Hindawi
Geofluids
Volume 2022, Article ID 2078289, 10 pages
https://doi.org/10.1155/2022/2078289

Research Article

Experimental Study on Vertical Propagation Behavior of Hydraulic Fracture Affected by Artificial Interlayer for Thick Oil Reservoirs

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Received 29 November 2021; Revised 24 December 2021; Accepted 30 December 2021; Published 20 January 2022

Academic Editor: Jiehao Wang

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Crude oil distribution in thick oil reservoirs is vertically heterogeneous; therefore, there is usually a dominant sublayer where oil resources are higher than that in other sublayers. The region of hydraulic fracture away from the dominant sublayer plays a negative role in production. In order to enhance efficiency of hydraulic fracturing, the hydraulic fracture height should be restricted around the dominant sublayer and the artificial interlayer is believed as an effective method. However, the propagation mechanism of fracture affected by artificial interlayer has been rarely investigated, which restricts the advance of optimization of artificial interlayer. In this paper, the impact of artificial interlayer on vertical propagation of hydraulic fracture is analyzed by hydraulic fracturing experiments and then the mechanism of artificial interlayer affecting propagation of hydraulic fracture is discussed. Based on the understanding of experimental observations and theory of fracture mechanics, the theoretical model of stress intensity factor for the fracture affected by artificial interlayer is proposed. The experimental data shows that the artificial interlayer can significantly decrease the hydraulic fracture height and the corresponding decrease magnitude of hydraulic fracture height depends on the thickness of artificial interlayer, proppant size, and fracture fluid pumping rate. The dominant mechanism of artificial interlayer restricting hydraulic fracture height is that the drop of fluid pressure induced by the artificial interlayer decreases the stress intensity factor at fracture tip. Based on the theory of fracture mechanics, the stress intensity factor at fracture tip is built and it can consider key factors shown by experimental observations. The fracture height solution from this model is consistent with experimental data, so this model can be used to optimize properties of artificial interlayer.

1. Introduction

In the process of oil and gas exploitation, the hydraulic fracturing is a commonly used reservoir stimulation method, which can sharply enhance oil and gas production rate. In Xinjiang oil field, the crude oil distribution is vertically heterogeneous and the top sublayer in thick oil reservoirs is the dominant sublayer where the oil resource is higher than that of other sublayers. If the hydraulic fracture height is much higher than the thickness of this dominant sublayer, the proppants injected into reservoirs usually flow down to the other sublayers. In this case, the fracture in the dominant sublayer cannot gain enough proppants to remain its width after flow back of hydraulic fracturing fluids, which negatively affects oil production for thick oil reservoirs. In addition, excessive hydraulic fracture height can bring problems such as invalid water injection and casing damage, seriously affecting later production [1]. More seriously, hydraulic fractures may communicate with water layer and cause water channeling, which leads to sharp rise of water content in oil wells. Therefore, controlling the hydraulic fracture height is significantly important to improve oil and gas production.

At present, the method to generate an artificial interlay inside hydraulic fracture is the widely used technique to

Table 1: Mechanical properties of physical model specimens [15].

Density (g/cm^3)	UCS (MPa)	Tensile strength (MPa)	Poisson's ratio	Elastic modulus (GPa)
2.11	27.98	3.55	0.17	20.6

control hydraulic fracture height. Initially, the low pumping rate is used to generate a hydraulic fracture with short length and then proppants or diverting agents are carried into the hydraulic fracture by fracturing fluids. When these proppants or diverting agent place at the bottom of the hydraulic fracture, the artificial interlayer is generated. After that, common pumping schedule is used to generate hydraulic fractures. Because of the artificial interlayer, the hydraulic fracture height usually decreases. Research on how to generate the artificial interlayer and the mechanism of artificial interlayer restricting fracture height have been investigated. Mukherjee [2] recommended the use of low viscosity fracturing fluids with lighter proppant to seal the top fracture ends and successfully restricted hydraulic fracture height. Talbot et al. [3] proposed a hydraulic fracturing method to limit fracture height propagation by adding front fluid with sand for bottom-water and energy-depleted reservoirs. It is widely believed that the stress difference between vertical layers of reservoirs is the dominant factor to suppress the vertical propagation of hydraulic fractures. The artificial interlay technique increases the pressure drop inside hydraulic fracture and the pressure at fracture tip decreases as well, so the hydraulic fracture height can be restricted [4]. Dali et al. [5–10] studied the factors influencing fracture height propagation of hydraulic fractures by using theoretical model and numerical simulation and proposed that the use of artificial interlayer, variable displacement, and low-viscosity fracturing fluid can effectively control the fracture height. Barree and Mukherjee [11] studied the effects of pumping rate, fluid viscosity, proppant concentration, proppant size, and specific gravity on the effectiveness of the placement of artificial interlayers according to a theoretical model. Salah et al. [12] used artificial interlayer to control fracture height growth in the absence of in situ stress contrasts in Egypt's Western Desert. Another field applications showed that successful placement of artificial interlayer can control the fracture height and increasing the fracture half-length [13, 14]. Theoretical model, numerical simulation, and field application results all show that artificial interlayers can significantly control the height of hydraulic fractures. For mechanism research, both the numerical model and theoretical model simplify the formation conditions, and it is difficult to describe the true fracture propagation process. Based on the true triaxial physical simulation experiment, the hydraulic fracture propagation process under the interference of real artificial interlay is simulated, which is more in line with the actual construction of the oil field. However, the experimental research on the principle and influencing factors of artificial interlayer controlling hydraulic fracture height is rarely reported.

