Research Article

Analytical Solution and Simulation of Oil Deliverability Analysis for Reorientation Hydraulic Fracture in Low-Permeability Reservoirs

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The hydraulic refracturing operations are often used to improve oil deliverability in the low-permeability reservoir. When the development of oilfields has entered a high water cut stage, oil deliverability can be promoted by refracturing reservoirs. The orientation of the new fracture formed by refracturing will be changed. The new formed fracture is called reorientation fracture. To calculate the oil deliverability of the refracture wells, a three-section fracture which includes reorientation fracture was established. The multiwell pressure drop superposition theory is used to derive the analytical solution of the refracture wells which includes the reorientation fracture. The numerical simulation was conducted to validate the results of the analytical solution. Comparing the refracture well deliverability of reorientation and nonreorientation, permeability, deflection angle, and the length of reorientation fracture will jointly control the productivity of refracture well. When the permeability in the direction of maximum principal stress is greater than the permeability in the direction of minimum principal stress, the capacity of reorientation fractures is relatively large. The deflection angles and the length of the reorientation fracture will directly affect the drainage area of the fracture, thus affecting productivity. The reorientation fractures generated by repeated fracturing have great potential for improving oil deliverability in the anisotropic low-permeability reservoirs.

1. Introduction

The hydraulic fracturing or refracture operations have been widely used to improve oil deliverability in developing low-permeability reservoirs. The parameters of permeability and porosity can be improved by multiple fracturings [1–3]. The benefit of existing refracture wells has been proved by a lot of studies [4, 5]. Compared to drill new wells, refracture operations have been an economical way for improving oil deliverability [6–9].

Refracture can be created in two forms: one form is that the directions of the new fracture propagate the same as the original fracture, and the other is that the directions of the new fracture propagate to a new direction with the redistribution of pressure. The conventional theory of hydraulic

fracturing is built on tensile failure of rocks [10–12]. Many studies have been carried out that the formation of fractures is mainly affected by induced stress, geological conditions, and production conditions. The direction of initial fracture is parallel to the direction of maximum principal stress [13]. The stresses surrounding the fracture decrease when a fractured well output for some time [14–16]. During a repeated fracturing treatment, if the directions of the maximum formation stress changes, the new fracture and original fracture could be at a certain angle [17, 18]. The results of the laboratory test, as showing in Figure 1, also proved that the directions of refracture are not all along the original fracture direction [19, 20]. What is more, the Chevron oil technology company's multiple fracturing fracture location in the Lost Hill Oilfield is about 30 degrees from the original fracture

azimuth, which reveals the possibility of a new fracture in the repeated fracturing fractures [21]. The new orientation fracture is called a reorientation fracture. The reorientation fracture will propagate to the nonleaking oil area, increasing the drainage area of the oil well [22–24].

In the actual production process, reorientation fracture characterized by multiple branches has become the main purpose of refracture [25]. It is also the main way to actually increase production. Many studies have been carried out that the porosity and permeability near the well can be increased by fractures [26]. The generation of hydraulic fracturing fractures creates favorable conditions for the development of low permeability reservoirs [27–30]. Scholars have a variety of seepage interpretations of single fracture [31–33]. Raghavan and Gringarten have presented methods to calculate well productivity, considering the anisotropy of the hydrocarbon reservoir [34]. Wang summarized the productivity evaluation and of hydraulic fracturing wells and obtained a radial flow formula for vertically fractured wells with finite conductivity [35, 36]. There are a number of analytical and semianalytical models for the simulation of vertical two-wing fractures or horizontal wells [37]. However, there are still few studies on analysis of the productivity of the reorientation fracture.

A mathematical model to describe the oil deliverability of a reorientation fracture in anisotropic low-permeability hydrocarbon reservoirs was proposed in this paper. The model used multiwell pressure drop superposition principle to calculate integral for the oil productivity formulation of the reorientation fracture, which is validated by using reservoir numerical simulation and comparing the productivity of the nonreorientation fracture. The proposed model is used to study the sensitivity of infinite diversion fracture parameters. It is proved that the productivity of the diverting fracture in different anisotropic low-permeability is controlled by the anisotropy of reservoir permeability, the length of reorientation fracture, and the angle between the reorientation fracture and the original fracture.

