A Study of Fracture Penetration Law of Tight Sandstone Gas Reservoir in Block LX

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Abstract. The fracture of tight sandstone gas reservoir in Block LX is characterized by thick sand body and thin gas layer. The production layer is adjacent to water layer and coal fracture, and the longitudinal stress difference of the shielding layer is small. Based on the theory of fracture tip stress intensity factor, this paper adopts core experiment and theoretical analysis method, combined with fracturing engineering geological characteristics and construction parameters, to analyze the fracture penetration criterion and study the influence of construction factors and reservoir geological characteristics on the law of fracture penetration law. The results show that the minimum horizontal principal stress difference of artificial fracture passing through the interlayer is affected by the construction displacement, reservoir thickness and other factors; The construction displacement has obvious influence on the minimum horizontal principal stress when the artificial fractures pass through the interlayer, and the construction with small displacement can prevent the artificial fractures from passing through the interlayer when the stress difference of the reservoir interlayer is less than 3.5MPa. The minimum horizontal principal stress difference of the reservoir layer when the artificial fracture extends to the interface of the reservoir layer can be determined by using the criterion of the artificial fracture behavior and the model of the artificial fracture behavior, which will provide some technical guidance for the field hydraulic fracturing construction.

Keywords: fracture penetration, tight sandstone, construction factors

1. Introduction

Tight sandstone gas reservoirs are characterized by low porosity, low permeability, low formation pore pressure, low natural production and high water saturation. The natural productivity of a single well is lower than the lower limit of industrial airflow, and industrial airflow can only be produced through technical transformation such as large-scale hydraulic fracturing, horizontal well and multilateral well. In addition, some reservoirs are characterized by thick sand layer and thin gas layer, which leads to unsatisfactory fracturing effect and easy communication with interference layer. Therefore, it is necessary to study the influencing factors of fracture penetration based on fracturing engineering geological characteristics and fracturing operation parameters to summarize the law of fracture height penetration.
As for the factors that inhibit fracture extension, Simon [1] believes in 1978 that the density of fracturing fluid, stress difference of reservoir interlayer and fracture toughness are important factors affecting fracture extension. Huang Rongzun [2] analyzed the influence of pressure in fracture and rock mechanics on fracture extension when fracture expands in different stress layers in 1981. In 2006, based on the principle of controlling fracture height, Zhou Wengao [3] studied the influence of fracture height on privacy of oil and gas formation with weak stress layers in upper and lower interlayers, such as rock characteristics, formation stress and construction parameters and so on. Wang Han [4] established a mathematical model of hydraulic fracturing simulation using cohesive unit in 2013 to study the influence of rock mechanics and in-situ stress on fracture height. In 2014, Wang Zedong [5] established the criterion of fracture passing through the interlayer or slip when the fracture extends to the interlayer. Xu Chaolan et al. [6] analyzed the influence of rock mechanics and in-situ stress, fracturing fluid performance and construction parameters on fracture height in 2015. In 2016, Tao Gaojie [7] carried out controlled fracture high fracturing of low permeability reservoir by improving fracturing fluid system, variable displacement and other fracturing supporting technologies. Zhang Guisheng et al. [8] analyzed the influence of interlayer mechanics and construction parameters on the fracture height through physical simulation test in 2017. At present, most scholars have studied the law of fracture extension after fracture penetration, but the influence law of fracturing construction parameters, rock mechanics and in-situ stress during fracture penetration is not clear enough. Therefore, based on the previous scholars’ study of influence factors on fracture height extension, this paper studies the variation rule of stress intensity factor during artificial fracture penetration, summarizes the criterion of artificial fracture penetration, and analyzes the influence rule of fracturing construction parameters when stress difference of different reservoir layers is different. So the author will use fracture tip stress intensity factor to analyze and study the law of artificial fracture penetration in tight sandstone gas reservoir.

2. Introduction to Basic Situation

Block LX is characterized by low porosity, low permeability, low formation pore pressure, low natural production, high water saturation, and strong reservoir heterogeneity.

A study of the overburden pressure and pore permeability of some cores in the Section 8 of the block box shows that the porosity of sandstone ranges from 0.35% to 21.91%, with an average of 6.35%. The permeability ranges from 0.001 to 4.06 mD, with an average of 0.161 mD. According to the histogram of physical property distribution frequency (Fig. 7), the porosity is mainly concentrated in the range of 2% - 10%, and reservoirs with porosity less than 10% account for 94% of the total. The permeability is mainly concentrated in the range of 0.01 - 0.5 mD, and reservoirs with permeability less than 0.5 mD account for 96% of the total. The reservoir of Section 8 is characterized by low porosity and low permeability.