In this paper, hydraulic fracturing experiments are first conducted to illustrate the impact of artificial interlay on hydraulic fracture height. An artificial interlayer is generated in artificial rock samples before hydraulic fracturing experiments are conducted. The triaxial stress condition is applied at artificial rock samples to reflect the in-situ stress of thick oil reservoirs. Based on the theory of fracture mechanics and experimental observations, the main mechanics of artificial interlay controlling fracture height is discussed. Finally, the theoretical solution of stress intensity factor for fractures with artificial interlayer is proposed and it is validated by experimental data. Experiment results and theoretical model show that the thickness and pressure drop gradient are the main factors influencing artificial interlayer restricting fracture height.

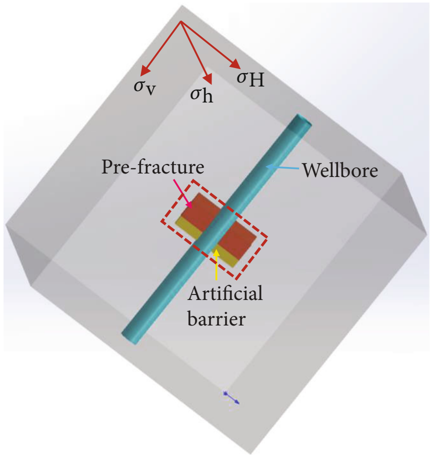
2. Physical Simulation Experiment with Artificial Interlayer

The main influencing factors of artificial interlayer controlling fracture height include fracture pressure, fracture toughness, thickness, and pressure drop gradient of artificial interlayer. In the process of hydraulic fracturing, the fracture toughness and in situ stress are reservoirs' properties. Therefore, a true triaxial physical simulation experiment with artificial interlayer is carried out in this paper to study the influence of fracture pressure, thickness, and pressure drop gradient of artificial interlayer on hydraulic fracture height.

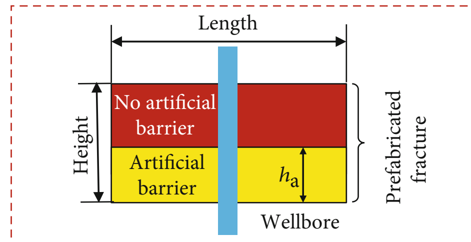
2.1. Experimental Design. The physical simulation test piece is mixed with PC32.5R composite Portland cement and 0.12~0.38 mm quartz sand in a certain proportion and cured for 24 days. Its mechanical properties are cited from Reference [15] and shown in Table 1. The size of the test piece is 300 mm × 300 mm × 300 mm.

Artificial fractures are prefabricated inside the prefabricated specimens in advance, and artificial interlayer made of ceramic particles is placed at the bottom of the prefabricated artificial fractures. Artificial interlayers generated by different sizes ceramic particles have different pressure drop gradients. The design and boundary conditions of specimens are shown in Figure 1. The prefabricated artificial fracture is in the middle of the artificial wellbore to simulate vertical well. The normal direction of prefabricated fractures is parallel to the minimum horizontal principal stress direction (as shown in Figure 1(a)). An artificial interlayer is formed at the bottom of the prefabricated fracture by sedimentation of proppant, and its thickness is half of the height of the prefabricated fracture (as shown in Figure 1(b)).

In reality, the permeability and fluid loss capacity of reservoir are limited and increasing the injection rate can increase the fracture pressure [7]. By changing the thickness h_a of the artificial interlayer, the particle size R of the proppant, and the fracturing fluid pumping rate v, the impacts of the thickness of the artificial interlayer, the pressure drop gradient, and the fracture pressure on fracture height are studied.



(a) Schematic diagram of physical simulation specimen



(b) Schematic diagram of prefabricated fracture and artificial interlayer

Figure 1: Sketch of experimental sample.

The 300R2 high temperature and high stress hydraulic fracturing simulation equipment (Figure 2) is used for this experiment, and it is designed and constructed by the Rock Mechanics Laboratory of China University of Petroleum (Beijing). The maximum load capacity of this equipment is 50 MPa, and the maximum temperature is 180°C; the required size of the specimen is 300 mm × 300 mm × 300 mm.

The specific experimental grouping design is shown in Table 2. In this paper, 5 physical simulation experiments are designed. In experiments 1-1, 1-2, and 1-3, the thickness (h_a) of artificial interlayer is 5, 15, and 20 mm, respectively, which is formed by 40/70 proppant (R). The fracture fluid pumping rate (v) is 6 ml/min in the above three experiments. For experiment 1-4, h_a is 15 mm, R is 40/70 mesh, and v is 12 ml/min. For experiment 1-5, h_a is 15 mm, R is 70/140 mesh, and v is 6 ml/min.

