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Research Article

Production Behavior Analysis of Multibranched Horizontal Oil Well considering Reservoir and Well-Type Factors

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Multibranched horizontal well is an important means to develop low permeability reservoirs. Fishbone multibranched horizontal well has the advantages of increasing drainage area, reducing drilling number, utilizing existing wells, and saving oilfield development cost, especially for marginal oilfield exploitation. The morphological structure of fishbone multibranched horizontal well is very complex, so the numerical simulation study is of great significance to guide the production of fishbone multibranched horizontal well. In this paper, the numerical model is established for fishbone multibranched horizontal well in the oil reservoir. The finite element method is used to numerically solve the mathematic model. The oil well production can be achieved by using the material balance method. Sensitivity analysis is made on the important reservoir and well-type factors that affect the production behavior and transient pressure distribution of fishbone multibranched horizontal well. It is concluded that the effective reservoir thickness and flowing bottomhole pressure have great influence on the productivity, but the influence of heterogeneity is not obvious. The length of main wellbore has great effect on the productivity in the early stage. Fishbone multibranched horizontal wells should be placed in the middle of the reservoir to increase productivity. Branch length, branch angle, branch number, and branch spacing are important parameters affecting the productivity of fishbone multibranched horizontal well. The variation of these parameters has obvious influence on the stimulation effect in the early stage of production, but the influence degree is different. Under the premise of drilling technology and drilling safety, the comprehensive impact of these four factors on productivity should be considered simultaneously. The presented model and obtained results not only enrich production behavior analysis of fishbone multibranched horizontal well but also have significance on formulation of stimulation measures and efficient low permeability reservoir development.

1. Introduction

Multibranch horizontal well refers to one horizontal well as the main borehole, and two or more branch boreholes into oil and gas reservoir are drilled in each part of the horizontal well, which can give play to the advantages of high efficiency and high production of horizontal wells, increase the drainage area, tap the remaining oil potential, increase the recovery rate, and improve the field development effect and is widely used in low-permeability reservoirs, thick oil reservoirs, thin reservoirs, and multilayer reservoirs [1–8]. Multibranch horizontal wells have become an important way to develop low-permeability oil and gas reservoirs, and it is of great significance to study the capacity of multibranch horizontal wells and its influencing factors in depth [9–12]. Each branch of a multibranch horizontal well can be regarded as a horizontal well, and there are more factors affecting the productivity of a multibranch horizontal well than a normal horizontal well. The numerical simulation model can provide an important basis for the determination of the reservoir exploitation plan, especially for the understanding of the sensitivity of various factors in the development process and the environmental impact [13, 14]. Many scholars have already conducted studies on the sensitivity analysis of each influencing factor of multibranch horizontal wells and have preliminary experiences and conclusions.

Fishbone spur horizontal wells are one kind of multibranch horizontal wells, the current research ideas and methods are based on the conventional black oil model, and the numerical solutions are all finite difference method. Due to the limitation of finite difference method, the description of fishbone spur horizontal wells by this method has a large gap with the actual conditions, which is one of the difficulties in the current numerical simulation theory research of fishbone spur horizontal wells [15]. Hu et al. studied the effects of structural parameters such as branch symmetry, number of branches, branch angle, and branch length on the productivity of horizontal wells with fishbone spurs [16]. Ozkan et al. proposed a mathematical model for a two-branch horizontal well and gave an analytical solution based on the branch length, angle, vertical distance, and longitudinal distance of the two branches [17]. Wu et al. established a set of semianalytical capacity prediction model for multibranch horizontal wells. The results of the study indicated that the largest possible branch length, the number of branches with more than three branches, and a branch angle of not less than 30° should be selected [18]. Huang et al. studied the effects of uneven flow density distribution in branch wells and main wellbore and uneven skin distribution in each production section on the bottomhole pressure in herringbone multibranch horizontal wells [19].

In terms of benefits and costs, Ren et al. established a numerical simulation model of coal reservoir. The productivity of different well types is predicted and compared with field data [20]. With the development of numerical simulation software, Dai et al. established a variety of geological models by using ECLIPSE numerical simulation software based on the steady-state productivity calculation formula of horizontal and branch wells and physical property parameters of a domestic oil field [1]. Lv et al. conducted a numerical simulation study on horizontal wells with different branch angles and branch lengths. This study showed that the increase of branch angle has little effect on the time to water and water content of horizontal wells with fishbone spur. The increase of the number of branches has a great effect on the production of horizontal wells with fishbone spur in the early stage of exploitation. The longer the branches, the longer the time to water [21–23]. Duan et al. [24] used the mutual coupling of wellbore flow and reservoir inflow to obtain several multibranched well pressure instability curves and delineate the characteristic sections of seepage flow in different multibranch wells.

In this paper, the numerical model of fishbone multibranch horizontal well in reservoir is established to evaluate the effect of reservoir and well-type factors on well production. To numerically solve the mathematic model, the finite element method is employed. The production rate of fishbone multibranch horizontal well is calculated by using the material balance method. The effects of formation thickness, heterogeneity, production pressure differential, main wellbore length and position, branch length, branch angle, branch numbers, and branch spacing on production behavior and transient pressure distribution characteristics are analyzed. The paper is organized as follows: Section 1 is the introduction; Section 2 is the physics and mathematical model; Section 3 is the solution workflow; Section 4 is the sensitivity analysis; Section 5 is the conclusions.

2. System Description

2.1. Physical Model. There are many forms of multibranched horizontal well, among which fishbone branch well is the most representative one, which can reflect all the characteristics of branch well. Therefore, this paper takes fishbone multibranched horizontal well as an example to study the influence of different factors on productivity. The schematic diagram for the physical model of fishbone multibranched horizontal well in reservoir is shown in Figure 1. In this paper, we consider a fishbone multibranched horizontal well with n branch wells in a reservoir with closed top and bottom, where both the main horizontal well and branch wells are perpendicular to the Z axis. The branch wellbore is at a specific angle to the main wellbore in the XY plane (shown in Figure 1(c)), with single-phase fluid (oil) flowing to both main horizontal and branch wells. It is assumed that the branch wellbores are staggered and evenly distributed on both sides of the main wellbore. In addition, there are some parameters that need to be described: (1) the radius of reservoir can be assumed to be r; (2) the reservoir is horizontal with uniform thickness of h and original pressure p_i; (3) the horizontal permeability is K_h, the vertical permeability is K_v, the comprehensive compressibility is C_t, and the porosity is φ; (4) the influence of gravity and capillary forces is ignored. As shown in Figure 1(b), the length of the main wellbore is L, the main wellbore center coordinate is (x, y, z), the length of each branch wellbore is l, the branch angle between branch wellbore and main wellbore is α, and the branch spacing between two branch wellbores is d.

2.2. Mathematical Model. With orthogonal coordinate system, the flow equation can be expressed as follows.

Flow equation in the reservoir is

$$\frac{\partial}{\partial x}\left(\frac{K_h}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{K_h}{\mu}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{K_v}{\mu}\frac{\partial p}{\partial z}\right) = \phi C_t \frac{\partial p}{\partial t} + q. \tag{1}$$

If the sink or source is ignored, Equation (1) can be simplified into the following.

Flow equation in the reservoir is

$$\frac{\partial}{\partial x}\left(\frac{K_h}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{K_h}{\mu}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{K_v}{\mu}\frac{\partial p}{\partial z}\right) = \phi C_t \frac{\partial p}{\partial t}. \tag{2}$$