![Figure 1. Porosity distribution map of Section 8](image1)

![Figure 2. Permeability distribution map of Section 8](image2)
Moreover, according to the logging curve, some intervals in Block LX have the following characteristics:

1. Thick sand body and thin gas layer.
2. The production layer is adjacent to water layer and coal fracture, and the longitudinal stress difference of the shielding layer is small.

It can be seen from the logging curve that longitudinally the reservoir is characterized by the development of sand layer, thin mudstone interlayer and weak barrier ability. Thus when hydraulic fracturing is carried out in Block Linxing, it will face the risk of fracture height out of control, and easy to press through water layer and coal fracture. Therefore, it is necessary to study the law of fracture penetration in this block so as to avoid pressing through water layer and coal fracture and improve the effect of hydraulic fracturing.

According to the interpretation of logging curves, the minimum horizontal principal stress of Section 8 is between 1.23 g/cm³ and 1.51g/cm³, and the maximum horizontal in-situ stress is between 1.68 g/cm³ and 2.28g/cm³. The overburden pressure ranges from 2.31 to 2.59g/cm³. The overburden pressure is the maximum principal stress, and the difference between horizontal ground stress is not significant. However, the stress difference of interlayer varies greatly, of which the stress difference of upper interlayer is the difference between the minimum horizontal principal stress of reservoir and the minimum horizontal principal stress of upper interlayer, while the stress difference of lower barrier is the difference between the minimum horizontal principal stress of reservoir and the minimum horizontal principal stress of lower barrier. It can be seen from the histogram that the stress difference between the upper and lower interlayers is mainly concentrated in 1-4MPa and 4-7MPa. The stress difference between the lower interlayer and the upper interlayer is slightly larger than that of the upper interlayer, so it is more difficult for fractures to pass through the lower interlayer.

![Figure 3. Distribution map of stress difference of reservoir interlayer in Section 8](image)

### 3. Physical model of thin interlaminating fracture height control

When the hydraulic fracture extends vertically and encounters the interlayer, it may break through the layer. When slippage occurs when the fracture extends to the interface, the height of the fracture is limited to a certain extent, and the technology of controlling the height of the fracture is not needed. When the net pressure in the fracture is large enough or the interface connection is tight, the artificial fracture is easy to penetrate the barrier layer. Therefore, it is necessary to establish the model of artificial fracture penetration, study the influencing factors of artificial fracture height control, and summarize the law of artificial fracture penetration and the control method of fracture height.

Therefore, based on the Palmer pseudo-three-dimensional fracture extension model, fractures are divided into numerous independent vertical sections in the direction of fracture length, and each vertical section can be regarded as a two-dimensional linear fracture to study the law and criteria of artificial fracture penetration.
3.1. Criterion for the behavior of artificial fractures passing through interlayers

In the process of vertical extension of hydraulic fracture, it will encounter the interface of reservoir interlayer. When the fracture extends to the interface, it may slip along the interface or pass through the layer. Therefore, it is necessary to study the judgment basis of two kinds of extension behaviors, namely, the hydraulic fracture passing through the rock interface or the hydraulic fracture sliding along the interface [4].

![Diagram of artificial fracture passing through interlayer](image)

**Figure 4.** Diagram of artificial fracture passing through interlayer

The conditions of fracture passing through the interface are obtained by Mohr-Coulomb criterion:

\[ |r_{xy}| < S - \mu \sigma_{yy} \]

It is assumed that when the fracture begins to extend at the interface, the induced tensile stress of the fracture must be equal to the tensile strength \( T \):

\[ \sigma_{xx}^{(max)} = -T, \]

The hydraulic fracture is perpendicular to the direction of minimum principal stress, so \( r'_{yy} = 0 \),

\[
\left(-\frac{S + \sigma'_{yy}}{\mu}\right) \sqrt{r(P/2)} > \cos\left(\frac{\pi}{4}\right) \left(1 - \sin\left(\frac{\pi}{4}\right) \sin\left(\frac{3\pi}{4}\right)\right) + \frac{1}{\mu} \left(\sin\left(\frac{\pi}{4}\right) \cos\left(\frac{3\pi}{4}\right)\right)
\]

\[
\sqrt{r\left(\pm\frac{\pi}{2}\right)} = \frac{K_i}{-T + \sigma'_{xx}} \left[\cos\left(\frac{\pi}{4}\right) \left(1 + \sin\left(\frac{\pi}{4}\right) \sin\left(\frac{3\pi}{4}\right)\right)\right]
\]

