Hydrofracture plugging mechanisms and evaluation methods during temporary plugging and diverting fracturing

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Abstract
Temporary plugging and diverting fracturing (TPDF) technique shows great advantages in stimulating unconventional oil and gas reserves. Revealing the fracture plugging mechanism and establishing the evaluation method are beneficial for revealing the mechanism of forming multiple fractures during TPDF. This work revealed the processes of plugging the fractures based on the typical injection pressure curve of hydraulic fracturing operation and then applied the stress cage model, the fracture closure stress model, and the fracture propagation resistance model to reveal the fracture plugging mechanisms. Moreover, this paper establishes a 2D XFEM model to evaluate the fracture plugging effect, and the reliability of the model is verified against the finite element model. Based on the XFEM model, this work investigates the fracture plugging effects influenced by the uneven distribution of net pressure within the fracture. The results prove that fracture mouth plugging of TPF mainly enhances the wellbore circumferential stress, in-fracture plugging mainly enhances fracture closure pressure, fracture tip plugging mainly hinders fracturing fluids flowing toward fracture tips, all of them aim at enhancing the reopen pressure of the existing fractures and prevent the propagation of the existing fracture. Diverter bridging and plugging can change the distribution of fracture net pressure and dramatically reduce the fracture tip stress factor, and thus, the existing fracture propagation can be efficiently stopped.

KEYWORDS
evaluation of temporary plugging, extended finite element method, reservoir stimulation, unconventional oil/gas
1 | INTRODUCTION

To date, hydrocarbon resources are still the main energy source. The conventional hydrocarbon resource (oil/gas from the reservoir with high permeability) has become into the late development stage and the corresponding production decreases gradually, while the unconventional hydrocarbon resources demonstrate the great potential, and the corresponding production accounts for nearly 70% of the total hydrocarbon production. Moreover, hydraulic fracturing is an indispensable technique to economically develop unconventional hydrocarbon resources because the hydrofractures can be created and the contact area with a reservoir can be greatly enhanced through hydraulic fracturing. Reported researches proved that the more complex the hydrofractures, the higher the hydrocarbon production. However, hydrofractures tend to propagate along the path with less resistance, and the reservoir cannot be stimulated evenly. Recently, temporary plugging and diverting fracturing (TPDF) have been applied to plug the previously created hydrofractures with self-degradable diverters and divert the injection fluids to the poorly treated regions, and thus, the whole reservoir can be stimulated uniformly. During TPDF, particulate-shaped diverters and fiber-shaped diverters are injected into the hydrofractures, the bridging and plugging position can be controlled by adjusting the size and the concentration of the diverters.

As shown in Figure 1, TPDF can be divided into four categories according to the construction purpose: (1) in-plane TPDF near the wellbore, staged TPDF along the horizontal well, layered TPDF along the vertical well, and in-fracture TPDF. Similarly, diverters are injected to plug the previously created hydrofractures, and the net pressure can be enhanced to a high level within the wellbore or the hydrofractures; the subsequent fluids can then be diverted to the unstimulated layer, perforation clusters, and thus, the stimulated volume of the reservoir can be enlarged greatly. After that, the diverter can be dissolved within the fracturing fluids, flow back to the ground, and do no damage to the reservoir. The created hydrofractures recover their conductivity and the well begins to produce the hydrocarbons. Therefore, the key to TPDF lies in the plugging and pressurization mechanism of the previously created hydrofractures.

To date, the mechanism of plugging and pressurization during TPDF has not been thoroughly studied. Fortunately, three models have been proposed to reveal the mechanism of wellbore fracture plugging during the well-drilling operation. The models include the stress cage model, the fracture closure stress model, and the fracture propagation resistance model. However, these three models can only qualitatively analyze the plugging mechanism of hydrofracture. For quantitative analysis, researchers mainly calculate the fracture tip stress intensity factor under the condition of wellbore fracture plugging based on the mathematical or numerical methods. The hydrofracture can be effectively plugged when the fracture tip stress intensity is less than the rock fracture toughness.