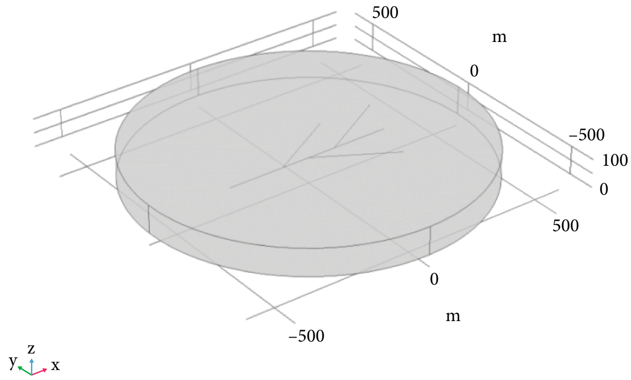
Initial condition:

$$p(x, y, z, t = 0) = p_i. \tag{3}$$

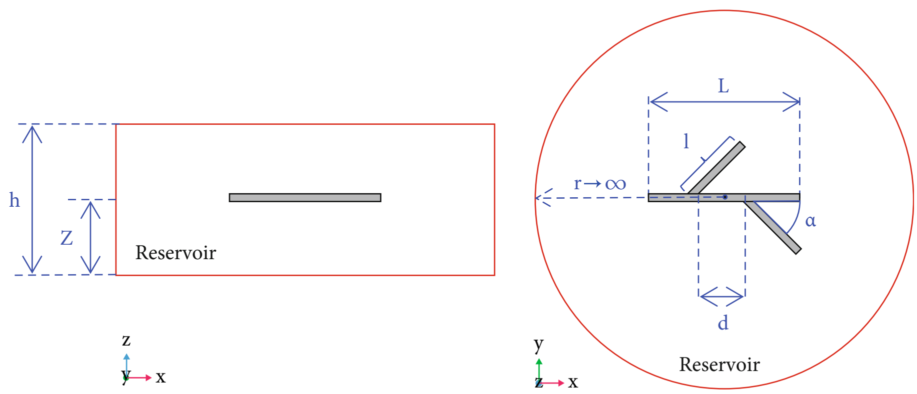
Outer boundary:

$$\begin{aligned} \frac{\partial p}{\partial z} &= 0, \quad z = 0 \text{ or } h, \\ p &= 0, r = \infty, \end{aligned} \tag{4}$$

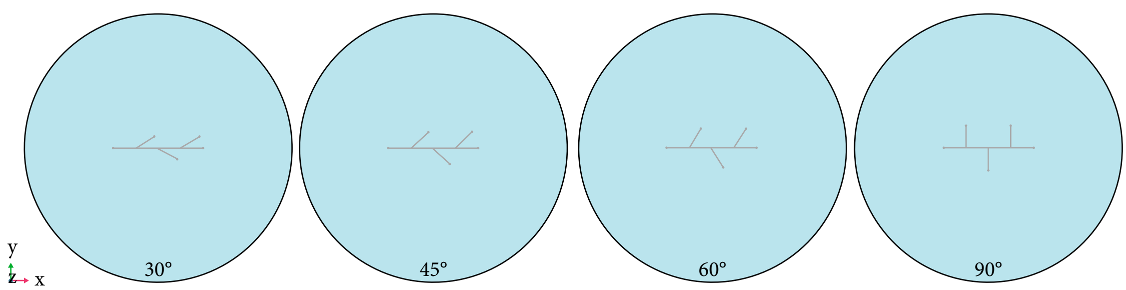
where x, y, and z are the directional coordinates, m; K_h and K_v are horizontal permeability and vertical permeability



(a) 3D view of reservoir with fishbone multibranched horizontal well



(b) 2D view of reservoir with fishbone multibranched horizontal well



(c) Fishbone multibranched horizontal wells with different branch angles

Figure 1: Physical model of fishbone multibranched horizontal well in oil reservoir.

at any point in reservoir, respectively, m^2; p is reservoir pressure, Pa; p_i is reference pressure, Pa; μ is viscosity of oil, Pa·s; t is time, sec; C_t is comprehensive compressibility factor, 1/Pa; and φ are the formation porosity, fraction.

3. Model Solution

In this study, we use finite element method to solve the equation system. The basic function is defined as

$$N = (N_1, N_2, \cdots, N_n). \quad (5)$$

The displacement function is

$$\tilde{p} = \sum_{i=1}^{n} N_i p_i. \quad (6)$$

We can get the integrating form for reservoir:

$$\iiint_{\Omega_e} N_i \left[\frac{\partial}{\partial x}\left(\frac{K_h}{\mu}\frac{\partial \tilde{p}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{K_h}{\mu}\frac{\partial \tilde{p}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{K_v}{\mu}\frac{\partial \tilde{p}}{\partial z}\right)\right] dV = \iiint_{\Omega_e} (\phi C_t) N_i \frac{\partial \tilde{p}}{\partial t} dV. \quad (7)$$

The final equation form is:

$$\iiint_{\Omega_e}\left\{\left(\frac{K_h}{\mu}\right)\begin{pmatrix}\frac{\partial N_1}{\partial x}\\ \frac{\partial N_2}{\partial x}\\ \vdots\\ \frac{\partial N_n}{\partial x}\end{pmatrix}\begin{pmatrix}\frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial x} & \cdots & \frac{\partial N_n}{\partial x}\end{pmatrix}+\left(\frac{K_h}{\mu}\right)\begin{pmatrix}\frac{\partial N_1}{\partial y}\\ \frac{\partial N_2}{\partial y}\\ \vdots\\ \frac{\partial N_n}{\partial y}\end{pmatrix}\begin{pmatrix}\frac{\partial N_1}{\partial y} & \frac{\partial N_2}{\partial y} & \cdots & \frac{\partial N_n}{\partial y}\end{pmatrix}+\left(\frac{K_v}{\mu}\right)\begin{pmatrix}\frac{\partial N_1}{\partial z}\\ \frac{\partial N_2}{\partial z}\\ \vdots\\ \frac{\partial N_n}{\partial z}\end{pmatrix}\begin{pmatrix}\frac{\partial N_1}{\partial z} & \frac{\partial N_2}{\partial z} & \cdots & \frac{\partial N_n}{\partial z}\end{pmatrix}\right\}$$
$$\begin{pmatrix}p_1\\ p_2\\ \vdots\\ p_n\end{pmatrix}dV+\iiint_{\Omega_e}(\phi C_t)\begin{pmatrix}N_1\\ N_2\\ \vdots\\ N_n\end{pmatrix}\begin{pmatrix}N_1 & N_2 & \cdots & N_n\end{pmatrix}\begin{pmatrix}\frac{p_1^n-p_1^{n-1}}{\Delta t}\\ \frac{p_2^n-p_2^{n-1}}{\Delta t}\\ \vdots\\ \frac{p_n^n-p_n^{n-1}}{\Delta t}\end{pmatrix}dV=0. \tag{8}$$

The production rate can be obtained by material balance method.

4. Discussion and Analysis

4.1. Effect of Reservoir Properties

4.1.1. Effect of Formation Thickness (h). The effect of formation thickness on production behavior is discussed in this section. The reservoir properties and main well parameters are shown in Table 1. Basic parameters of branch well to be paid attention to are $n = 3$, $\alpha = 90°$, $l = 100$ m, and $d = 100$ m.

The effect of formation thickness on transient pressure distribution and oil production of fishbone multibranched horizontal well is presented in Figure 2. Figure 2(a) describes the transient pressure distributions characteristics at 5000 d considering different formation thickness. As shown in Figures 2(b) and 2(d), the oil production rate for 30 m of formation thickness is higher than that of the other two scenarios in the early stage of production. However, the influence of formation thickness on production rate can be ignored in the later stage of production. This is because in the late stage of production, the oil production capacity of the formation is close to the limit, the remaining oil around the well is less, and the water cut is too high. The cumulative production for 30 m of formation thickness is higher than that of the other two scenarios in the whole process of production. Figure 2(c) shows that for different time at initial stage of production, oil production rate increases linearly with increasing formation thickness. The formation thickness can be considered as the effective thickness. This indicates that with the increase of effective thickness, oil reserves increase and multibranched well recovery capacity increases.

4.1.2. Effect of Formation Heterogeneity (K_v/K_h). The effect of formation heterogeneity on production behavior is discussed in this section. The reservoir properties and main well parameters are shown in Table 2. It should be noted that the well structure used here is the same as that used in Section 4.1.1.

The effect of formation heterogeneity on production behavior of fishbone multibranched horizontal well is presented in Figure 3. The effect of formation heterogeneity on transient pressure distribution at 5000 d for 100 m of formation thickness is presented in Figure 4. As shown in Figure 3, the effect of K_v/K_h on oil production behavior is sensitive to the formation thickness. In the formation with large h, the difference of oil production behavior is more obvious due to the difference of formation heterogeneity. Figures 3(d) and 3(e) show that with the increase of K_v/K_h value, that is, with the increase of vertical permeability, vertical seepage resistance decreases and productivity increases in the early stage of production. In the later stage of production, the influence of K_v/K_h on production rate can be basically ignored, but a there are some differences in cumulative production. In addition, as shown in Figures 3(c) and 3(f), the production rate at the initial stage of production increases with the decrease of reservoir heterogeneity, but the increase rate gradually decreases. The gradual decrease in the growth rate is mainly due to the existence of the limit oil production capacity of the formation. Figure 4 shows that the pressure drop propagation is slowly due to the small K_v/K_h, that is, the strong heterogeneity of formation. Different K_v/K_h have different effect on area and shape of control area. The vertical permeability of reservoirs has an important influence on the productivity of multibranched horizontal well. When using multibranched horizontal well to develop oil reservoirs with the same other conditions, reservoirs with higher vertical permeability should be given priority.