Put (3-9) into Formula (3-6) to obtain the passing criterion:

\[
\frac{S + \sigma'_{yy}}{\mu \left(\frac{T + \sigma'_{xx}}{3}\right)} > \frac{1}{3} + \frac{1}{3\mu}
\]
3.2. Stress Intensity Factors of Artificial Fractures Passing Through interlayers

3.2.1. k criterion of artificial fracture extension. The shape of artificial fracture extension is affected by the stress intensity factor from the fracture tip. In the process of fracture extension, there is one horizontal stress intensity factor and two vertical stress intensity factors, while on the two-dimensional vertical profile, the stress intensity factor at the fracture tip $K_i$ is:

$$K_{i1} = \frac{1}{\sqrt{\pi l}} \int_{-l}^{l} p(z) \sqrt{\frac{l+z}{l-z}} dz$$

$$K_{i2} = \frac{1}{\sqrt{\pi l}} \int_{-l}^{l} p(z) \sqrt{\frac{l-z}{l+z}} dz$$

![Figure 5. Diagram of artificial fracture passing through interlayer](image)

3.2.2. Net pressure distribution in the middle fracture of vertical section. The minimum horizontal principal stress in the reservoir is simplified to a linear distribution and the minimum horizontal principal stress pressure gradient is $g_s$, considering the gravity of fracturing fluid $g_p z$ and the friction pressure drop $g_v z$ in the direction of fracture height.

![Figure 6. Diagram of net pressure distribution in the fracture](image)


When $l=L$, the formula is changed to:

$$p(z)=\begin{cases}
\begin{align*}
p_f-S_b+g_w\Delta z-g_r z-g_p z & \quad (L \leq z \leq l) \\
p_f-S_a+g_w\Delta z-g_r z-g_p z & \quad (0 \leq z \leq L) \\
p_f-S_a+g_w\Delta z-g_r z+g_p z & \quad (-L \leq z \leq 0) \\
p_f-S_c+g_w\Delta z-g_r z+g_p z & \quad (-L \leq z \leq -l)
\end{align*}
\end{cases}$$

When $l=L$, the formula is changed to:

$$K_{f1}=(S_b-S_a)\sqrt{\pi L}+(P_f-(g_v+g_p)L^2+g_wL^2)\sqrt{\pi L}$$

When $K_{f1} > K_{IC}$, the artificial fracture passes through the upper interlayer.

When the artificial fracture passes through the lower interlayer, it can be obtained from Formula (2) and Formula (3) that:

$$K_{f2}=(S_c-S_a)\sqrt{\pi L}+(P_f-(g_v+g_p)L^2+g_wL^2)\sqrt{\pi L}$$

When $l=L$, the formula is changed to:

$$K_{f2}=(S_c-S_a)\sqrt{\pi L}+(P_f-(g_v+g_p)L^2+g_wL^2)\sqrt{\pi L}$$

When $K_{f2} > K_{IC}$, the artificial fracture passes through the lower interlayer.

3.2.3. Calculation of Fluid Pressure in the Fracture. The construction pressure of wellhead is obtained during construction, so the wellhead pressure needs to be converted into the fluid pressure in the fracture when calculating the fluid pressure in the fracture. At this time, it is necessary to consider fracturing fluid friction along the way, perforation friction and the pressure generated by wellbore fluid injection during construction, and the following formula can be obtained:

$$P_f = P + P_{\text{hydrostatic}} - P_{\text{fric}} - P_{pf}$$

Combined with various calculation methods of friction, the wellhead pressure can be transformed into fluid pressure in the fracture.