2. Mathematical Model

2.1. Physical Model. A schematic of the stress distribution of generating reorientation fractures is displayed Figure 2. It is important to note here that this model is a simplified model describing the actual fracture deflection. The model in this paper describes a fracture that experiences only one deflection. This model describes the principle of practical calculation by simplifying multisection deflected fracture into three sections. This simplified model greatly reduces the complexity of calculation.

Actual reorientation fractures often undergo multiple deflections and form complex fracture morphology. No matter how complicated the reorientation fracture is, it can be dispersed into multiple fractures that experience small angle deflection. Compared with the fractures described in this paper, more complex fractures only increase the complexity of the computational process, without putting forward new requirements on the analytical solution process.

FIGURE 1: Fracture deflecting occurred in actual fracturing experiments.

FIGURE 2: Schematic of the stress distribution of generating reorientation fractures.

From Figure 2, the hydraulic fracture will result in an elliptical pressure drop zone. Initial fractures extend to the direction of the maximum initial stress, which is indicated by $\sigma'_{\max}$. After certain production processes have been carried out, the direction of maximum principal stress in the stress fall zone changes to the $\sigma_{\max}$ direction. The refractured fracture will extend in the direction of $\sigma_{\max}$.

Figure 3 displays a schematic of physical model of a refractured fracture including reorientation fracture. In order to calculate the refractured fracture production, Cartesian axes are set up parallel to the direction of the reorientation fracture. Some basic assumptions are presented as follows.

- (1) The refractured fracture is divided into three sections in the Cartesian coordinate system. The middle part of the fracture is angled θ to the X axis, and both sides of it are parallel to the X axis. Transpose the Cartesian coordinate system θ angle to the X axis parallel to the middle part to form a new coordinate axis
- (2) The position of well in the reservoir is set as (x_w, y_w) . The position of any point in the reservoir is set as (x, y) . The maximum distance from the fracture to the X axis is H , and the maximum distance from the fracture to the Y axis is l
- (3) In this paper, the whole fracture includes before and after refracturing $(l - H/K + H/\sin \theta)$. The original fracture refers to the fracture before reorientation $(H/\sin \theta)$. Reorientation fracture refers to the fracture after reorientation $(l - H/K)$. Nonreorientation

FIGURE 3: Schematic of the physical model of a refractured fracture including reorientation fracture.

FIGURE 4: Schematic of ordinary straight production wells in circular closed formation.

is the fracture extended along the origin direction. The length of the fracture is denoted by x_f

- (4) In the production process of refracture wells, the fluid output per unit length of the fracture is uniform. Therefore, the flow rate of each point is equal to the output at the origin of coordinates

The method of establishing coordinate axes along different fracture directions greatly simplifies the difficulty of calculation. It also provides a simplified method for the calculation of ideal fractures for multistage fracturing and actual fractures that can be dispersed into multiple stages.

2.2. Mathematical Model and Solution. Figure 4 displays a schematic of conventional vertical production wells in circular closed formation. The paper studies the quasisteady state seepage for the center of the circular closed formation. Based on the multiwell pressure drop superposition principle of single conventional vertical production well, the production of the vertical well in Figure 3 is calculated by integration.

From Figure 4, in the center of a homogeneous formation with a boundary radius of r_e , there is a production well with a production capacity of q with a well radius of r_w . The model assumptions are listed below:

- (1) The model is homogeneous, and the permeability is anisotropic. In this study, coordinate transformation is used to simplify the calculation. The anisotropy is reflected in the different permeability of Y and Y'
- (2) The pressure is constant, and both fluids and rock are slightly compressible. Formation permeability, formation fluid viscosity, porosity, and comprehensive compressibility are constants
- (3) Fractures are the main flow channel, and the seepage flow is laminar and isothermal. The fluid output per unit length of the fracture is uniform
- (4) The conductivity of reorientation fracture is infinite, ignoring fluid flows in fractures

The pseudosteady state pressure distribution is given by

$$\Delta p(r, t) = p_i - (r, t) = \frac{q\mu B}{2\pi kh} \left(\frac{2\eta t}{r_e^2} - \frac{3}{4} + \frac{r^2}{2r_e^2} - \ln \frac{r}{r_e} \right), \quad (1)$$

$$\Delta P(r, t) = P_i - P(r, t) = \frac{q\mu B}{2\pi kh} \left(\frac{2\eta t}{r_e^2} - \frac{3}{4} + \frac{r^2}{2r_e^2} - \ln \frac{r}{r_e} \right).$$