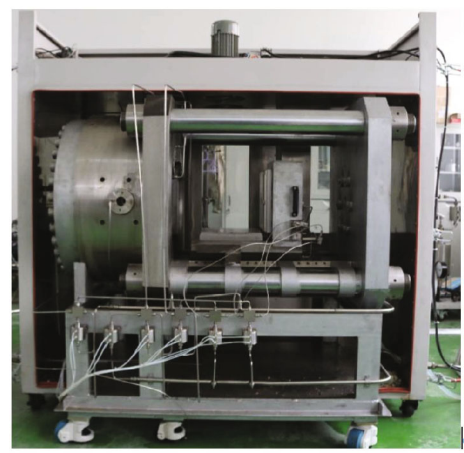


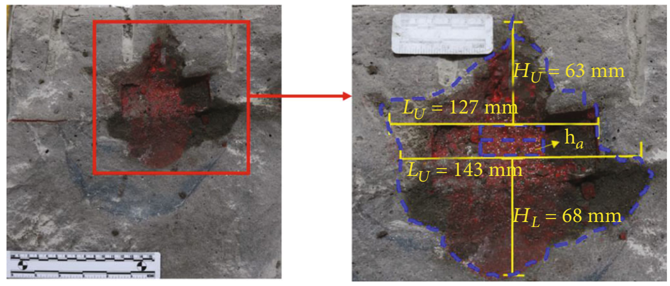
Figure 2: 300R2 high temperature and high stress hydraulic fracturing simulation equipment.

Table 2: Physical simulation experiment parameters.

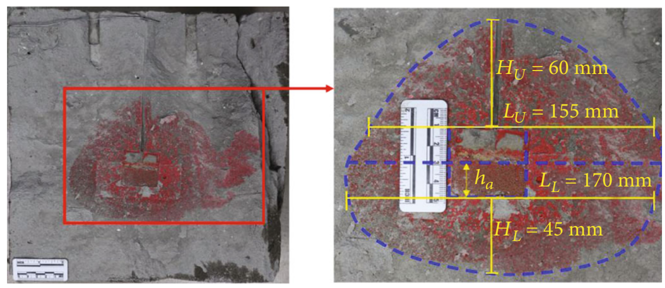
Sample no.	h_a (mm)	v (ml/min)	R (mesh)
1-1	5		
1-2	15	6	40/70
1-3	20		
1-4	15	12	
1-5	15	6	70/140

2.2. Experimental Results. The illustration of samples used in this experiment is shown in Figure 1. A prefabricated fracture and an artificial interlay are first prefabricated in the physical simulation test piece. The length of this fracture is 25 mm, and its height is 20 mm. The length of this artificial interlay is 25 mm. In order to investigate the impact of pressure drop on hydraulic fracture propagation, different height values of the artificial interlay are set, and they are 5 mm, 15 mm, and 20 mm in different cases. In addition, the triaxial stresses are applied at this sample and they are the vertical stress σ_v, the minimum horizontal stress σ_h, and the maximum horizontal stress σ_H. Their values are set the same in different cases, and they are 25 MPa, 10 MPa, and 15 MPa, respectively. The directions of these three stresses are set based on the theory of fracture mechanics. The value of minimum horizontal stress is the least among these three stress values, so its direction is parallel to the normal direction of prefabricated fracture. The direction of vertical stress is the same with the well direction. The value of vertical stress is the highest among these three stress values, so the hydraulic fracture generated in this experiment propagates vertically.

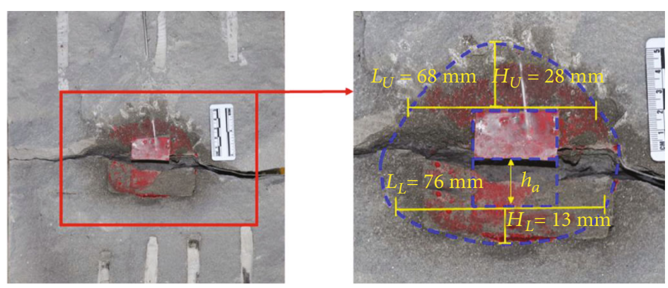
The experimental results are shown in Figure 3. In order to quantitatively analyze the effect of artificial interlayers, the ratio of the height of fracture with the artificial interlayer $(H_L + h_a)$ to the height of fracture without the artificial interlayer $(H_U + h_a)$ is used to evaluate the effect of the artificial interlayer controlling fracture height. The high ratio value indicates a low magnitude of artificial interlayer restricting hydraulic fracture height. The ratio of the length of the hydraulic fracture to its height (H_L/L_L or H_U/L_U) is used to evaluate the influence of the artificial interlayer on the shape of the hydraulic fracture. The high ratio value