Ito et al. used the flat fracture model to analyze the increase of injection pressure after fracture plugging. Wang
et al. divided the whole hydrofracture into two parts: the fracture tip section and the fracture plugging section when the hydrofracture is effectively plugged. Based on the principle of linear elastic superposition, they calculated the stress intensity at the fracture tips under the conditions of various boundary loads and pressure distribution. Kang et al. summarized the three plugging theories of the stress cage, the plugged zone, and the strength ring and established the corresponding plugging pressure-bearing capacity enhancement models. Moreover, the calculation model of the fracture stress factor was derived based on the stress cage theory. Jia et al. proposed the calculation formula of fracture tip stress intensity factor considering the pressure distribution based on the superposition principle and analyzed the influences of the plugging section length, the fluid viscosity, the plugging section permeability, the fracture length, and the wellbore pressure on the fracture tip stress intensity factor. Feng and Gray derived a computational model of stress intensity factor at fracture tip after fracture plugging, based on the Kirsh stress equation and the fracture mechanics criteria. The model considers the effects of fracture geometry (fracture length and plugging location), stress conditions (far-field stress, pore pressure, wellbore pressure, and intrafracture pressure), and the rock mechanical properties. Loloi et al. studied the stress cage effect by using the finite element method and clarified the stress concentration mechanism near the wellbore with single or multiple fractures. Zhao et al. established a fluid-solid fully coupled fracture propagation model based on the cohesive zone model and systematically analyzed the factors that cause the hydrofracture to stop propagation.

Typically, there are obvious differences in the plugging and pressurization mechanisms between the TPDF and well drilling in terms of scale and fluid pressure distribution within the fractures. This paper focuses on the mechanical mechanism of fracture plugging and pressure enhancement during TPDF. Furthermore, a new evaluation method of plugging effect is established, which can consider the influence of the nonuniform distribution of the net pressure within the fractures. Typically, the surfaces of the hydrofracture are rough and tortuous, fluid friction exists during fluid flow, and thus, the fluid pressure varies along the hydrofracture. Moreover, during TPDF, the bridging and plugging position of the diverters depends on the fracture morphology and the diverter recipe, which further changes the fluid flow distribution. The structure of the work is presented as: (1) the first part introduces the theory of the fracture plugging and diversion based on the typical pumping pressure curve during hydraulic fracturing; (2) the physical models of stress cage, fracture closure stress, and fracture propagation resistance are applied to reveal the mechanism of fracture plugging and pressurization; (3) a 2D XFEM model is established to evaluate the fracture plugging effects based on the extended finite element method and the fracture mechanics theory.

The innovation of this work includes (1) revealing the mechanical mechanism of fracture plugging and pressure enhancement during TPDF; (2) proposing a numerical method for the calculation of the hydrofracture stress intensity factor when considering in-fracture plugging; (3) establishing a numerical model to evaluate the influence of the nonuniformly distributed fluid pressure on the fracture plugging effect.

2 | PHYSICAL MODEL OF FRACTURE PLUGGING AND PRESSURIZATION

During TPDF, fracture plugging can be divided into three categories based on the plugging position: the fracture mouth plugging, the fracture throat plugging, and the fracture tip plugging. Wherever the position of the tight plug, the purpose of TPDF is to prevent the further propagation of the previously created hydrofractures. During hydraulic fracturing, the whole process includes three stages: hydraulic fracture initiation, hydraulic fracture propagation, and hydraulic fracture closure. As shown in Figure 2, when the injection pressure reaches the fracture initiation pressure (FIP), the injected fluid flows into the formation to form microfractures; when the injection pressure reaches the fracture breakdown pressure (FBP), a large amount of injected fluid flows into the formation to form an obvious hydrofracture; after the FBP, the injection pressure rapidly decreases to the level of the fracture propagation pressure (FPP), and the hydrofracture gradually propagates forward; after shutting in the pump, the fluid pressure within the fracture immediately decreases to the value of the instantaneous shut-in pressure (ISIP), and the hydrofracture gradually closes as the fluid within the fracture continuously flows into the formation. Finally, the fluid pressure within the fracture equals the fracture closure pressure (FCP). Therefore, the fracture plugging and pressurization effects can be achieved by increasing the fracture breakdown pressure, the fracture propagation pressure, or the fracture closure pressure.