The superposition principle of multiwell pressure drop follows as

$$\Delta p(r, t) = \Delta p_1(r, t) + \Delta p_2(r, t) + \dots + \Delta p_n(r, t). \quad (2)$$

The three sections of the pressure difference are set to Δp_1 , Δp_2 , Δp_3 , and the total pressure difference

$$\Delta p(r, t) = \Delta p_1(r, t) + \Delta p_2(r, t) + \Delta p_3(r, t). \quad (3)$$

The pressure drop equation for the three-stage fracture is as follows:

$$\Delta p_1(r, t) = \int_{-l}^{\frac{H}{K}} \frac{q\mu B}{2\pi k_y h} \left[\frac{2\eta t}{r_e^2} - \frac{3}{4} + \frac{(x - x_w)^2 + (y + H)^2}{2r_e^2} - \frac{1}{2} \ln \frac{(x - x_w)^2 + (y + H)^2}{r_e^2} \right] dx_w, \quad (4)$$

$$\Delta p_2(r, t) = \int_{\frac{H}{K}}^l \frac{q\mu B}{2\pi k_y h} \left[\frac{2\eta t}{r_e^2} - \frac{3}{4} + \frac{(x - x_w)^2 + (y - H)^2}{2r_e^2} - \frac{1}{2} \ln \frac{(x - x_w)^2 + (y - H)^2}{r_e^2} \right] dx_w, \quad (5)$$

$$\Delta p_3(r, t) = \int_{-\frac{H}{\sin \theta}}^{\frac{H}{\sin \theta}} \frac{q\mu B}{2\pi k'_y h} \left[\frac{2\eta' t}{r_e^2} - \frac{3}{4} + \frac{(x' - x'_w)^2 + (y' - y'_w)^2}{2r_e^2} - \frac{1}{2} \ln \frac{(x' - x'_w)^2 + (y' - y'_w)^2}{r_e^2} \right] dx'_w. \quad (6)$$

Integrating the right side of Eqs. (4)–(6) with respect to x_w and adding them up, the expression of the pressure drop is obtained:

$$\Delta p = \frac{q\mu B}{2\pi k_y h} \left[\frac{2\eta t}{r_e^2} \left(2l - 2\frac{H}{K} \right) + A \right] + \frac{q\mu B}{2\pi k_y h} \left(\frac{2\eta t}{r_e^2} \frac{2H}{\sin \theta} + E \right), \quad (7)$$

where

$$\begin{aligned} A &= B + C + D, \\ B &= -\frac{3}{2} \left(l - \frac{H}{K} \right) + \frac{x^2(l - H/K) + 1/3(l^3 - H^3/K^3)}{r_e^2} \\ &\quad + \frac{(l - H/K)(y^2 + H^2)}{r_e^2} + 2 \left(l - \frac{H}{K} \right) (1 + \ln r_e), \\ C &= \frac{1}{2} \ln \frac{[(x + (H/K))^2 + (y + H)^2]^{(x+(H/K))}}{[(x + l)^2 + (y + H)^2]^{(x+l)}} \\ &\quad + \frac{1}{2} \ln \frac{[(x - H/K)^2 + (y - H)^2]^{(-x+(H/K))}}{[(x - l)^2 + (y - H)^2]^{(-x+l)}}, \\ D &= -(y - H) \left(\tan^{-1} \frac{l - x}{y - H} - \tan^{-1} \frac{H/K - x}{y - H} \right) \\ &\quad - (y + H) \left(\tan^{-1} \frac{-H/K - x}{y + H} - \tan^{-1} \frac{-l - x}{y + H} \right), \end{aligned} \quad (8)$$

where

$$E = F + G + I,$$

$$F = -\frac{3H}{2 \sin \theta} + \frac{(H/\sin \theta)x'^2 + 1/3(H/\sin \theta)^3}{r_e^2} + \frac{Hy'^2}{r_e^2 \sin \theta} + \frac{2H(\ln r_e + 1)}{\sin \theta},$$

$$G = -\frac{1}{2} \left(\frac{H}{\sin \theta} - x' \right) \ln \left[\left(\frac{H}{\sin \theta} - x' \right)^2 + y'^2 \right] - \frac{1}{2} \left(\frac{H}{\sin \theta} + x' \right) \ln \left[\left(\frac{H}{\sin \theta} + x' \right)^2 + y'^2 \right],$$

$$I = -y' \tan^{-1} \frac{H/\sin \theta - x'}{y'} - y' \tan^{-1} \frac{(H/\sin \theta) + x'}{y'}. \quad (9)$$