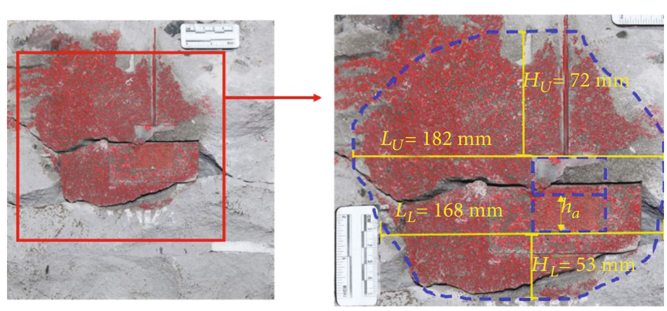
(a) Experiment 1-1



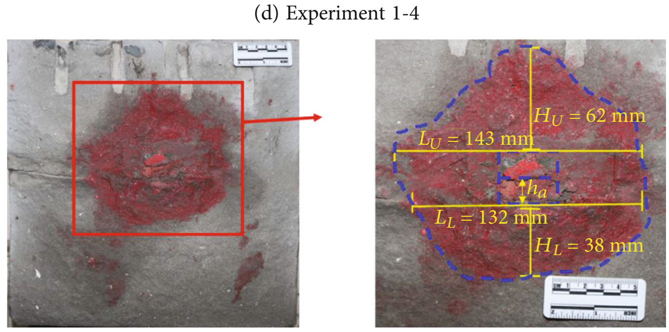
(b) Experiment 1-2



(c) Experiment 1-3



(d) Experiment 1-4



(e) Experiment 1-5

Figure 3: Experimental results of physical model with artificial interlayers.

Table 3: Experimental results of physical model with artificial interlayers.

Exp no.	$(H_L + h_a)/(H_U + h_a)$	H_L/L_L	H_U/L_U
1-1	0.92	68/143 = 0.48	63/127 = 0.50
1-2	0.8	45/170 = 0.26	60/155 = 0.39
1-3	0.69	13/76 = 0.17	28/68 = 0.41
1-4	0.78	53/168 = 0.30	72/182 = 0.38
1-5	0.69	38/132 = 0.29	62/143 = 0.43

Table 4: Factor normalization.

Factors	h_a (mm)			v (ml/min)		R (mesh)	
	5	15	20	6	12	40/70	70/140
Control effect	0	25%	53%	25%	26%	25%	38%
Normalized results	0	0.47	1	0.47	0.49	0.47	0.72

indicates a low magnitude of artificial interlayer restricting hydraulic fracture shape.

By comparing the results of experiments 1-1, 1-2, and 1-3 (seen in Figures 3(a)–3(c)), the thickness of artificial interlayer has a significant influence on the propagation morphology of hydraulic fracture. When the thickness of artificial interlayer is 5 mm, H_U/L_U and H_L/L_L are approximately equal (0.50 and 0.48). However, when the thickness is 15 mm and 20 mm, H_U/L_U is significantly greater than H_L/L_L (0.39 and 0.26; 0.41 and 0.17). When there is an artificial interlayer with a suitable thickness (>5 mm), the hydraulic fracture always preferentially expands in the horizontal direction and the fracture length increases sharply. At the same time, the artificial interlayer can effectively control the height of hydraulic fracture. When the thickness of artificial interlayer increases from 5 mm to 15 mm and 20 mm, $(H_L + h_a)/(H_U + h_a)$ decreases from 0.92 to 0.8 and 0.69, and the effect of artificial interlayer to control the height of the fracture is gradually increasing.

The fracture fluid pumping rates used in experiments 1-2 and 1-4 are 6 ml/min and 12 ml/min, respectively. By comparing Figures 3(b) and 3(d), as shown Table 3, H_U/L_U is greater than H_L/L_L for both of experiments 1-2 and 1-4. The interlayer can always influence the morphology of hydraulic fracture under different pumping rate. When the pumping rate increases from 6 ml/min to 12 ml/min, $(H_L + h_a)/(H_U + h_a)$ decreases from 0.8 to 0.78. It indicates that the pumping rate has no obvious impact on fracture height.

In experiments 1-2 and 1-5, artificial interlayer is fabricated with 40/70 and 70/140 proppant, respectively. The results of experiment 1-5 are the same as that of experiment 1-2; H_U/L_U is greater than H_L/L_L. When the proppant size decreases (the size of 40/70 proppant is larger than that of 70/140 proppant), $(H_L + h_a)/(H_U + h_a)$ decreases from 0.8 to 0.69. Therefore, the impact of artificial interlayer on restricting fracture height increases with the decrease of proppant size of artificial interlayer.

In order to analyze the influence degree of the thickness of artificial interlayer, pumping rates, and proppant sizes on fracture height restriction induced by artificial interlayer, the experimental results in Table 3 are normalized by influencing factors, and the results of factor normalization are shown in Table 4. The control effect is defined as $(H_U - H_L)/H_U$ to describe the effect of artificial interlayer controlling the height of hydraulic fracture. The normalized results are between 0 and 1, which is calculated by the maximum and minimum value of control effect (normalized results = control effect − minimun/maximum − minimum).

It can be seen from Table 4 that the impact of the artificial interlayer on fracture height restriction can be significantly improved by increasing thickness of the artificial interlayer, decreasing pumping rate, and decreasing proppant size. The normalization results show that the thickness of artificial interlayer has the most significant impact on fracture height restriction by artificial interlayer, followed by the proppant size and the pumping rate.

2.3. Discussion. The artificial interlayer inside fracture affects fluid flow behavior and may induce pressure drop; therefore, the fluid pressure in fracture with artificial interlayer is less than that in fracture without artificial interlayer [16–18]. In order to show whether the pressure drop can be induced by artificial interlayer, the permeability of artificial interlayer is measured. According to Darcy's law, the pressure drop can be calculated if the velocity and viscosity of fluid flow and the permeability are known.