During well-drilling operation, the measure of wellbore wall reinforcement proves to effectively improve the bearing capacity of the borehole, and thus, the density window of a drilling mud can be expanded. There are two kinds of wellbore reinforcement measures: preventive measure and repair measure. The former one refers to that a low permeability and high plasticity filter cake is formed on the wellbore wall before the occurrence of lost circulation; the
latter one refers to that the plugging material is applied to plug the created fracture and stop them propagating after the occurrence of lost circulation. Researchers have put forward three main physical models to explain the mechanism of the remedial measures, including the stress cage model, the fracture closure stress model, and the fracture propagation resistance model. These three physical models can also comprehensively explain the mechanism of fracture plugging and pressurization during TPDF.

2.1 | Stress cage model

The stress cage model refers to that the plugging materials are injected to plug and support the fractures, and thus, the fracture can remain at a certain aperture and the circumferential stress around the well can be enlarged to a certain level. As shown in Figure 3A, the plugging materials are pushed into the mouth of the created hydrofracture. The large particles bridge and the small particles fill the pores among the large particles, and thus, a tight plug can be created. Beyond the tight plug, the fracturing fluids gradually infiltrate into the matrix from the wall of the fracture, and the fluid pressure decreases and the fractures close. The compressed and compacted tight plug can support the fracture to maintain a certain aperture. The circumferential stress can be enhanced around the wellbore, thus increasing the reopening pressure of the created fracture. The stress cage model can better explain the mechanism of the fluid diversion forced by the tight plug during TPDF. After the formation of the tight plug at the fracture mouth, the previously created fracture can be plugged and supported, the wellbore pressure will be increased, and the subsequent injection fluid is forced to divert to the unstimulated section, thus creating new hydrofracture. Ultimately, the overall stimulation volume of the reservoir can be enlarged.

2.2 | Fracture closure stress model

The fracture closure stress model refers to supporting the whole fracture to maintain a certain opening, and thus, the fracture closure stress can be increased and the fracture reopen pressure will be enhanced to a certain level. As shown
in Figure 3B, the process of enhancing the fracture closure model includes four steps: (1) forms a hydraulic fracture with a certain aperture; (2) the diverter enters the fracture, as the fluid filtrates into the matrix, the concentration of the diverter increases, the fluidity decreases, and a residual plug is formed gradually; (3) as fluid continues to flow out of the fracture, the residual slug is compacted to support the fracture and increase the fracture closure stress; (4) subsequent injection fluid with diverter continuously increase the volume of the tight plug, providing a larger propped fracture and further increasing the fracture closure pressure. The increment of the fracture closure pressure will cause the enhancement of the fracture reopening pressure, to prevent the further propagation of the previously created fracture. During TPDF, a higher strength of the tight plug can be formed when a mixture of diverter and proppant is pumped, it is more efficient to support the previously created fracture and increase the fracture closure pressure. Therefore, new fractures can be generated because of the enhancement of the old fracture reopen pressure.

2.3 | Fracture propagation resistance model

The fracture propagation resistance model is also called the fracture tip plugging model. The purpose of this model is not to support the fracture to increase the circumferential stress or the fracture closure stress. Diversers should transport deep into the tip of the hydrofracture and build a tight plug at the hydrofracture tips. The tight plug cannot support the hydrofracture but block the fluid pressure transmitting into the fracture tips. Therefore, it can prevent the fluid flow to the fracture tip and stop the further propagation of the active fracture (Figure 3C). The fracture propagation resistance model can efficiently explain the mechanism of the in-fracture plugging during TPDF. The above-mentioned three models, without strict mathematical derivation, can only be used to qualitatively evaluate the mechanism of fracture plugging and pressurization during TPDF. Therefore, it is necessary to further establish an effective method to quantitatively evaluate the effect of fracture plugging and pressurization. The following parts give two solving methods: the analytical method and the numerical method.