It should be noted that the q here is the flow rate in the point of origin of coordinates. In this work, the fluid output per unit length of the fracture is assumed to be uniform, and under these circumstances, the production formula of reorientation fracture as Eq. (10) is obtained:

$$Q = 2L \times q = \frac{2L\Delta p}{(\mu B/2\pi k_y h) \left[(2\eta t/r_e^2)(2l - 2(H/K)) + A \right] + (\mu B/2\pi k_y h) \left((2\eta t/r_e^2)(2H/\sin \theta) + E \right)}. \quad (10)$$

According to the ideas of Raghavan and Joshi [38], the yield formula for the nonreorientation vertical fracture is

$$\begin{aligned} \Delta p &= \frac{q\mu B}{2\pi k_y h} \left(\frac{2\eta' t}{r_e^2} 2x_f + J \right), \\ J &= K + M + N, \\ K &= -\frac{3}{2}x_f + \frac{x_f x'^2 + 1/3x_f^3}{r_e^2} + \frac{y'^2 x_f}{r_e^2} + 2x_f(\ln r_e + 1), \\ M &= -\frac{1}{2} \left(x_f - x' \right) \ln \left[\left(x_f - x' \right)^2 + y'^2 \right] - \frac{1}{2} \left(x_f + x' \right) \ln \left[\left(x_f + x' \right)^2 + y'^2 \right], \\ N &= -y' \tan^{-1} \frac{x_f - x'}{y'} - y' \tan^{-1} \frac{x_f + x'}{y'}. \end{aligned} \quad (11)$$

The production formula for the nonreorientation fracture with the same assumption is obtained:

$$Q = 2x_f q = \frac{\Delta p}{(\mu B/2\pi k_y h) \left((2\eta' t/r_e^2) + (J/2x_f) \right)}. \quad (12)$$

3. Results and Discussion

3.1. Mathematical Model Validation. A numerical simulation conceptual model is established to verify the reliability of the mathematical model. The ideal model of numerical simulation for reorientation fracture is established by the black oil model of ECLIPSE. Figure 5 describes the schematic of the grid simulation model and hydraulic reorientation fracture.

Figure 5(a) displays the schematic of the grid simulation model. From Figure 5(a), a block-shaped reservoir is built in ECLIPSE. The center of the reservoir has three fractures with the same shape as Figure 2. There is a vertical well at the center of the original fracture. The reservoir parameters are the

FIGURE 5: Schematic of the grid model and hydraulic reorientation fracture. (a) The grid simulation model. (b) The magnified hydraulic reorientation fracture.

FIGURE 6: The phase-permeability curves of the matrix and hydraulic fracture. (a) Matrix phase permeability curve. (b) Hydraulic fracture phase permeability curve.

same as those in the productivity formula. There are 194 grids in the X direction and 196 grids in the Y direction. Their steps are 1.0 m. The grid of the Z direction is divided into three layers, and the single layer thickness is 2 m. The total number of grids is $194 \times 196 \times 3 = 114072$. The permeability in the X direction is $0.1 D$, and the permeability in the Y direction is $0.05 D$. The porosity is 0.1.

Figure 5(b) displays the schematic of the magnified hydraulic reorientation fracture. The fracture is set as an infinite conductivity fracture. The fracture penetrates the entire reservoir in the Z direction. Usually, the fracture width is about a few millimeters while the fracture length is a few hundred meters. The width of the fracture is too small to set. If the needed grid is divided by actual values, the number of grids is very large, so that it is time-consuming or impossible for the simulation work. In order to make numerical simulation more accurate, grids that intersect with hydraulic fractures are refined until the grid sizes are small enough to be in the same order of fracture width. The grid-refining process enables us to

accurately describe flow characteristics near the hydraulic fracture region and guarantees the efficiency and accuracy of simulation results. Figure 6 displays the matrix and hydraulic fracture different phase-permeability curves.