3.3. Establishment of artificial fracture penetration model

Based on the above formula setting, the artificial fracture penetration model is established, and its parameters are shown in the table below:
Table 1. Parameters of artificial fracture penetration model

| Parameters                                                                 | Numerical Value |
|----------------------------------------------------------------------------|-----------------|
| formation pore pressure /MPa                                               | 13.5            |
| overburden pressure /MPa                                                   | 40              |
| minimum horizontal principal stress of the reservoir /MPa                 | 26              |
| minimum horizontal principal stress of upper interlayer /MPa              | 32              |
| minimum horizontal principal stress of upper interlayer/MPa               | 28              |
| Minimum horizontal principal stress pressure gradient of the reservoir/(MPa-m-1) | 0.016           |
| reservoir thickness /m                                                     | 30              |
| reservoir elastic modulus /GPa                                             | 20              |
| elastic modulus of upper interlayer /GPa                                  | 20              |
| elastic modulus of lower interlayer/GPa                                   | 20              |
| Poisson's ratio of reservoir                                              | 0.2             |
| Poisson's ratio of upper interlayer                                       | 0.2             |
| Poisson's ratio of lower interlayer                                       | 0.2             |
| compressive strength of reservoir /MPa                                    | 58              |
| compressive strength of upper interlayer/MPa                             | 37              |
| compressive strength of lower interlayer /MPa                            | 37              |
| compressive strength of reservoir /MPa                                    | 6               |
| compressive strength of upper interlayer /MPa                            | 4               |
| compressive strength of lower interlayer /MPa                            | 4               |
| fracture toughness of reservoir /(MPa·m1/2)                              | 0.995           |
| fracture toughness of upper interlayer/(MPa·m1/2)                        | 0.416           |
| fracture toughness of lower interlayer/(MPa·m1/2)                        | 0.416           |
| perforation position                                                      | middle of reservoir |
| gravity gradient of fracturing fluid /(MPa·m-1)                          | 0.01            |
| gradient of friction pressure drop in fracture height direction/(MPa·m-1) | 0.005           |
| friction coefficient of rock interface                                    | 0.7             |
| bore diameter/mm                                                          | 11.7            |
| bore flow coefficient                                                     | 8.9             |
| bore number/m                                                             | 16              |
| pipe length/m                                                             | 1456            |
| pipe internal diameter /mm                                                 | 114.3           |
| concentration of thickening agent /(kg·m-3)                               | 0.3             |
| pumpage/(m³·min-1)                                                        | 3               |

3.4. Analysis of Influencing Factors

It has been proved by theory and experiment that the formation stress difference is the main factor controlling the growth of fracture height, but the significant stress difference can hinder or even stop the growth of fracture in the direction of fracture height. Whether the extension of artificial fractures in the direction of fracture height passes through the interlayer is subject to the rock mechanical properties of the production layer and interlayer as well as the fracturing operation parameters, and the stress difference between reservoir interlayer that prevents artificial fractures from penetrating layers is also different for strata of different structures. Therefore, the fracture length is fixed in the model, and the construction displacement, fracturing fluid density, rock fracture toughness and reservoir thickness are changed to study the influence on the stress difference of reservoir interlayer when the artificial fracture passes through the interlayer.

3.4.1. Construction Displacement. For artificial fractures, on the premise of the same fracture length, the principle of fluid volume balance is followed. The larger the construction displacement is, the more artificial fractures extend to the direction of fracture height. Therefore, the following is the stress...
difference of reservoir interlayer when the simulated displacement is 2m³/min, 3m³/min, 4m³/min and 5m³/min, and the artificial fracture passes through the interlayer.

As it can be seen from the figure, with the increase of displacement, the smaller the stress difference of the reservoir interlayer that restricts the penetration of artificial fractures, which means that the artificial fracture is more likely to penetrate the reservoir interlayer. The stress difference through the upper interlayer decreases from 5.1 MPa to 2.5 MPa, while the stress difference through the lower interlayer decreases from 5.5 MPa to 3.1 MPa, indicating that the increase of displacement will lead to the easier penetration of artificial fractures, which requires a large stress difference between reservoir interlayer to inhibit fracture height extension.

Figure 7. Influence of construction displacement on minimum horizontal principal stress difference of reservoir interlayer

3.4.2. Fracturing fluid density. Simon believes that the gravity gradient of fracturing fluid and the minimum horizontal principal stress gradient can control the extension direction of fracture height. If the gravity gradient of fracturing fluid is greater than the minimum horizontal principal stress gradient, the fracture height extends downward through the lower interlayer. If the gravity gradient of fracturing fluid is less than the minimum horizontal principal stress gradient, the fracture height extends upward through the upper interlayer. Therefore, the following is the stress difference of reservoir interlayer when the simulated fracturing fluid gravity gradient is 0.009MPa/m, 0.010MPa/m, 0.011MPa/m, 0.012MPa/m, 0.013MPa/m, 0.014MPa/m, 0.015MPa/m and 0.016MPa/m, and the artificial fracture passes through the interlayer.