3 | ANALYTICAL MODEL FOR EVALUATING THE EFFECT OF FRACTURE PLUGGING AND PRESSURIZATION

Based on the theory of linear elastic fracture mechanics, when the stress intensity factor of the fracture tip is less than the inherent fracture toughness of the reservoir rock, the fracture cannot propagate forward. Therefore, the effective plugging of the previously created fracture should meet:

\[ k_1 < k_{IC} \] (1)

where \( k_1 \) is the type I stress intensity factor at the fracture tip, MPa-m\(^{0.5}\); \( k_{IC} \) is the type I fracture toughness of the reservoir rock, MPa-m\(^{0.5}\).

In the infinite plane, the stress intensity factor at the fracture tip can be calculated using Equation (2), an integral equation of the positive total pressure along the fracture surface.

\[ k_1 = \frac{1}{\sqrt{\pi L}} \int_{-L}^{L} \sigma(x) \sqrt{\frac{L-x}{L+x}} \, dx \] (2)

where \( L \) is the half length of fracture, m; \( \sigma(x) \) is the normal stress applied on the fracture surface.
According to Equation (2), the main parameters affecting the stress intensity factor at the fracture tip include the length of the fracture and the normal stress acting on the fracture surface. The latter one refers to the net pressure within the hydraulic fracture (the difference between the fluid pressure within the fracture and the minimum horizontal principal stress). As shown in Figure 4, it is assumed that the diverter forms a tight plug within the fracture, which divides the hydraulic fracture into two parts. The net pressure ahead of the tight plug equals the net pressure of the wellbore fluid. The net pressure behind the tight plug equals 0. The width of the hydrofracture is wide ahead of the tight plug and the fluid flow friction can be negligible, and thus, the net pressure equals the wellbore fluid net pressure. Behind the tight plug, the fluid within the hydrofracture will gradually flow into the matrix and the fluid pressure equals the pore pressure of the reservoir fluid, and thus, the net pressure equals 0. Based on the principle of linear elastic superposition, the stress intensity factor at the fracture tip can be calculated by the following equation:

\[ K_1 = (F_1 + F_2) \cdot \left[ 2P_w - (\sigma_H + \sigma_h) \right] + (F_1 + 3F_3) \cdot (\sigma_H - \sigma_h) - 2F_4 \cdot (P_w - P_p) \]  

where \( \sigma_{H} \) and \( \sigma_{h} \) are the horizontal maximum and minimum principal stress, respectively, MPa; \( R \) is the wellbore radius, m; \( r \) is the integral variable; \( P_w \) is the pressure in the wellbore, MPa; \( P_p \) is the formation pore pressure, MPa; \( D \) is the distance between the tight plug and the wellbore center, m; \( L \) is the distance from fracture tip to wellbore center, m; \( a \) is the fracture length, m; \( F_1, F_2, F_3, \) and \( F_4 \) are integral functions.

The analytical model considers the influence of fracture geometry parameters (fracture length and plugging location) and stress conditions (in situ stress, pore pressure, and fluid pressure in the fracture) on the stress intensity factor at the fracture tip. The analytical formula is convenient for field application and can reflect the influence pattern of key parameters. However, the influence of nonuniform net pressure and rock plastic deformation cannot be considered in the analytical formula.

4 | NUMERICAL METHOD FOR EVALUATING THE EFFECT OF FRACTURE PLUGGING AND PRESSURIZATION

The numerical method can consider the influence of nonuniform net pressure and elastoplastic deformation on the stress intensity factor at the fracture tip during TPDF.