In order to analyze the reorientation fracture productivity, the oil production of reorientation fractures and nonreorientation fractures is compared between the mathematical model and the numerical simulation.

A schematic of oil productivity curve comparison between the mathematical model and the numerical simulation solution is displayed in Figure 7. From Figure 7, at the beginning of the production phase, the two curves of the mathematical model and the numerical simulation basically overlap. With the increase of oil production time, the curve of the mathematical model drops rapidly. At the end of production, the two curves basically coincide. The results of the mathematical model and the numerical simulation are still somewhat different. The differences between the two curves may be as follows:

FIGURE 7: Schematic of curves comparison between numerical simulation solution and numerical solution.

- (1) Due to the use of equivalent conductivity capability, the permeability in the model has some differences with that in the formula. The permeability in the model is greater than that calculated in the formula, resulting in larger numerical simulation solution
- (2) In the process of derivation, the fractures are divided into three sections, ignoring the flow between the fractures and making the deduced result smaller
- (3) Since the grid is a block center grid, the circular borders of the model are not smooth, and the total area size has some differences

In general, the results of numerical solution and numerical simulation solution are the same on the whole. Therefore, the formula has practical value, and the formula can be used to calculate the output during the actual production process.

3.2. Reorientation Hydraulic Fracture Productivity Sensitivity Analysis. The proposed mathematical model indicates that the productivity of fractures is controlled by several factors. By studying the permeability of anisotropic reservoir, the advantages and disadvantages of refracture wells in anisotropic reservoir are illustrated. In isotropic reservoirs, the effect of deflection angles and length of reorientation fracture on stimulation is studied. If the deflection fracture does not extend in the advantage direction of permeability, reorientation fracturing will not increase productivity. The deflection angle should be minimized and increase the length to increase the drainage area and increase production.

3.2.1. The Effect of Anisotropy on Permeability. In order to analyze the effect of anisotropic permeability, the permeability is set to be anisotropic, and reorientation and nonreorientation fractures of the same length were assumed. The angle

of reorientation deflection is 45 degrees. The reorientation fracture has the same length as the origin fracture.

The production of reorientation fractures and nonreorientation fractures is calculated by using reservoir data in an oilfield. Permeability in the Y' axis and in the Y axis directions is $k_{y'} = 0.01 D$, $k_y = 0.005 D$, $k_{y'} = 0.01 D$, $k_y = 0.01 D$, $k_{y'} = 0.01 D$, and $k_y = 0.02 D$. Other reservoir data include average porosity = 0.1, formation fluid viscosity = 1.5 mPa · s, comprehensive compressibility = $6.0 \times 10^{-4} \text{ MPa}^{-1}$, average thickness of reservoir = 40.0 m, the volume compressibility of fluid = 1.08, the boundary radius = 700 m, the original formation pressure = 52.0 MPa, and the production pressure difference = 15.0 MPa. The above data is substituted into the equation of the reorientation fracture and nonreorientation fracture for production calculation.

Figure 8 displays the oil production changes at the different anisotropic low permeability. This plot for $k_{y'} = 0.01 D$ and $k_y = 0.005 D$, $k_{y'}/k_y = 2$; $k_{y'} = 0.01 D$ and $k_y = 0.01 D$, $k_{y'}/k_y = 1$; and $k_{y'} = 0.01 D$ and $k_y = 0.02 D$, $k_{y'}/k_y = 0.5 D$. In this study, the fracture length is set to be consistent.

From Figure 8(a), the permeability in the Y' direction is obviously higher than that in the Y axis ($k_{y'}/k_y = 2$). The productivity of both types of fractures decreases with production time. Reorientation fracture well is less productive than the nonreorientation fracture well. From Figure 8(b), the permeability in the Y' direction is equal to that in the Y axis ($k_{y'}/k_y = 1$). The productivity of both types of fractures decreases with production time. The two curves are almost coincidentally. It should be noted that reorientation fractures have slightly lower productivity than vertical fractures. From Figure 8(c), the permeability in the Y' direction is obviously lower than that in the Y axis ($k_{y'}/k_y = 0.5$). The production of reorientation fracture is beneficial. The production of reorientation fracture is much higher than that of the nonreorientation fracture. And with the increase in production time, the production of the reorientation fracture is decreasing faster than that of the nonreorientation fracture.