4.2. Effect of Flowing Bottomhole Pressure (FBHP). The effect of FBHP on production behavior is discussed in this section. The reservoir properties and main well parameters are shown in Table 3. Basic parameters of branch well to be paid attention to are $n = 3$, $\alpha = 90°$, $l = 100$ m, and $d = 100$ m.

Table 1: Input parameters of simulation for considering different formation thickness.

Parameter	Value	Parameter	Value
Formation thickness, h (m)	10, 20, 30	Initial reservoir pressure, p_i (MPa)	20
Porosity, φ	0.4	Flowing bottomhole pressure, p_w (MPa)	10
Permeability, K_h (μm^2)	0.005	Formation heterogeneity, K_v/K_h	1
Formation rock compressibility, C_f (1/MPa)	2×10^{-4}	Formation fluid compressibility, C_l (1/MPa)	10×10^{-4}
Formation fluid viscosity, μ (mP·s)	5	Formation fluid density, ρ (kg/m^3)	1000
Reservoir radius, r_1 (m)	600	Main horizontal well length, L (m)	400
Main horizontal well center coordinates (x, y, z)		(0, 0, 5)	

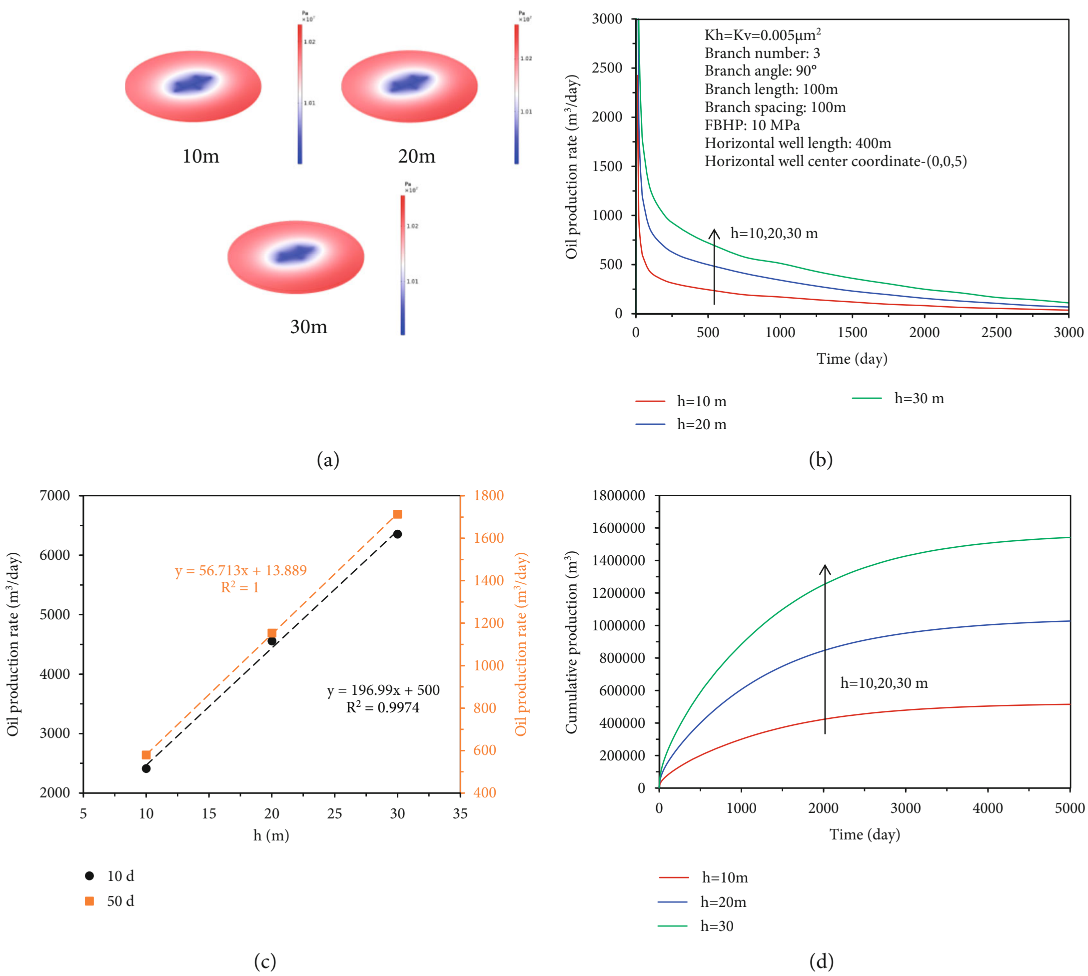


Figure 2: Effect of formation thickness on transient pressure distribution and production behavior.

The effect of FBHP on production behavior of fishbone multibranched horizontal well is presented in Figure 5. The effect of FBHP on transient pressure distribution at 5000 d is presented in Figure 6. It should be noted that different FBHPs represent different production pressure differentials. As shown in Figure 5, as the FBHP decreases (i.e., the production pressure differential increases), the production rate and cumulative production increase in early stage of production, indicating that lower bottom hole pressure (i.e., the larger production pressure differential) results in greater elastic productivity. Figure 5(a) shows that the influence of FBHP on production rate can be ignored in the later stage of production. The cumulative production for 8 MPa of FBHP is higher than that of the other two scenarios in the whole process of production. Figure 5(c) shows that for different times at the initial stage of production, oil production rate increases linearly with increasing production pressure differential. However, the oil production rate increases

Table 2: Input parameters of simulation for considering different formation heterogeneity.

Parameter	Value	Parameter	Value
Formation thickness, h (m)	10,100	Initial reservoir pressure, p_i (MPa)	20
Porosity, φ	0.4	Flowing bottomhole pressure, p_w (MPa)	10
Horizontal permeability, K_h (μm^2)	0.005	Formation heterogeneity, K_v/K_h	1,0.5,0.1,0.05
Formation rock compressibility, C_f (1/MPa)	2×10^{-4}	Formation fluid compressibility, C_l (1/MPa)	10×10^{-4}
Formation fluid viscosity, μ (mP·s)	5	Formation fluid density, ρ (kg/m^3)	1000
Reservoir radius, r_1 (m)	600	Main horizontal well length, L (m)	400
Main horizontal well center coordinates (x, y, z)		(0, 0, 5)	

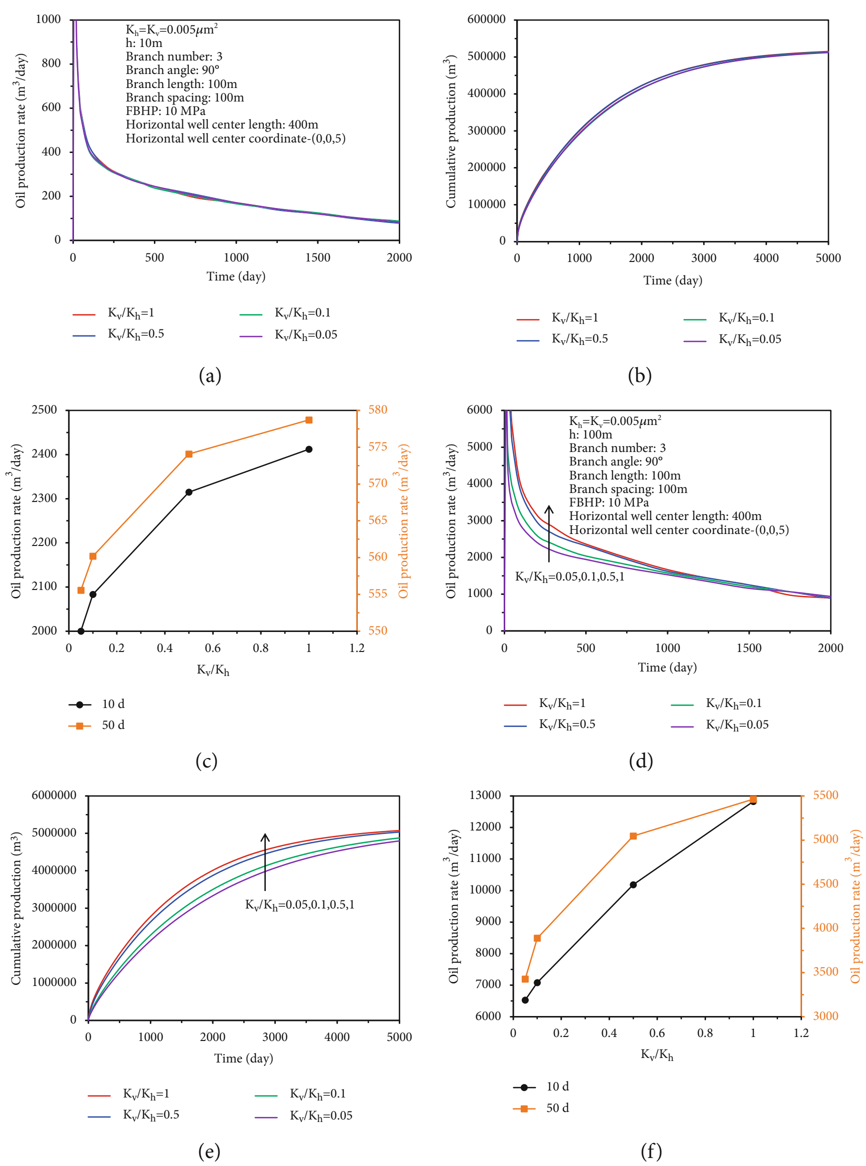


Figure 3: Effect of formation heterogeneity on production behavior.

slowly with increasing production time. Figure 6 shows that the pressure drop propagation is slowly due to the small production pressure differential, that is, the large FBHP.