In this paper, FCS-842 equipment produced by Core-Lab is used to get permeability of artificial interlayer. In order to simulate the different closing pressure in hydraulic fractures, different confining pressure is applied on two rock slabs during this experiment. At the same time, pressure drop gradient can be calculated using the Darcy' law:

$$dp = \frac{v\mu}{kA}, \tag{1}$$

where v is pumping rate, μ is viscosity, k is permeability, A is cross-section area, and dp is pressure drop gradient. The pumping rate, viscosity, and cross-section area can be

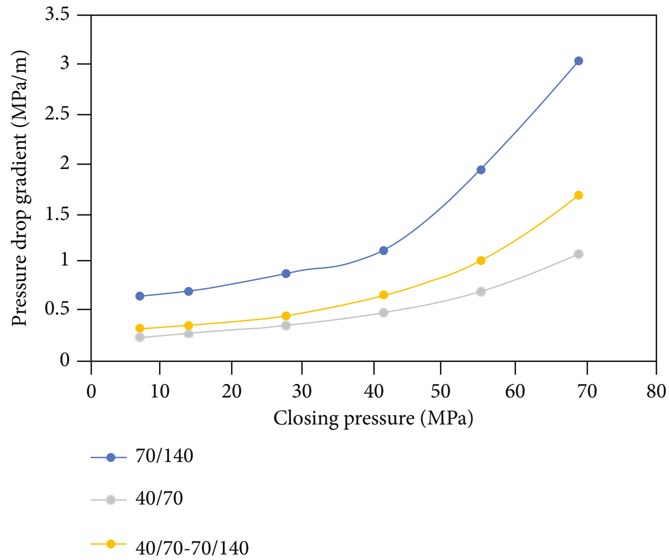


Figure 4: Pressure drop gradient of artificial interlayer.

recorded and measured in experiments. The permeability value can also be obtained by experiments. Therefore, the pressure drop gradient can be calculated. The proppant is statically placed in the rock slab to simulate the artificial interlayer formed in the hydraulic fracture. Short-term permeability tests of artificial interlayer with proppant sizes of 40/70 and 70/140 and mixed particle sizes (40/70 and 70/140; mass ratio 1 : 1) are carried out to calculate the pressure drop gradient of artificial interlayers, as shown in Figure 3.

As shown in Figure 4, by comparing the pressure drop gradient of artificial interlayer formed by different proppant sizes, the pressure drop gradient of 70/140 is about 50% higher than that of 40/70. At the same time, under the high closing pressure (>41 MPa), the pressure drop gradient of 70/140 artificial interlayer is significantly higher than that of 40/70. The above results indicate that artificial interlayer formed by small proppant size can increase the drop of fluid pressure inside hydraulic fracture to decrease stress intensity factor at fracture tip and restrict fracture height. In addition, the pressure drop of fluid pressure in hydraulic fracture increases with the increase of thickness of artificial interlayer. These conclusions can explain the phenomenon of physical simulation experiment in Section 2.3.

3. Theoretical Model

For thick reservoirs with less stress difference between vertical layers, hydraulic fracture propagation is less constrained by this stress difference between vertical layers, and the excessive fracture height is generated. The hydraulic fracture with large height can connect reservoirs with the water layer and reduce the efficiency of hydraulic fracturing stimulation. In order to predict the fracture height, a theoretical model of stress intensity factor for hydraulic fracture with artificial interlay is established. This model includes main factors affecting stress intensity factor. According to theory of fracture mechanics, when the stress intensity factor exceeds the fracture toughness, the fracture can propagate. After fracture propagates, more in situ stress is applied at this fracture, so the stress intensity factor decreases. If the new stress intensity factor still exceeds the fracture toughness, the hydraulic fracture can continue propagating. When the stress intensity factor equals to the fracture toughness, the hydraulic fracture can stop to propagate. Therefore, making stress intensity factor equal to fracture toughness can obtain the hydraulic fracture height.

3.1. Illustration of Hydraulic Fracture with Artificial Interlayer. In order to simplify the model and calculation, the theory of fracture mechanics for elasticity material is used in this paper. Although the plastic region exists around fracture tip and affects the solution of stress intensity, the plastic region size is less than the size of hydraulic fracture so the impact of plastic region on stress intensity factor on hydraulic fracture is ignorable. Therefore, the theory of fracture mechanics for elasticity material is widely used to predict the propagation behavior of hydraulic fracture. In order to build the theoretical model of stress intensity factor for hydraulic fracture with artificial interlayer, the following assumptions are used:

(1) The stress difference between thick reservoir and up/down interlayer are large enough so the hydraulic fracture only propagates within the thick reservoir. This assumption is consistent with geology features of thick reservoirs in Xinjiang oil field

(2) The rock is an ideal linear elastic material. The shape of the reservoir and hydraulic fracture is axisymmetric

(3) The permeability of reservoir is low, and the period of hydraulic fracturing is short, so the loss of fracturing fluid into reservoir is ignored

(4) The pressure drop gradient in hydraulic fracture is much lower than that in artificial interlayer, so the pressure drop in hydraulic fracture is ignored

The conceptual illustration of hydraulic fracture with artificial interlayer is shown in Figure 5. The thick reservoir is divided into two regions. The top region is the region where the oil resource is high, and the bottom region is the region where the oil resource is low. The fracture height can be divided into three parts. The top part is the fracture in top region of reservoir (h_r) and is the fracture beneficial to production. The bottom part is the fracture in bottom region of reservoir (h_b). The third part of fracture is the one filled by artificial interlayer (h_a). If there is no artificial interlayer, this hydraulic fracture can go through the whole reservoir. If the artificial interlayer exists, the hydraulic fracture stops at some position in bottom region of reservoir. The minimum horizontal stress values between top and bottom regions are also different and are represented by symbols σ_r and σ_b. The artificial interlayer is a porous medium. According to Darcy's law, the hydraulic fracturing fluid flows through this artificial interlayer can experience an additional pressure drop and the pressure gradient of pressure drop is represented by K_a.