The above studies confirm that reservoir permeability is an important factor controlling fracture productivity during fracture production. It is proved that the permeability anisotropy has a great significance in the productivity of fractures. The anisotropy of reservoir permeability determines the effect of reorientation fractures to productive. When the reservoir is isotropic, the productivity of the reorientation fracture well is similar to that of the equal-length vertical fracture well. When the formation has anisotropic properties, the reorientation fracture well will increase productivity if the reorientation direction is high permeability. On the contrary, there will be a decline in production capacity. It can be concluded that, in anisotropy reservoirs, the fracture should be controlled to extend to a more beneficial direction, or it will not perform better productivity.

3.2.2. The Influence of Angle on Fracture Productivity. The deflection angle is an important property of the reorientation fracture. According to Figure 8(b), it can be concluded that

FIGURE 8: The oil production changes at the different anisotropic low permeability.

the existence of deflection angle will not only affect the productivity through the anisotropy of the reservoir but also affect the productivity of the well in the isotropic formation. In isotropic reservoirs, the influence of the deflection angle on fracture productivity is studied by setting θ as 0, $\pi/4$, $\pi/2$, and $3\pi/4$. The productivity of the vertical two-wing fractured well is also described. It must be emphasized that the length of the reorientation fracture ($l - H/K$) is always equal to the length of the original fracture ($H/\sin \theta$). In this study, the total fracture length was set at 300 m.

The oil production changes at different angles are displayed in Figure 9(a). From Figure 9(a), compared to vertical fractures, the production of reorientation fractured well decreases gradually, and the decline rate is gradually accelerated with the increase of the angle. It can be expected that when the angle is increased to 2π , it will coincide with the original fracture, and this production will revert back to the production of the vertical fracture well. The production of the reorientation fractured wells will be minimized, but such hydraulic fracture is not possible in practice. It is only an extreme case for analysis and explanation.

This study shows that in isotropic reservoirs, the reorientation fracture does not increase fracture productivity but will reduce productivity. It is because the angle will affect the effective length of reorientation fracture and decrease the drainage area, thus decreasing the productivity of reorientation fracture wells. It can be concluded that the reorientation fracture is disadvantaged in isotropic formations during vertical well fracturing production. In anisotropic reservoirs, the deflection angle will also have an adverse effect on production for the same reason.

3.2.3. The Influence of Length on Fracture Productivity. Fracture length is another important factor affecting fracture productivity. The study of fracture length consists of two parts, one is the total length of the whole fracture, and the other is the influence of the ratio of the deflected fracture to the original fracture length.

The research on the total length of whole fracture is to study the influence of the total length on productivity when the deflection angle is determined. The oil productivity changes at different lengths of the whole fracture are

FIGURE 9: Continued.

FIGURE 9: The oil productivity changes with time. (a) The oil productivity changes at angles. (b) The oil productivity changes at different lengths of the whole fracture. (c–f) are the productivity changes when the ratio of length varies: (c) the angle is $\pi/4$, (d) the angle is $\pi/2$, (e) the angle is $3\pi/4$, and (f) the angle is π .

displayed in Figure 9(b). From Figure 9(b), when the total length of reorientation fracture become longer, the fracture productivity increases gradually. This is because the drainage area of the fracture increases when the total length and side length of the fracture are increased, leading to the increase of the fracture productivity. Therefore, during the fracturing process, the length of the fracture should be as long as possible.

For the reorientation fracture, the fracture length and deflection angle are the property of the fracture in space, they will jointly affect the production of the reservoir. The compatibility between the reorientation fracture and the angle must be considered. To study the effect of reorientation fracture length on productivity, the total length of the fracture is set as a constant value. The productivity of the fracture is studied by changing the ratio of length of the reorientation fracture and the original fracture in the circumstance of different deflection angles.

When the reorientation fracture reaches a certain length, it will inevitably turn back to the same stress direction as the initial principal stress direction, leading to limit length reorientation fracture. Here, the ratio of reorientation fracture length $(l - H/\sin \theta)$ to the original fracture length (H/K) is assumed as 0.5, 1.0, 1.5, and 2.0. In order to prevent the influence of permeability anisotropy on the reorientation fracture, the study was carried out under the condition of isotropic permeability. The angles between the directional fracture and original fracture are set as $\pi/4$, $\pi/2$, and $3\pi/4$.

