_1 r_2}\right)^{\frac{3}{2}} \sin\theta \cos\dfrac{3}{2}(\theta_1+\theta_2) \end{cases} \quad (1)$$

Type: $\sigma_{z\text{ICS}}$, $\sigma_{x\text{ICS}}$, $\sigma_{v\text{ICS}}$ and $\tau_{zx\text{ICS}}$ are the induced component stress of the existing fractures in the formation, MPa; p is the internal pressure of existing fractures, MPa; d is half fracture fracture height, m; R is wellbore radius, m; r is the distance of between the fracture and wellbore intersections and a particle, m; r_1 and r_2 are distances between fracture height and a particle, m; θ_1 and θ_2 are included angles between fracture height to a particle distance and fracture, °; ν is rock Poisson ratio, zero dimension; α_1 is the distance between perforating point and the former fracture, m.

The relationship between the following geometrical parameters:

$$\begin{cases} r = \sqrt{z^2 + R^2\cos^2\alpha} \\ r_1 = \sqrt{z^2 + \left(d + R\cos\alpha\right)^2} \\ r_2 = \sqrt{z^2 + \left(d - R\cos\alpha\right)^2} \end{cases} \quad (2)$$

$$\begin{cases} \theta = \arctan\left(\dfrac{z}{R\cos\alpha}\right) \\ \theta_1 = \arctan\left(\dfrac{z}{d + R\cos\alpha}\right) \\ \theta_2 = \arctan\left(\dfrac{z}{d - R\cos\alpha}\right) \end{cases} \quad (3)$$

2. THE CALCULATION MODEL OF INITIATION PRESSURE OF MULTISTAGE FRACTURING HORIZONTAL WELLS'FRACTURES

2.1 Stress Distribution of Perforation During the Fracturing Process

Assuming the perforation horizontal well and borehole vertical intersection, the pressures both eyehole and wellbore are same[7].The stress distribution model of Perforated horizontal wells and perforation as shown in Figure 2. $\sigma_{\theta l}$ and $\sigma_{\theta t}$ are eyehole tangential stresses respectively on behalf of fracture initiation Azimuth θ' being 0°and 90°, eyehole circumferential stress is $\sigma_{\theta l}$.

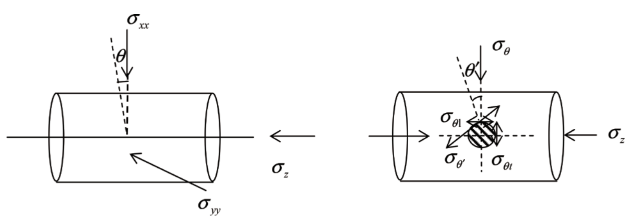

Figure 2
The Diagram of the Stress Distributional Model of Perforating Horizontal Wellbore and Perforation

Perforating wellbore stress distribution within the wellbore internal pressure, combined stress, fracturing fluid percolation threshold effect and thermal stress under the joint action:

$$\begin{cases} \sigma_r = -P_w + \delta\phi\left(P_w - P_p\right) + \dfrac{\alpha_T E\left(T - T_0\right)}{1-2v} \\ \sigma_{\theta'} = 2P_w\left(1+\cos 2\theta'\right) + \left(\sigma'_{xx} + \sigma'_{yy} + \sigma'_z\right) + 2\left(\sigma'_{xx} + \sigma'_{yy} - \sigma'_z\right)\cos 2\theta' \\ \quad -2\left(\sigma'_{xx} - \sigma'_{yy}\right)\cos 2\theta\left(1 + 2\cos 2\theta'\right) - 4\sigma_{xy}\sin 2\theta\left(1+2\cos 2\theta\right) \\ \quad -4\sigma_{z\theta}\sin 2\theta' - 2\delta\left[\dfrac{\alpha\left(1-2v\right)}{\left(1-v\right)} - \phi\right]\left(P_w - P_p\right)\left(1+\cos 2\theta'\right) + \dfrac{\alpha_T E\left(T-T_0\right)}{1-2v} \\ \sigma'_z = cP_w + \sigma'_{zz} - v\left[2\left(\sigma'_{xx} - \sigma'_{yy}\right)\cos 2\theta + 4\sigma_{xy}\sin 2\theta\right] \\ \quad -\delta\left[\dfrac{\alpha\left(1-2v\right)}{\left(1-v\right)} - \phi\right]\left(P_w - P_p\right) + \dfrac{\alpha_T E\left(T-T_0\right)}{1-2v} \\ \tau_{r\theta} = 0 \\ \tau_{\theta z} = 2\left(-\sigma'_{xz}\sin\theta + \sigma_{yz}\cos\theta\right) \\ \tau_{rz} = 0 \end{cases} \tag{4}$$