3.2. Fracture Propagation Model considering Impact of Artificial Interlayer. Based on the theory of linear elastic fracture mechanics, the stress intensity factor generated by the stress acting on the fracture surface at the upper and lower tips of the fracture is [19]

$$K_{It} = \frac{1}{\sqrt{\pi H}} \int_0^H p(y) \sqrt{\frac{H+y}{H-y}} dy, \tag{2}$$

$$K_{Ib} = -\frac{1}{\sqrt{\pi H}} \int_H^0 p(y) \sqrt{\frac{H-y}{H+y}} dy, \tag{3}$$

where K_{It} and K_{Ib} are the stress intensity factor at the top and bottom tips of the fracture; H is the height of fracture; and $p(y)$ is the net pressure inside hydraulic fracture.

According to the stress condition shown in Figure 5, the net pressure inside hydraulic fracture ($p(y)$) is

$$p(y) = \begin{cases} p_f - \sigma_r \, 0 < y < h_r, \\ p_f - \sigma_b \, h_r < y < H. \end{cases} \tag{4}$$

Substituting the above equation into Equation (2), the stress intensity factor at lower tip of fracture (K_{Ib}^1) is

$$K_{Ib}^1 = \frac{1}{\sqrt{\pi H}} \left(\int_0^{h_r} \left(p_f - \sigma_r\right) \sqrt{\frac{H+y}{H-y}} dy + \int_{h_r}^H \left(p_f - \sigma_b\right) \sqrt{\frac{H+y}{H-y}} dy \right). \tag{5}$$

The thickness of the artificial interlayer is $y = h_a$, and the pressure drop gradient of this interlayer is K_a. According to Darcy's law, the pressure drop is [20]

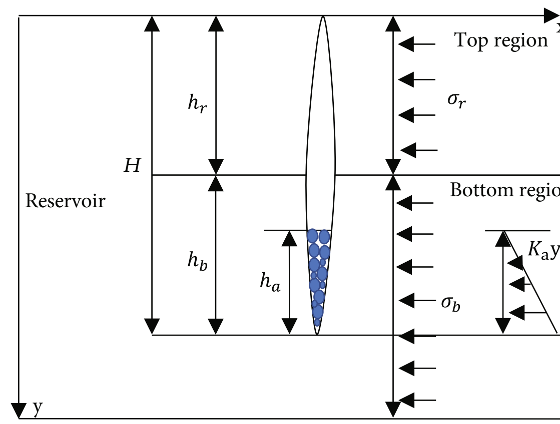


Figure 5: Stress distribution on fracture surface with artificial interlayer.

$$p(y) = K_a y. \tag{6}$$

Substituting the above equation into Equation (2), the stress intensity factor induced by pressure drop (K_{Ib}^2) is

$$K_{Ib}^2 = -\frac{1}{\sqrt{\pi H}} \int_0^{h_a} K_a y \sqrt{\frac{H+y}{H-y}} dy. \tag{7}$$

The stress intensity factor at lower fracture tip equals the sum of values of stress intensity factors shown in Equations (5) and (7):

$$K_{Ib} = \frac{1}{\sqrt{\pi H}} \left(\int_0^{h_r} \left(p_f - \sigma_r\right) \sqrt{\frac{H+y}{H-y}} dy + \int_{h_r}^H \left(p_f - \sigma_b\right) \sqrt{\frac{H+y}{H-y}} dy - \int_{H-h_a}^H K_a y \sqrt{\frac{H+y}{H-y}} dy \right). \tag{8}$$

When the stress intensity factor at lower fracture tip equals to fracture toughness, the vertical propagation of hydraulic fracture will stop. This critical condition is

$$K_{Ib} = K_{Ic}. \tag{9}$$

By combining Equations (8) and (9), the model to solve hydraulic fracture height is

$$\begin{aligned} \frac{K_{Ic}}{\sqrt{\pi (h_b + h_r)(\sigma_b - \sigma_r)}} &= \arcsin\left(\frac{h_r - h_b}{h_r + h_b}\right) + \frac{p_f - \sigma_b}{\sigma_b - \sigma_r}\left(\frac{\pi + 2}{2}\right) \\ &+ \frac{K_a \left(\dfrac{h_a - 3(h_r + h_b)}{2} \sqrt{(h_b + h_r)^2 - (h_a - h_b + h_r)^2} \right)}{2\pi (h_b + h_r)(\sigma_b - \sigma_r)} \\ &+ \frac{K_a (h_r + h_b)^2}{4\pi (h_b + h_r)(\sigma_b - \sigma_r)} \arcsin \frac{h_r}{h_r + h_b} - \frac{K_a}{4(h_b + h_r)(\sigma_b - \sigma_r)}. \end{aligned} \tag{10}$$