4.3. Effects of Well-Type Factors. Compared with traditional vertical and horizontal well, fishbone multibranched horizontal well has complex well structure and complex seepage

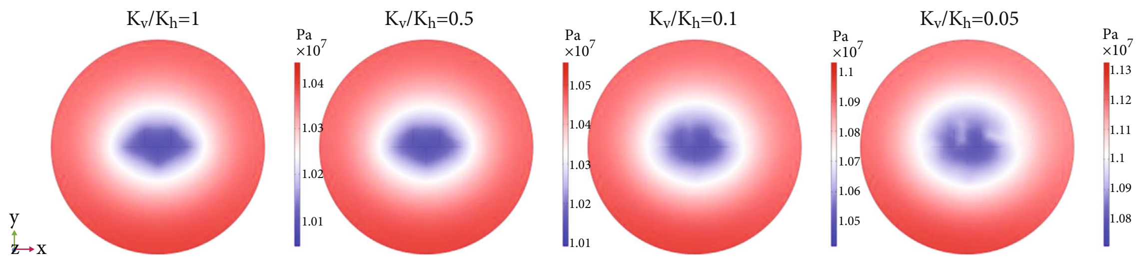


FIGURE 4: Effect of formation heterogeneity on transient pressure distribution.

TABLE 3: Input parameters of simulation for considering different FBHP.

Parameter	Value	Parameter	Value
Formation thickness, h (m)	10	Initial reservoir pressure, p_i (MPa)	20
Porosity, φ	0.4	Flowing bottomhole pressure, p_w (MPa)	8,10,12
Horizontal permeability, K_h (μm^2)	0.005	Formation heterogeneity, K_v/K_h	1
Formation rock compressibility, C_f (1/MPa)	2×10^{-4}	Formation fluid compressibility, C_l (1/MPa)	10×10^{-4}
Formation fluid viscosity, μ (mP·s)	5	Formation fluid density, ρ (kg/m^3)	1000
Reservoir radius, r_1 (m)	600	Main horizontal well length, L (m)	400
Main horizontal well center coordinates (x, y, z)		(0, 0, 5)	

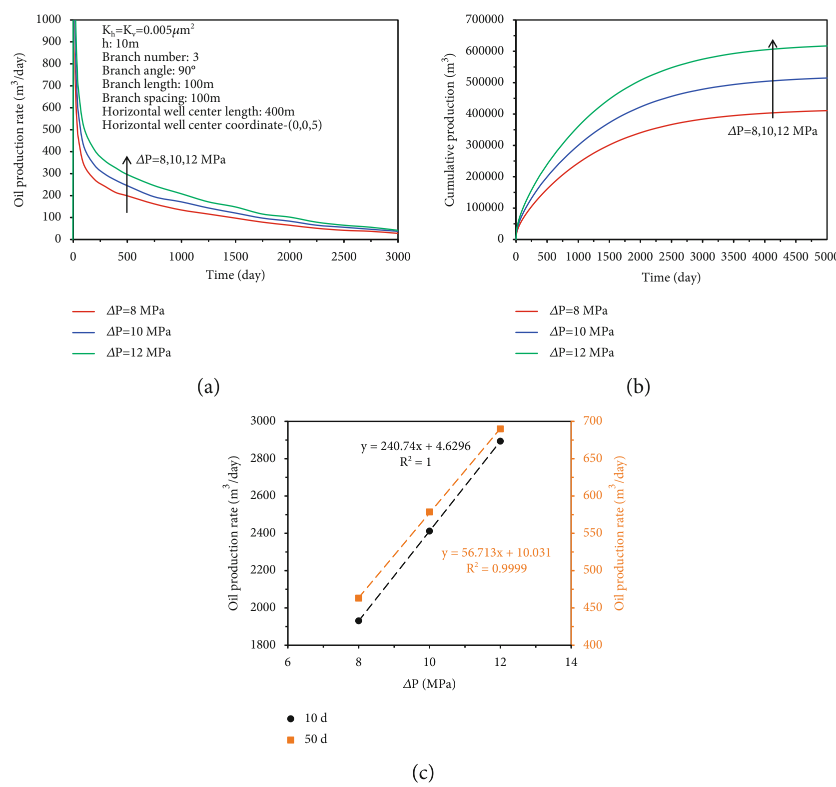


FIGURE 5: Effect of FBHP on production behavior.

law in the formation near the wellbore. In this section, the effects that various well-type factors on the transient pressure distribution and production behavior in an oil reservoir described mathematically in the previous section are discussed. The well-type factors include the length of main horizontal wellbore, L; the location of main horizontal wellbore in reservoir, (x, y, z); the length of branch wellbore, l; the number of branch wellbore, n; the branch angle between

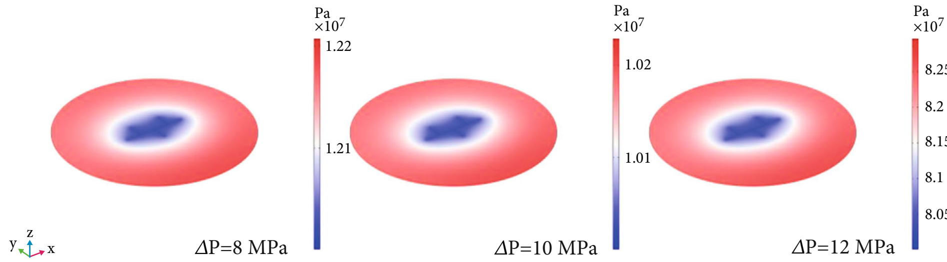


Figure 6: Effect of production pressure differential on transient pressure distribution.

Table 4: Input parameters of simulation for considering different L.

Parameter	Value	Parameter	Value
Formation thickness, h (m)	10	Initial reservoir pressure, p_i (MPa)	20
Porosity, φ	0.4	Flowing bottomhole pressure, p_w (MPa)	10
Horizontal permeability, K_h (μm^2)	0.005	Formation heterogeneity, K_v/K_h	1
Formation rock compressibility, C_f (1/MPa)	2×10^{-4}	Formation fluid compressibility, C_l (1/MPa)	10×10^{-4}
Formation fluid viscosity, μ (mP·s)	5	Formation fluid density, ρ (kg/m^3)	1000
Reservoir radius, r_1 (m)	600	Main horizontal well length, L (m)	400,600,800
Main horizontal well center coordinates (x, y, z)		$(0, 0, 5)$	