Type:σ_r is the radial stress of wellbore, MPa; $\sigma_{\theta'}$ is the tangential stress of perforation, MPa; $\sigma_z$is axial stress of wellbore, MPa; $\tau_{r\theta}$, $\tau_{\theta z}$ and τ_{rz} is the tangential stress component around wellbore, MPa; α is Biot poroelastic factor; v is rock Poisson ratio, zero dimension; P_p is the pore pressure, MPa; P_w is the internal pressure of wellbore, MPa;σ'_{xx}, σ'_{yy} and σ'_{zz} are crustal stresses along the x, y, z direction of the component considered the former fracture induced stress, MPa; c is the operational impact coefficient, zero dimension; θ is the azimuth of perforation, ^0c; T is the rock temperature after change, ^0c.

Including:

$$\begin{cases} \sigma'_{xx} = \sigma_v + \sigma_{x\mathrm{ICS}} \\ \sigma'_{\mathrm{yy}} = \sigma_H\cos^2\beta + \sigma_h\sin^2\beta + \sigma_{\mathrm{yICS}} \\ \sigma'_{zz} = \sigma_H\sin^2\beta + \sigma_h\cos^2\beta + \sigma_{\mathrm{zICS}} \\ \tau_{xy} = 0 \\ \tau_{yz} = (\sigma_h - \sigma_H)\sin\beta\cos\beta \\ \tau_{zx} = \tau_{\mathrm{zxICS}} \end{cases} \tag{5}$$

Type:τ_{xy}, τ_{yz} and τ_{xz} are the shearing stress component in coordinate system(x, y, z), MPa; σ_v, σ_H and σ_h are the vertical stress, the maximum principal stress and the minimum principal stress in coordinate system(1,2,3), MPa; β is the included angle between the orientation of wellbore and the minimum principal stress.

2.2 THE CRITERION OF FRACTURES INITIATION

Fractures initiation pressure is the size of borehole pressure when the shaft wall fracture occurs, fractures initiation angle is the size of angle between wellbore axial line and fracture plane. In hydraulic fracturing, fracture initiation of rock is mainly due to the tensile fracture[8]. Based on tensile failure criterion, when extensional stress of rock is achieved tensile strength, that is $\sigma_{\max}(\theta_0) \geq \sigma_t$, rock material will occur the initial abruption. Based on the theory of elastic mechanics, the maximum tensile stress is:

$$\sigma_{\max}\left(\theta'\right) = \frac{1}{2}\left[\left(\sigma_{\theta'} + \sigma'_z\right) + \sqrt{\left(\sigma_{\theta'} - \sigma'_z\right)^2 + 4\tau_{\theta z}^2}\right] \tag{6}$$

For a perforation azimuth θ, to formula (6) derivate, that can obtain fractures initiation azimuth θ' when the shaft wall fails in tension:

$$\frac{d\sigma_{\max}\left(\theta'\right)}{d\theta'} = 0 \tag{7}$$

When the maximum effective extensional stress on the wall surface z-θ' is not less than the tensile strength σ_{t} of rock, the rock on shaft wall began to fracture, to produce the initial fracture, that is:

$$\sigma_{\max}\left(\theta'\right) - \eta p_p \geq \sigma_t \tag{8}$$

Type:η is the contribution coefficient of pore pressure, P_p is Pore fluid pressure, MPa; σ_t is the rock tensile strength, MPa.

As shown figure 2, $\sigma_{\theta 1}$ and $\sigma_{\theta t}$ are eyehole tangential stresses respectively on behalf of fracture initiation Azimuth θ' being 0° and 90°, among them, $\sigma_{\theta 1}$ is the maximum tensile stress in order to fracture breakdown.

$$\begin{aligned} \sigma_{\theta'} &= 4P_w + \left(\sigma'_{xx} + \sigma'_{yy} + \sigma'_z\right) + 4\left(\sigma'_{xx} + \sigma'_{yy} - \sigma'_z\right) - 6\left(\sigma'_{xx} - \sigma'_{yy}\right)\cos 2\theta \\ &\quad -4\tau_{xy}\sin 2\theta\left(1+2\cos 2\theta\right) - 4\delta\left[\frac{\alpha\left(1-2v\right)}{\left(1-v\right)} - \phi\right]\left(P_w - P_p\right) + \frac{\alpha_T E\left(T-T_0\right)}{1-2v} \end{aligned} \tag{9}$$

The actual fracture initiation pressure is:

$$P_w = \min(P_{w0}, P_{w90}) \tag{10}$$

Type: P_w is the fracture initiation pressure, MPa; P_{w0} is the fracture initiation pressure located perforational fracture θ=0°, MPa; P_{w90} is the fracture initiation pressure located perforational fracture θ=90°, MPa.