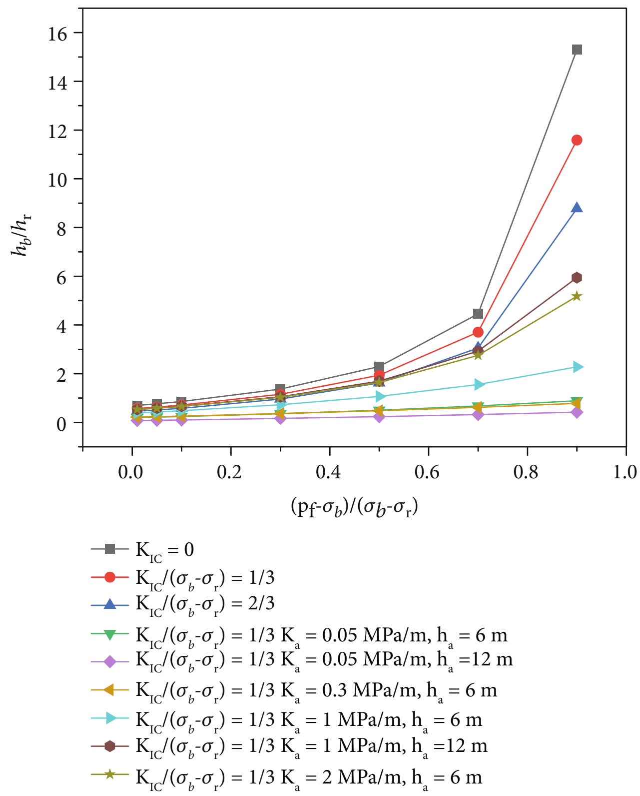


Figure 6: The ratio of the fracture height in the reservoir and the interlayer (h_b/h_r) under different conditions (hr equals to 10 m).

Table 5: Experimental results of physical model and solution results of theoretical model.

Sample no.	1-2	1-3	1-4	1-5
h_a (mm)	15	20	15	15
σ_b, σ_r (MPa)	5	5	5	5
K_a (MPa/m)	0.32	0.32	0.32	0.65
h_r (mm)	60	28	72	62
h_b (mm)	45	13	53	38
P_f (MPa)*	4	4	4	5
K_{Ic} (MPa $\sqrt{m}$)	1.8	1.75	1.9	1.15
Experimental results	0.80	0.69	0.78	0.69
Theoretical results	0.92	0.81	0.89	0.83
Error	15%	17%	14%	20%

*P_f is from fracture fluid injection pressure curve of physical model experiments.

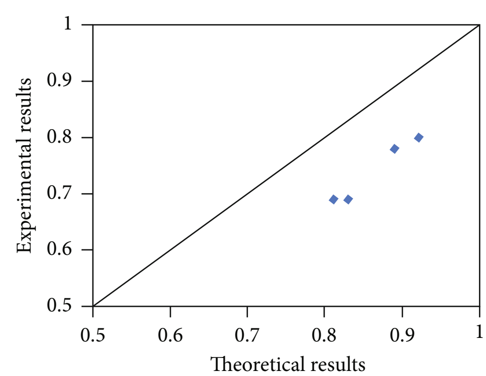


Figure 7: Comparison between theoretical solutions and experimental results.

In the above equation, h_r is the height of top region of reservoir; K_{IC} denotes fracture toughness of rocks; σ_r, σ_b are stress values within the reservoir layer and bottom layer, respectively; K_a and h_a are properties of artificial interlayer; and P_f is fracture pressure. If these parameters are known, the unknown h_b can be solved by this equation. Several sensitivity study results are shown in Figure 6. The ratio of h_b to h_r increases with P_f. In order to restrict hydraulic fracture height, the P_f cannot be too large. When the fracture pressure is large enough ($(p_f - \sigma_b)/(\sigma_b - \sigma_r) > 0.6$), the h_b starts to increase sharply. The increase of fracture toughness is beneficial to restrict the fracture height. The artificial interlayer can also significantly decrease fracture height because it induces more pressure drop inside fracture and makes fracture pressure at fracture tip decrease. The impact of pressure drop induced by artificial interlayer on decrease of fracture height is obviously higher than that of fracture toughness increase. When the fracture toughness becomes two times of its initial value, the ratio of h_b to h_r decreases from 15 (last point in red line with rhombus) to 10 (last point in blue line with circle). When the K_a is very few (only 0.05 MPa/m), the ratio of h_b to h_r decreases from 15 (last point in red line with rhombus) to 7 (last point in green line