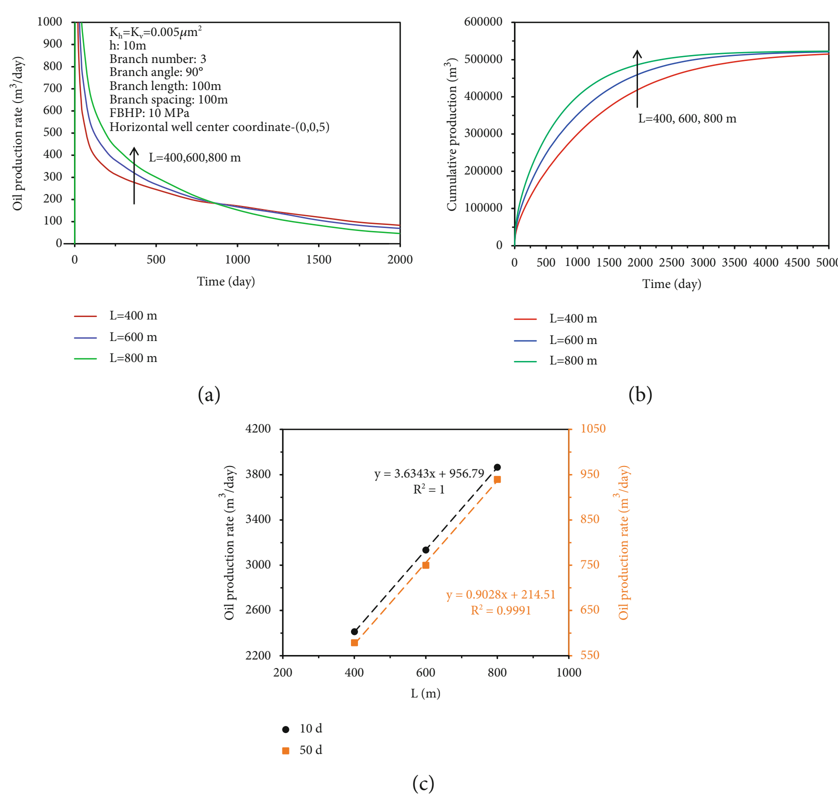


Figure 7: Effect of main wellbore length on production behavior.

branch wellbore and main wellbore, α; and the branch spacing between two branch wellbores, d. Sensitivity analysis of different factors is as follows.

4.3.1. Effect of the Length of Main Horizontal Wellbore (L). The effect of L on production behavior is discussed in this section. The reservoir properties and main well parameters

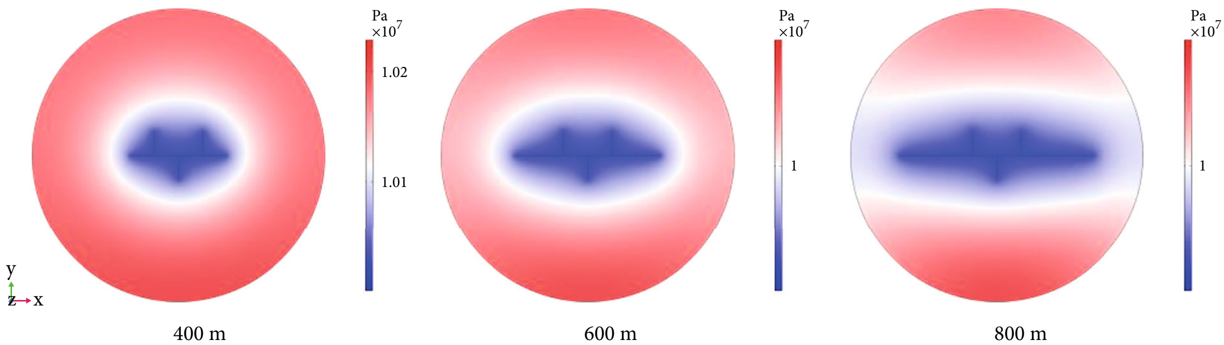


Figure 8: Effect of main wellbore length on transient pressure distribution.

Table 5: Input parameters of simulation for considering different locations of the main horizontal wellbore.

Parameter	Value	Parameter	Value
Formation thickness, h (m)	10,100	Initial reservoir pressure, p_i (MPa)	20
Porosity, φ	0.4	Flowing bottomhole pressure, p_w (MPa)	10
Horizontal permeability, K_h (μm^2)	0.005	Formation heterogeneity, K_v/K_h	1
Formation rock compressibility, C_f (1/MPa)	2×10^{-4}	Formation fluid compressibility, C_l (1/MPa)	10×10^{-4}
Formation fluid viscosity, μ (mP·s)	5	Formation fluid density, ρ (kg/m^3)	1000
Reservoir radius, r_1 (m)	600	Main horizontal well length, L (m)	400
Main horizontal well center coordinates (x, y, z)		z : (0, 0, 10), (0, 0, 25), (0, 0, 50) y : (0, 0, 5), (0,200,5), (0,400,5) x : (0, 0, 5), (150,0, 5), (300,0, 5)	

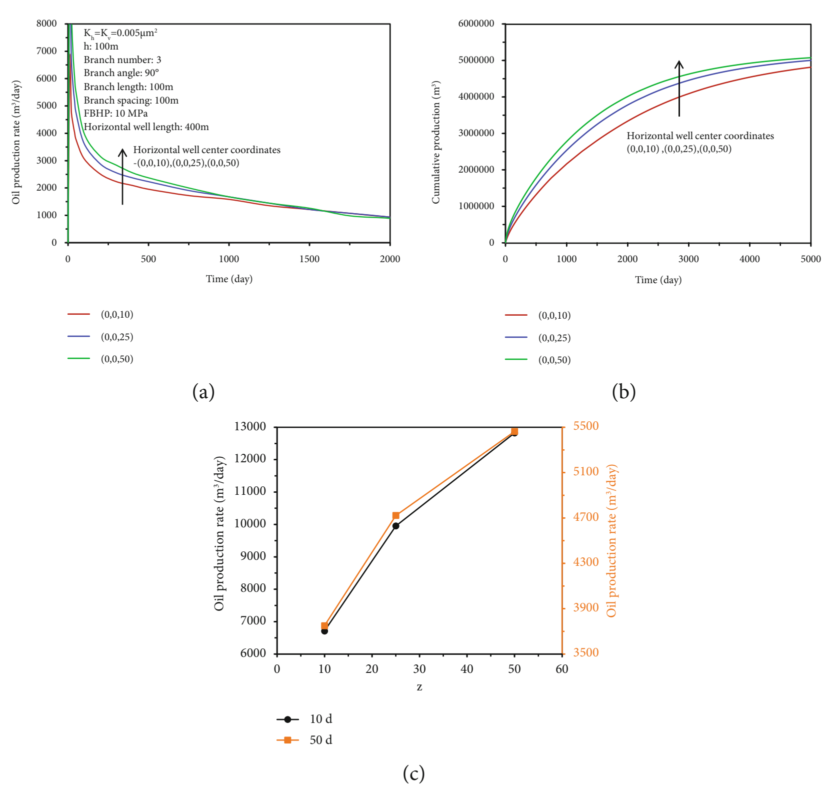


Figure 9: Effect of vertical height of the main wellbore on production behavior.

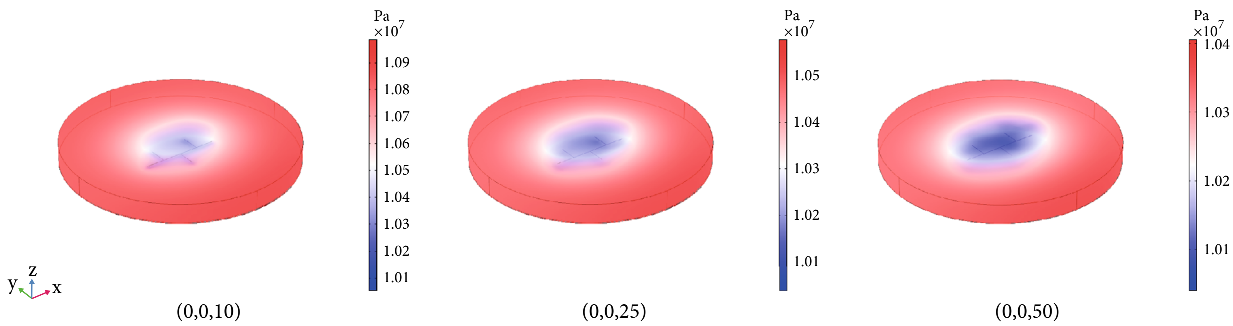


Figure 10: Effect of vertical height of the main wellbore on transient pressure distribution.