3. EXAMPLE CALCULATION

Black A well is located in the south tectonic region of the Qingzi well in Heidimiao sublevel concave of the central depression area of Changling depression in the south of Songliao Basin. The depth of drilled well is 2301 m, the vertical depth is 1567.48 m, azimuth is 100.01°, the maximum principal stress orientation at the well point is NE106.6°, the included angle between the orientation of wellbore and the minimum principal stress is 16.59°. The horizontal length is 100 m, and the formation temperature is 53.82 ℃. The mean permeability of the target bed is 32.95 mD, the porosity is 19.77%, the overburden pressure is 34.45 MPa, the maximum horizontal principal stress is 36.52 MPa, the minimum horizontal principal stress is 27.17 MPa. The rock elastic modelling quantity around wellbore is 13218 MPa, the Poisson ratio is 0.23, perforation is ten section, the fracture pressures are 34.25 MPa, 35.43 MPa, 34.36 MPa, 36.35 MPa, 34.77 MPa, 34.32 MPa, 35.25 MPa, 34.57 MPa, 33.15 MPa, 34.47 MPa respectively. Using the calculation model, the comparison with the observed results is shown in Table 1 and Figure 3.

Table 1
The Table of the Comparison of the Theoretical Value and the Actual Value of the Black A Well Initiation Pressure

Segment level	Fracture No	Actual initiation pressure /MPa	Initiation pressure under the influences induced stress /MPa	Initiation pressure ignoring the influences of induced stress/ MPa	Average accuracy rate under the influences induced stress/%	Average accuracy rate ignoring the influences of induced stress /%
The first Segment	1	34.25	30.98	30.98	90.45	90.45
The second Segment	2	35.43	32.62	30.98	92.06	87.44
The third Segment	3	34.36	32.93	30.98	95.83	90.16
The fourth Segment	4	36.35	33.11	30.98	91.08	85.22
The fifth Segment	5	34.77	33.28	30.98	95.71	89.09
The sixth Segment	6	34.32	33.29	30.98	96.99	90.26
The seventh Segment	7	35.25	33.66	30.98	95.48	87.88
The eighth Segment	8	34.57	33.67	30.98	97.39	89.61
The ninth Segment	9	33.15	33.85	30.98	97.88	93.45
The tenth Segment	10	34.47	33.98	30.98	98.58	89.87

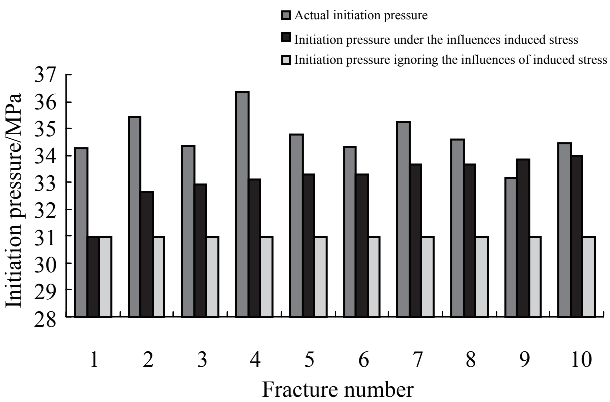

Figure 3
The Comparison of the Theoretical Value and the Actual Value of the Black A Well Initiation Pressure

The fracture initiation pressure's calculation results show that considering the influences of induced stress effect and ignore the influences of induced stress conditions, the fracture initiation pressure and observed fracture initiation pressure is significantly different; considering the influence of induced stress, the fracture initiation pressures of the Black well's ten sections' ten fractures calculation accuracy is higher, and the average accuracy rate is 95.15%; the calculation result is consistent with the actual situation, and this model can be more accuratelly used for the prediction of initiation pressure of the multi-interval fracturing of horizontal wells' fracture.

CONCLUSION

a. Based on rock mechanics and elastic mechanics theory, taking multi-stage fracturing induced stress into consideration, established the calculation model of the initiation pressure of the multi-interval fracturing of horizontal wells' fracture, it can be used for calculating the initiation pressure of the multi-interval fracturing of horizontal wells' fracture.

b. The applied model calculates the initiation pressure of the Black A well section under the influence of induced stress, compared with the actual construction pressure, and the average accuracy rate is 95.15%,and it shows that the model has preferable applicability.

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