Figure 8. Influence of gravity gradient of fracturing fluid on minimum horizontal principal stress difference of reservoir interlayer
It can be seen from the figure that the variation of gravity gradient of fracturing fluid only has a certain influence on the artificial fracture passing through the upper interlayer. The stress difference through the upper interlayer decreases from 4.5MPa to 49MPa, and the artificial fracture doesn’t affect the lower interlayer, which is due to the minimum horizontal principal stress gradient of 0.006 MPa/m in the model. At present, the density of fracturing fluid is 1.0-1.5g/cm³, of which the density of clear water fracturing fluid is close to 1g/cm³. At present, the density of high density fracturing fluid is known to be 1.35g/cm³. Therefore, changing the density of fracturing fluid can inhibit fracture height extension and artificial fracture penetration to some extent.

3.4.3. Fracture toughness. The fracture toughness of rock reflects its ability to resist the forward propagation of fracture. It can be seen from the formula that when the stress intensity factor is greater than or equal to the fracture toughness of the rock, the fracture height will extend. Therefore, the following is the stress difference of the reservoir interlayers when the fracture toughness of the upper and lower interlayer of rock is simulated as 0.5MPa/m⁰.⁵, 1MPa/m⁰.⁵, 2MPa/m⁰.⁵, 3MPa/m⁰.⁵ and 4MPa/m⁰.⁵, and the artificial fractures penetrate the interlayer.

It can be seen from the figure that the greater the fracture toughness of rock interlayer, the greater the stress difference of artificial fracture through the interlayer. The stress difference of the upper interlayer decreases from 4.1MPa to 3.6MPa with the increase of fracture toughness, while the stress difference of the lower interlayer decreases from 4.4MPa to 3.8MPa with the increase of fracture toughness, indicating that the increase of fracture toughness of rock in upper and lower interlayers can prevent fracture height extension to some extent.

Figure 9. Influence of fracture toughness on minimum horizontal principal stress difference of reservoir interlayer

3.4.4. Reservoir thickness. Reservoir thickness is one of the important factors affecting fracture morphology. The thinner the reservoir is, the greater the net pressure in the fracture is, the greater the stress intensity factor at the fracture tip is, and the smaller the stress difference between the reservoir interlayer is when the artificial fracture passes through the reservoir. Therefore, the following is the stress difference of the reservoir interlayer when the simulated reservoir thickness is simulated as 5m, 10m, 15m, 20m, 25m and 30m, and the artificial fracture penetrates the interlayer.

It can be seen from the figure that with the increase of reservoir thickness, the larger the stress difference of the reservoir interlayer is when the artificial fracture passes through the reservoir. The stress difference of the upper interlayer increases from 3.6MPa to 5.1 MPA, while the stress difference of the lower interlayer increases from 3.9MPa to 5.5MPa.
4. Conclusion

1. The minimum horizontal principal stress difference of artificial fracture passing through interlayer is affected by construction displacement, reservoir thickness and other factors, so variable displacement fracturing and changing fracturing fluid density should be used to control fracture height extension direction for reservoirs with small minimum horizontal principal stress difference, and fracturing construction section should be selected based on reservoir thickness and minimum horizontal principal stress difference.

2. The construction displacement has obvious influence on the minimum horizontal principal stress when the artificial fracture passes through the interlayer. When the construction displacement increases from 2m³/min to 5m³/min, the minimum horizontal principal stress difference decreases obviously. Therefore, when the minimum horizontal principal stress difference of the reservoir is small, the construction displacement should be controlled and changed to the small displacement construction (below 3m³/min) to prevent the artificial fracture from passing through the interlayer when the stress difference of the reservoir is less than 3.5MPa.

3. The criterion of artificial fracture penetration behavior and fracture penetration model are established, which can be used to judge whether the artificial fracture will occur when the artificial fracture extends to the interface of the reservoir interlayer, and the minimum horizontal principal stress difference of the reservoir can be calculated when the artificial fracture extends to the interface of the reservoir interlayer so as to guide the fracturing design.

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