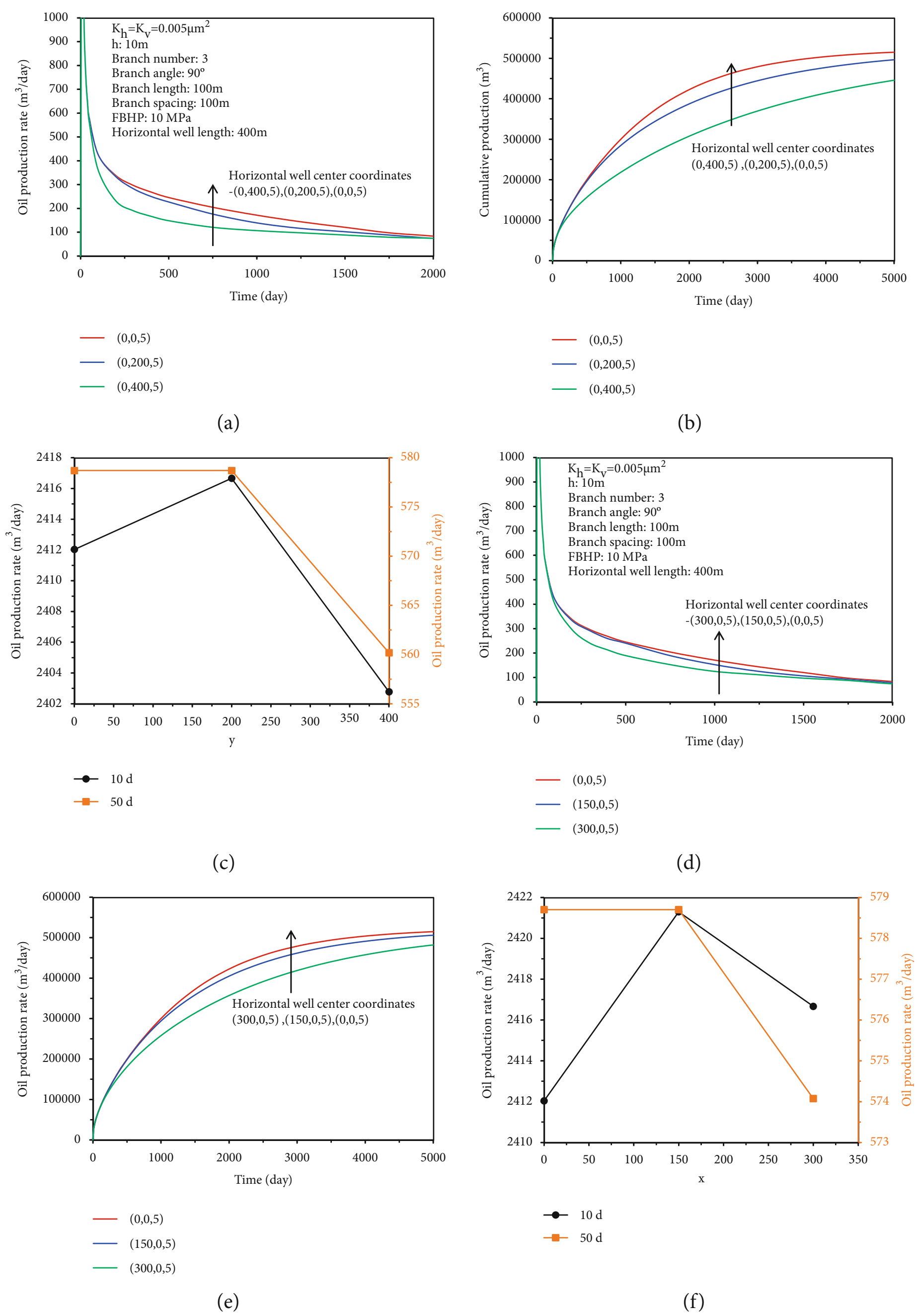


Figure 11: Effect of location of the main wellbore in horizontal plane on production behavior.

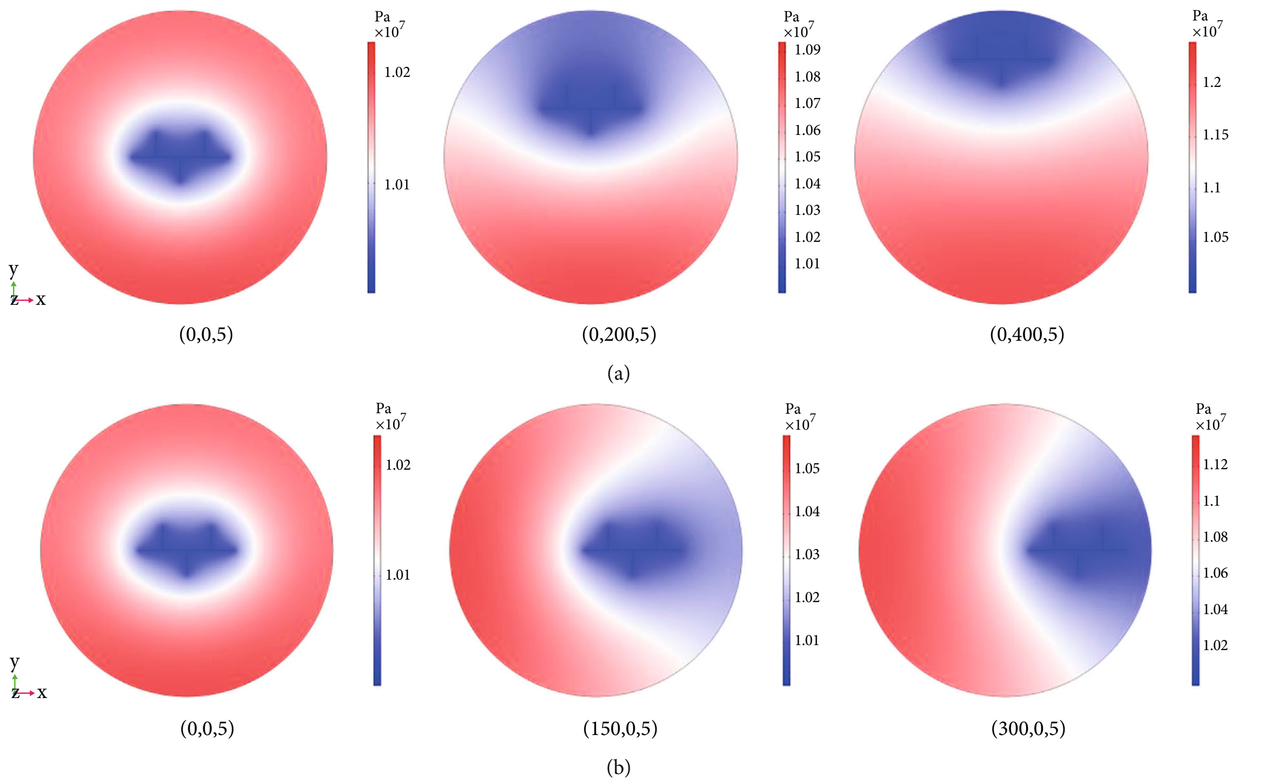


Figure 12: Effect of location of the main wellbore in horizontal plane on transient pressure distribution.

Table 6: Input parameters of simulation for considering different branch well structure.

Parameter	Value	Parameter	Value
Formation thickness, h (m)	10	Initial reservoir pressure, p_i (MPa)	20
Porosity, φ	0.4	Flowing bottomhole pressure, p_w (MPa)	10
Horizontal permeability, K_h (μm^2)	0.005	Formation heterogeneity, K_v/K_h	1
Formation rock compressibility, C_f (1/MPa)	2×10^{-4}	Formation fluid compressibility, C_l (1/MPa)	10×10^{-4}
Formation fluid viscosity, μ (mP·s)	5	Formation fluid density, ρ (kg/m^3)	1000
Reservoir radius, r_1 (m)	600	Main horizontal well length, L (m)	400
Main horizontal well center coordinates (x, y, z)		$(0, 0, 5)$	

are shown in Table 4. Basic parameters of branch well to be paid attention to are $n = 3$, $\alpha = 90^\circ$, $l = 100$ m, and $d = 100$ m.

The effect of L on production behavior of fishbone multibranched horizontal well is presented in Figure 7. The effect of L on transient pressure distribution at 5000 d is presented in Figure 8. As shown in Figure 7, as L decreases, both the production rate and cumulative production of multibranch well increase at the early stage of production. It indicates that large length of the main wellbore results in the increase of the initial production capacity. Figure 7(b) shows that the influence of L on cumulative production can be ignored in the later stage of production, but a there are some differences in production rate. Figure 7(c) shows that for different times at the initial stage of production, oil production rate increases linearly with increasing production pressure differential. Figure 8 shows that the contact area (i.e., drainage area) with reservoir can be increased by increasing the length of the main wellbore, and the pressure propagation can quickly spread to the boundary and provide a stable energy supply, which helps to increase the productivity.

4.3.2. Effect of the Location of Main Horizontal Wellbore in Reservoir (x, y, z). The effect of location of main horizontal wellbore in reservoir on production behavior is discussed in this section. The reservoir properties and main well parameters are shown in Table 5. It should be noted that the well structure used here is the same as that used in Section 4.3.1.