4.1 | Boundary element or finite element method

When applying the boundary element method (BEM) or the finite element method (FEM), the fracture tip area needs local mesh refinement to calculate the stress intensity factor value of the fracture tip. Based on the fracture mechanics theory, singularities exist at the fracture tips. The second-order collapse quadrilateral element (as shown in Figure 5) needs to be applied to capture the singularities. The specific steps include:

1. combining the three points a, b, and c as a point at the fracture tips;
2. moving the middle nodes on both sides to the positions of 1/4 boundaries close to the fracture tips.

In addition, the fracture front and the next direction of the fracture propagation should be specified. In short, when the boundary element or finite element method is applied to calculate the stress intensity factor, the modeling process is cumbersome and the computation cost is huge, and the calculation results have strong grid dependence.

4.2 | Extended finite element method

The extended finite element method (XFEM) overcomes the disadvantages of the traditional finite element method
(FEM) and allows the fracture to propagate along any path without the need for mesh reconstruction. The XFEM has high precision during 2D and 3D simulations and has no special requirement of mesh construction; the rough mesh can also get good results.

For XFEM, two local enriched functions are introduced to approximate the displacement field, that is, the discontinuous function \( H(x) \) represents the discontinuous jump across the fracture surface, and the asymptotic function \( \Phi_\alpha(x) \) represents the singularity close to the fracture tip. As shown in Figure 6, there are four types of elements for XFEM, namely the fracture across the element, the fracture tip element, the transition element, and the ordinary element. Moreover, there are three types of nodes, namely the throughout enriched node, the fracture tip enriched node, and the ordinary node. When calculating the local enriched function, only the elements and the nodes close to the fracture will be calculated.\(^{14}\) To avoid the propagation of the hydrofracture, static hydrofracture is adopted in this work. It means the hydrofracture will not propagate, and the value of the stress intensity factor can be calculated.

For XFEM, the approximate displacement function is expressed as\(^ {14}\):

\[
\mathbf{u} = \sum_{i=1}^{n} N_i(x) \mathbf{u}_i + \sum_{j=1}^{m} N_j(x) H(x) a_j + \sum_{k=1}^{q} N_k(x) \sum_{\alpha=1}^{4} \Phi_\alpha(x) b_\alpha^k
\]

(9)

where \( n, m, \) and \( q \) are the total number of domain nodes, the number of across-strengthened nodes and the number of fracture tip strengthened nodes, respectively. \( a_j \) and \( b_\alpha^k \) are the additional degrees of freedom. \( H(x) \) and \( \Phi_\alpha(x) \) are the step-up functions and fracture tip strengthened functions, respectively.

After constructing the displacement mode, the basic governing equation is derived based on the virtual work principle using the finite element method. Furthermore, the penalty function is applied to solve the basic governing equation. The degrees of freedom are set equal among the first layer strengthened nodes, and the fracture tip stress intensity factor can be obtained. To ensure the integration accuracy, the number of the integral point in Figure 6 is specified as follows: 2 \( \times \) 2 Gaussian integral points for the ordinary element; 7 \( \times \) 7 Gaussian integral points for the transition element; 13 \( \times \) 13 Gaussian integral points for the fracture cutting element; and 15 \( \times \) 15 Gaussian integral points for the fracture tip element.

5 | QUANTITATIVE EVALUATION OF FRACTURE PLUGGING AND PRESSURIZATION EFFECT

This work establishes a 2D XFEM model to evaluate the fracture plugging effect. The reliability of the XFEM model is verified against the FEM model. Based on the
XFEM model, this work further studies the influence pattern of the uneven distribution of the net pressure on the fracture tip stress factor.