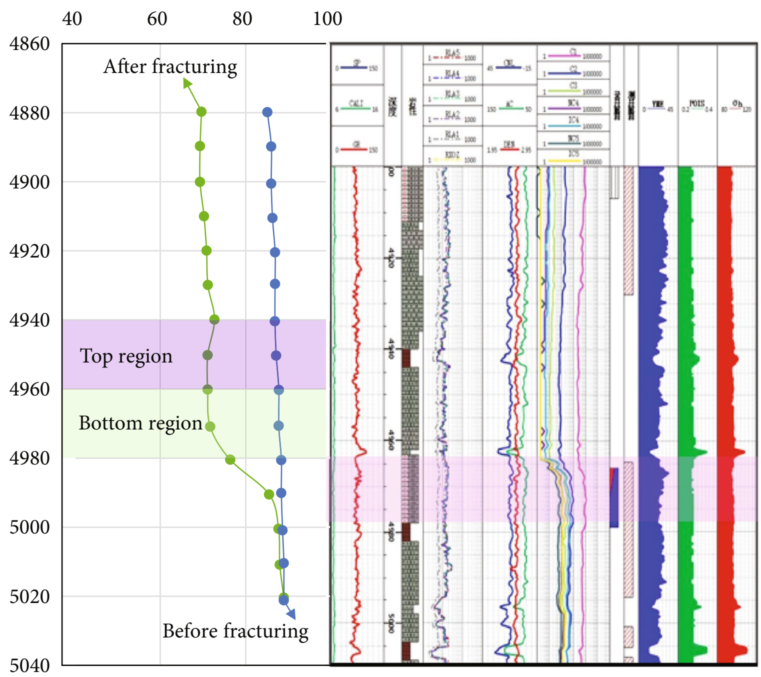


Figure 8: Well temperature monitoring curve of a well in Mahu before and after fracturing.

with cross). When K_a is over 1 MPa/m, the performance of artificial interlayer to restrict hydraulic fracture height is good enough. In this case, the ratio of h_b to h_r is less than 1.

4. Model Verification and Application

In order to validate the theoretical model proposed in Section 1, the conditions and parameters used in experiments completed in Section 2 are substituted into this theoretical model proposed in Section 3. The theoretical solutions are shown in Table 5. Since the artificial interlayer in experiment 1-1 does not restrict fracture propagation, the experimental results from experiments 1-2 to 1-5 are compared with the theoretical solution (shown in Figure 7). The maximum error between theoretical solution and the experimental data is less than 20%.Therefore, this theoretical model has a high accuracy.

Based on the above analysis, the theoretical model proposed in this study is accurate so it can be used to optimize the design of artificial interlayer. For a certain reservoir, the in situ stress values, the reservoir thickness, and fracture toughness are known by well-logging or experiments. The pressure drop gradient of artificial interlayer can be determined by permeability experiments and Darcy's law. Therefore, in this model, only three parameters are unknown, and they are fracture pressure (p_f), thickness of artificial interlayer (h_a) and fracture height in bottom reservoir (h_b). The fracture pressure (p_f) and thickness of artificial interlayer (h_b) can be variables. In this case, only h_b is unknown so it can be solved by the theoretical model. Figure 8 shows solutions of h_b/h_r for different cases. If engineers set a reasonable h_b/h_r, from these curves, the optimization parameters of artificial interlayer, such as h_a and K_a, can be determined.

Use the theoretical model derived in Section 3.2 to optimize the hydraulic fracture design for a well in the Mahu area in Xinjiang province. The reservoir thickness is 20 m, and the top 6 m is the target. The stress difference in vertical direction is only 2~3 MPa, and artificial interlayers are needed to control the bottom during hydraulic fracturing. Based on the theoretical model obtained in this paper, the design of the interlay height is 1 m, the pressure drop gradient is 1 MPa/m, and 40/70 mesh proppant is selected. The formation of the artificial interlay consumes a total of 4 m^3 of sand-carrying liquid with a viscosity of 30 mPa·s and a sand ratio of 6%, 7%, 8%, and 9%. According to the design parameters, the construction displacement is 4-5 m^3/min, the total guar gum fracturing fluid is 444 m^3, and the total sand is 45 m^3. From the well temperature monitoring curve, the lower fracture height is about 20 m, which has achieved the effect of height control by artificial interlayers (Figure 8).

5. Conclusion

In this paper, in order to illustrate the impact of artificial interlayer on fracture propagation, several physical simulation experiments are conducted and several factors affecting fracture height are shown. The mechanism of artificial interlayer restricting fracture height is discussed. Based on the theory of fracture mechanics and experimental observations, theory model for fracture height affected by artificial interlayer is proposed. The main findings are as follows:

(1) Experimental observations show that artificial interlayer can effectively restrict fracture height. The main factors include thickness of artificial interlayer, proppant size, and pumping rate

(2) The main mechanism of artificial interlayer restricting fracture height is that artificial interlayer can decrease fluid pressure inside fracture and then decrease stress intensity factor at fracture tip. In order to effectively restrict fracture height, the size of proppant generating artificial interlayer should be small enough and the artificial interlayer should be thick enough. The smaller proppant size and thicker artificial interlayer can induce more pressure drop

(3) The theoretical model proposed in this study is consistent with experimental data, and it can be used to optimize parameters of artificial interlayer, such as its thickness, proppant size, and fluid pressure inside fracture

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to acknowledge the financial contribution of Engineering Technology Research Institute of Xinjiang Oilfield Company through the project of Optimization of Key Parameters to Improve Fracturing Effect of Deep Exploration Wells. This work is also supported by the National Natural Science Foundation of China (Grant No. 52004302) and Science Foundation of China University of Petroleum, Beijing (No. 2462021YXZZ012).

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