(1) Effect of Vertical Height of the Main Wellbore (z). The effect of vertical height of the main wellbore (z) on production behavior of fishbone multibranched horizontal well for 100 m of formation thickness is presented in Figure 9. The effect of vertical height on transient pressure distribution at

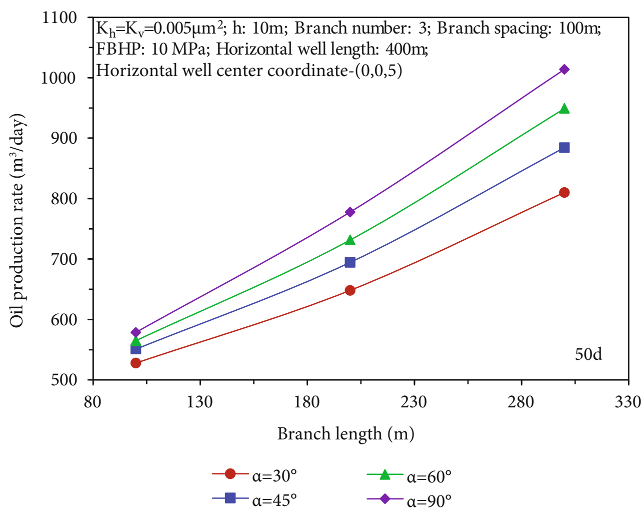


FIGURE 13: Effect of branch length on production rate.

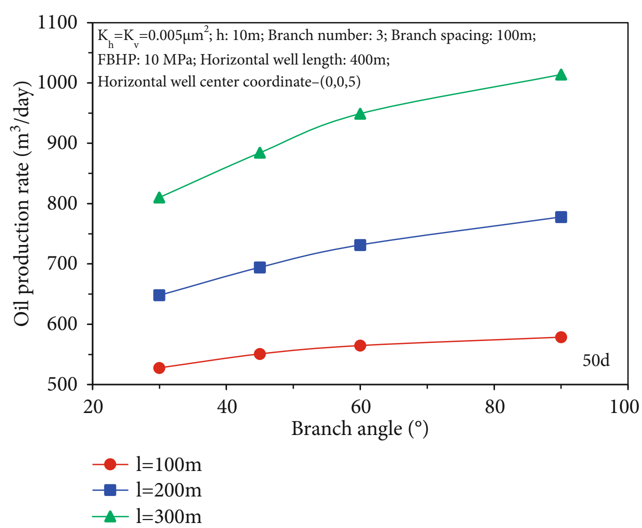


FIGURE 14: Effect of branch angle on production rate.

5000 d for 100 m of formation thickness is presented in Figure 10. As shown in Figures 9(a) and 9(b), as z increases from 10 to 50, both the production rate and cumulative production increase at initial stage of production. That indicates that well locating in the middle of the reservoir results in higher early production. In the later stage of production, the influence of vertical height on production rate can be basically ignored, but a there are some differences in cumulative production. In addition, as shown in Figure 9(c), the production rate at the initial stage of production increases with increasing z, but the increase rate gradually decreases. Figure 10 shows that the pressure drop propagation is slowly due to the small z (i.e., the closer the well is to the bottom boundary), thus leading to the relatively weak productivity.

(2) Effect of Location of the Main Wellbore in Horizontal Plane (x and y). The effect of location of the main wellbore in horizontal plane on production behavior for 10 m of h is presented in Figure 11. The effect of location in horizontal plane on transient pressure distribution at 5000 d for 10 m of formation thickness is presented in Figure 12. As shown in Figures 11(a), 11(b), 11(d), and 11(e), as the x or y decreases, both the production rate and cumulative production increase at the early stage of production. That indicates that well located in the middle of the reservoir resulted in higher early production. In the later stage of production, the influence of x or y on production rate can be basically ignored, but there are some differences in cumulative production. In addition, as shown in Figures 11(c) and 11(f), the production rate for $y = 200$ or $x = 150$ at 10 d are higher than other two scenarios, respectively. However, at 50 d, the production rate for $y = 0$ and 200 are equal, as well as or $x = 0$ and 150, and the production rate for $y = 400$ or $x = 300$ are the lowest. Figure 12 shows that the pressure drop propagation is slowly due to the big y or x (i.e., the closer the well is to the vertical boundary), thus leading to the relatively weak productivity.

4.3.3. Effect of the Branch Well Structure. The effect of branch well structure on production behavior is discussed in this section. The reservoir properties and main well parameters are shown in Table 6.

(1) Effect of the Length of Branch Well (l). The effect of l on production behavior is discussed in this section. Basic parameters of branch well to be paid attention to are $n = 3$ and $d = 100$ m. The initial production rate at production time of 50 d was taken as the comparison target. The effect of different branch lengths on production rate of multibranched horizontal well is shown in Figure 13. The production rate of multibranched horizontal well increases approximately linearly with the increase of branch length, and the increase rate gradually increases. The reason for this is that the larger the branch length, the less the increase in the length of the branch is affected by the main wellbore, and the greater the stimulation effect for each additional length of the branch. It can also be seen from Figure 13 that the effect of increasing branch length is different with different branch angles. The larger the branch angle is, the longer the branch length is, which makes the control area of the multilateral horizontal wells larger, the mutual interference between the lateral wells is weakened, the influence of the main well on the lateral wells is weakened, and the growth rate of the production rate is greater.

(2) Effect of the Branch Angles (α). The effect of α on production behavior is discussed in this section. Basic parameters of branch well to be paid attention to are $n = 3$ and $d = 100$ m. The initial production rate at production time of 50 d was taken as the comparison target. The effect of the number of branches on the production rate of multibranched horizontal well is shown in Figure 14. The production rate of multibranched horizontal well increases approximately linearly with the increase of branch angle, and the increase rate gradually decreases. The angle at which the increase rate slows down is generally around 45°. The larger the branch length, the greater the effect of the branch angle on production rate. The reason is that when the branch angle is small,

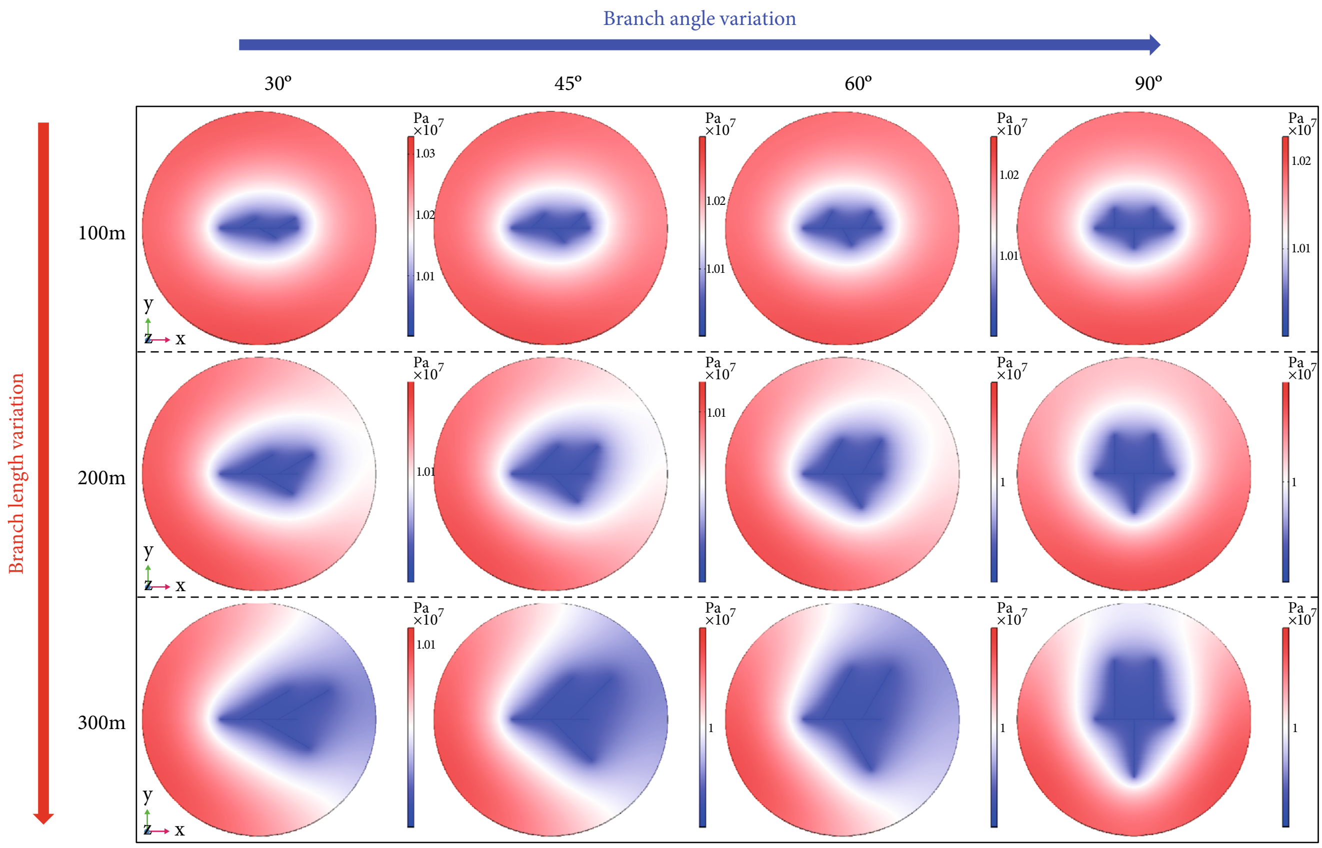


FIGURE 15: Effect of branch length and angle on transient pressure distribution at 5000 d.