Figures 9(c)–(e) display the productivity changes when the ratio of length varies. The degree of change is related to the deflection angle. At the circumstance of the same deflection angle, with the length ratio increased, the productivity of the reorientation fracture will drop at the isotropic. From

Figure 9(c), when the deflection angle is $\pi/4$, the productivity is similar. From Figures 9(d) and (e), at the angles of $\pi/2$ and $3\pi/4$, the productivity has been reduced to different degrees with the increase of length ratio. At the angle of $3\pi/4$, the decrease of productivity is faster with the length ratio. When the length ratio is greater than 1, with the increase of the length ratio, the rate of productivity declines gradually slows down.

Figure 9(f) displays an extreme example that the angle is π . This is not possible in reality, but from Figure 9(f), the decrease in production as the deflection angle increases can be better explained. With the increase of the length of reorientation fractures, the overlapping fractures with the original fractures are not effective fractures, which will not increase the productivity of the fractures, but will reduce the drainage area due to the overlap. This can happen with any fracture that has a deflection. However, when the deflection angle is small, as shown in Figure 9(c), the degree of interference between the reorientation fracture and the original fracture will be reduced. The productivity decline of the reorientation fracture wells will also be smaller.

These above results indicate that fracture length has an impact on fracture productivity. The longer the total fracture length is, the higher the fracture productivity is. The ratio of the length of the reorientation fracture and original fracture has a disadvantaged effect on productivity. As the ratio increases, the yield decreases more. The effect of length ratio on fracture productivity is controlled by the fracture angle. The larger the deflection angle is, the faster the productivity decreases with the length ratio.

Secondary fractures increase well production by extending the total fracture length. But under the premise that the total length of artificial fracture is certain, the longer the diversion fracture is, the larger the deflection angle is, and

the worse the fracturing stimulation effect is. Compared with nondeflection fractures of the same length, the productivity of deflection fractures will decrease to different degrees. Thus, it is necessary to avoid fracture deflection in actual production. However, in actual production fracturing, the diversion fracture is inevitable. In order to avoid the production decline caused by the deflection fracture, the total fracture length should be increased as much as possible, and the angle and fracture length ratio of the deflection fracture should be reduced.

4. Conclusions

- (1) The productivity formula of the reorientation fracture is deduced from the principle of multiwell pressure drop superposition. It is verified by numerical simulation that this method is accurate in calculating the production of reorientation fracturing wells. The calculation process of this formula is simple and the result is accurate. The formula has practical value, and the formula can be used to calculate the output in the actual production process
- (2) The fracture length affects fracture productivity strongly by controlling the effective drainage area. Longer fractures help create a larger drainage area, which will increase the productivity of refracture wells. So, refracture is necessary for the reservoir
- (3) Deflection angle and the ratio of the length of reorientation fracture to original fracture affect the drainage area when the total length of the fracture is determined. The increase in angle and ratio will reduce the productivity of refracture wells. When hydraulic refracture operations are used, the deflection of fracture should be avoided. Future research on refracture should focus on reducing fracture deflection in order to achieve higher fracture efficiency

Nomenclature

Δp :	Pressure difference, MPa
p_i :	Initial formation pressure, MPa
$p(r, t)$:	Stratospheric pressure at any point in the formation, MPa
q :	Production at any point in the formation, m ³
μ :	Fluid viscosity, mPa•s
B :	Volume compressibility
k :	Reservoir permeability, μm^2
h :	Average thickness of the reservoir, m
t :	Production time, d
r_e :	Boundary Radius, m
r :	Distance from any point in the formation to the fracture, m
η :	Pressure coefficient, $k/\phi\mu c_t$
k_y :	Permeability in the y direction, μm^2
k_y' :	Permeability in the y' direction, μm^2
H :	Distance from the horizontal section of the fracture to the X axis, m

l :	Half-length of hydraulic fractures horizontal length, m
L :	Total length of the fracture, m
K :	Slope of the middle section of the fracture, $\tan \theta$
θ :	Angle between the middle section fracture and the X axis
x_f :	Half-length of hydraulic fractures, m.

Data Availability

The data used to support the findings of this study are inter-section within the article.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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