### 5.1 Establishment of the 2D XFEM model

Figure 7 gives the geometry of the 2D XFEM model, a 1/2 model due to the symmetry, and the fracture plugging and pressurization effects are analyzed. The model is 120-m long and 80-m wide. At the middle region of the model, a 120-m-long and 10-m-wide enrichment zone is specified as the fracture zone. Binding constraints are applied at the junction between the enriched and non-enriched regions. Binding constraints means the two surfaces are tied together, and relative movement is not allowed. The mesh density can be different for the two surfaces, and the computational cost can be reduced greatly. In this way, the stress and strain can be transited smoothly between grids of different sizes. One hydraulic fracture is present in the middle of the model, and the influence of the wellbore is also considered. The upper and lower boundaries are fixed in the Y direction; the left and right boundaries are fixed in the X direction. In this way, the rigid body displacement can be eliminated. The minimum horizontal principal stress is along the Y direction; the maximum horizontal principal stress is along the X direction. Table 1 lists the model input parameters. The surface stress is acted on the fracture surface instead of the fluid pressure. The fluid net pressure is considered, and it equals the fluid pressure minus the total horizontal principal stress.

### 5.2 Model validation

Based on the data in Table 1, the FEM model and the XFEM model are, respectively, used to calculate the stress intensity factors at the fracture tips with different fracture lengths. The calculation results are shown in Figure 8. The more meshes the finite element method applies, the closer the calculation results are to those from the XFEM model. Therefore, the XFEM model can obtain higher accuracy.
with less mesh, and it is an effective means to evaluate the
effect of fracture plugging and pressurization.

5.3 Influence pattern of the fluid pressure within the fracture

During TPDF, the diverter can not only form a tight plug
by bridging somewhere within the fracture but also block
nearly the whole fracture along the direction of the frac-
ture height. It can also form a long and loose plug within
the fracture to reduce the fluid flow area and achieve the
immature plugging effect. The plug type determines the
distribution of the fluid pressure within the fracture. Four
distribution modes of the net pressure are specified as
shown in Figure 9: flat distribution (no bridge and plug-
ging, the net pressure equals 2 MPa along the whole frac-
ture); ladder distribution (diverter bridges in the middle of
the fracture, the net pressure ahead of the tight plug equals
2 MPa, while the net pressure behind the tight plug equals
0 MPa); linear distribution; and quadratic distribution (the
diverter distributes uniformly within the fracture and does
not form a tight plug, and the net pressure distribution is
influenced by the roughness and tortuosity of the fracture).

For the four types of net pressure distribution, the stress in-
tensity factor at the fracture tip was calculated based on the
model in Figure 7. As shown in Figure 10, the distribution
mode of the net pressure has a significant influence on the
stress intensity factor at the fracture tip. The bridge of
the diverter affects the net pressure distribution in the fracture,
which can greatly reduce the stress intensity factor at the
fracture tip, and thus, the previously created fracture can be
plugged effectively and can stop propagation forward.\textsuperscript{15,16}

6 CONCLUSIONS

Based on the theory of borehole reinforcement, the mech-
anism of fracture plugging and pressurization is analyzed
qualitatively. Based on the XFEM, the influence of nonu-
niform distributed net pressure on fracture plugging and
pressurization is evaluated quantitatively.

1. Fracture mouth plugging during TPDF mainly en-
hances the wellbore circumferential stress; in-fracture
plugging mainly enhances the fracture closure pres-
sure; and fracture tip plugging mainly hinders frac-
turing fluids flowing toward the fracture tips. All of
them aim at enhancing the reopening pressure of the
previously created fractures and prevent their propa-
gation forward.

2. The calculation of the stress intensity factor at the frac-
ture tip is the key to quantitatively evaluate the effect
of fracture plugging and pressurization. The analytical method cannot consider the influence of nonuniform distributed net pressure within the wellbore and fracture, and it is not suitable for large-scale hydraulic fractures; to calculate the stress intensity factor of the fracture tips, the FEM and BEM models need to refine the mesh of the fracture tip area. Moreover, the collapse element should be applied to capture the singularities of the fracture tips. In comparison, the XFEM has obvious advantages because mesh refinement and element collapsing are not necessary.

3. Based on XFEM, this paper establishes a 2D XFEM model to evaluate the fracture plugging effects influenced by the uneven distribution of net pressure within the fracture. The results prove that diverter bridging and plugging can change the distribution of fracture net pressure and dramatically reduce the fracture tip stress factor, thus stopping the previously created fracture from propagating forward.

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