the effect of the main wellbore on the branch wellbores decreases rapidly with each additional angle, and the contribution of the branch well to production rate increases rapidly. However, when the branch angle is large, the effect of the branch wellbores on the main wellbore becomes less obvious every time the angle increases, and the contribution of the branch well to the production rate is relatively small. Therefore, with the increase of the branch angle, the increase rate of production rate of the multibranched horizontal well gradually decreases. In the design of multibranched well, the angle between the branch wellbore and the main wellbore should be larger as far as possible.

The effects of branch length and angle on transient pressure distribution at 5000 d are presented in Figure 15. We can find that at a given branch length, with the increase of branch angle, the control area of fishbone multibranched horizontal well increases, and the interference between branch wellbore and main wellbore decreases. Similarly, at a given branch angle, with the increase of branch length, the control area increases, and the interference between branch wellbore and main wellbore decreases. It can also be seen that the increase of branch angle has different effects on the shape and area of control area of fishbone multibranched horizontal well under different branch lengths. The longer the branch length, the greater the influence of branch angle on the shape and area of control area.

After comparison, it can be concluded that the increase of branch length has a greater effect on the increase of control area (drainage area) of fishbone multibranched horizontal well than the increase of branch angle, thus resulting in the greater stimulation effect on production rate. Therefore, under the premise of drilling technology and drilling safety, the influence of branch length should be given priority, and longer branch length and larger branch angle should be selected.

The effect of branch angle on evolution of transient pressure distribution for different production stage is presented in Figure 16. At 10 d, the initial stage of production, the low-pressure area rapidly diffused outward. With further production, the low-pressure area begins to increase gradually. With the increase of branch angle, the change trend of the pressure field is similar to that of the branch angle of 30°, but the diffusion speed of the low-pressure area gradually becomes faster, and the area of the low-pressure area gradually becomes larger. In the late production period, the area of low-pressure area gradually tends to be stable, and the area of low-pressure area of the fishbone multibranched horizontal well with larger branch angle is larger.

(3) Effect of the Numbers of Branch Well (n). The effect of n on production behavior is discussed in this section. Basic parameters of branch well to be paid attention to are $\alpha = 45°$ and $d = 100$ m. The initial production rate at production time of 50 d was taken as the comparison target. The effect of the number of branches on the production rate of multibranched horizontal well is shown in Figure 17. With the

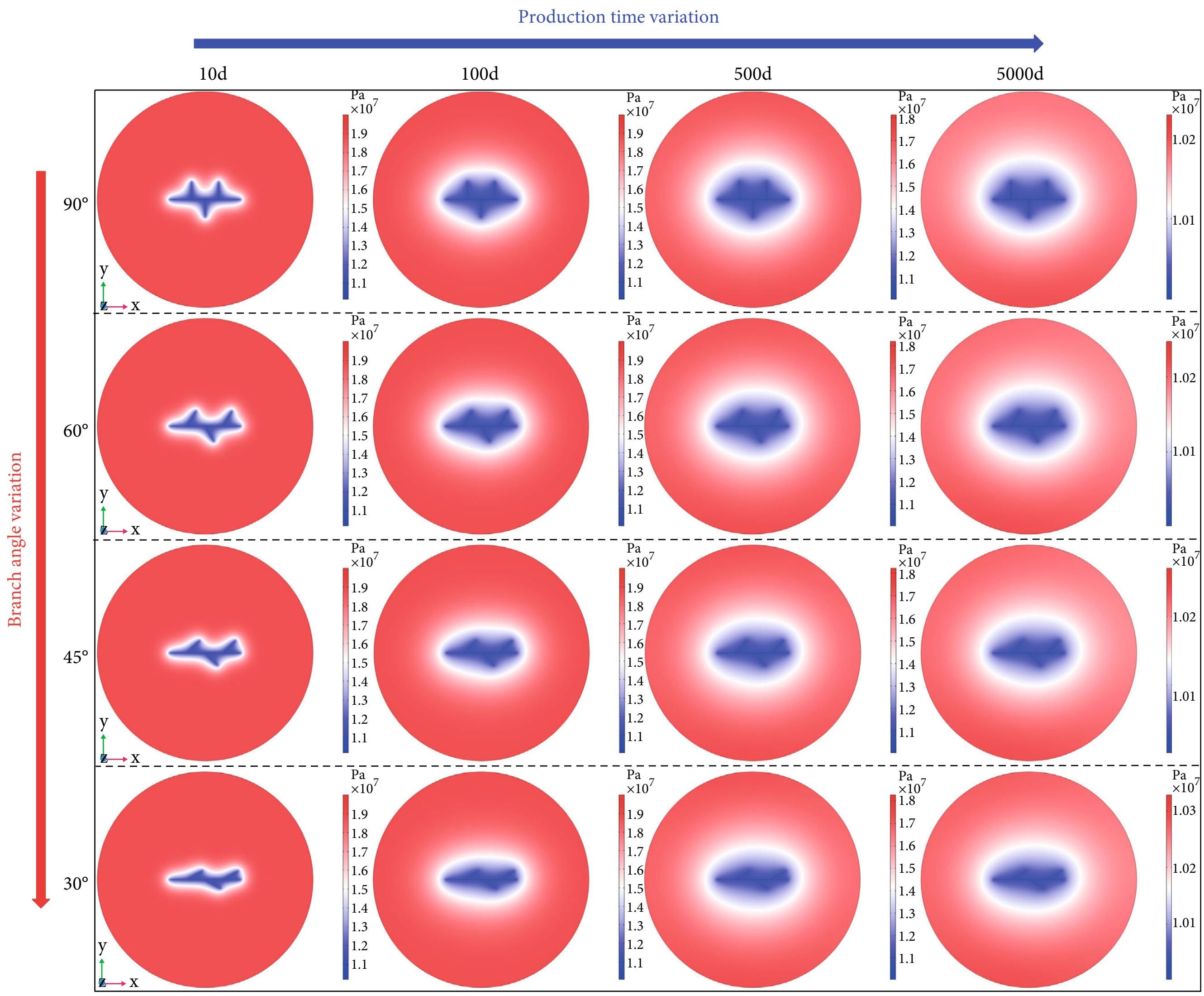


FIGURE 16: Effect of branch angle on evolution of transient pressure distribution.

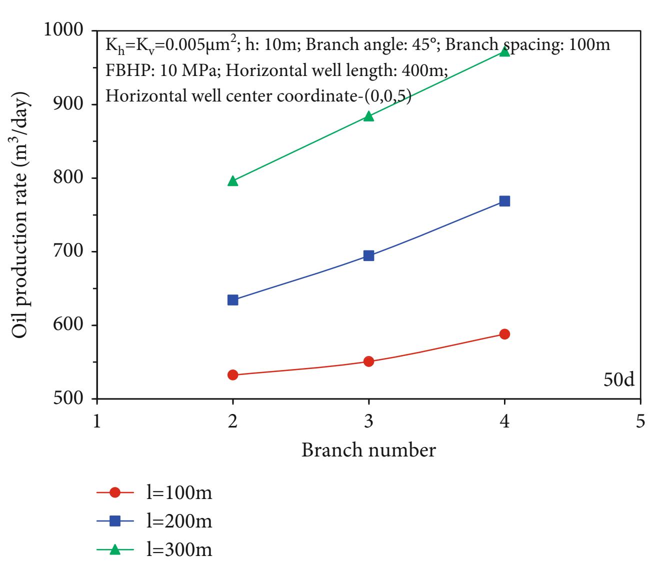


FIGURE 17: Effect of branch numbers on production rate.

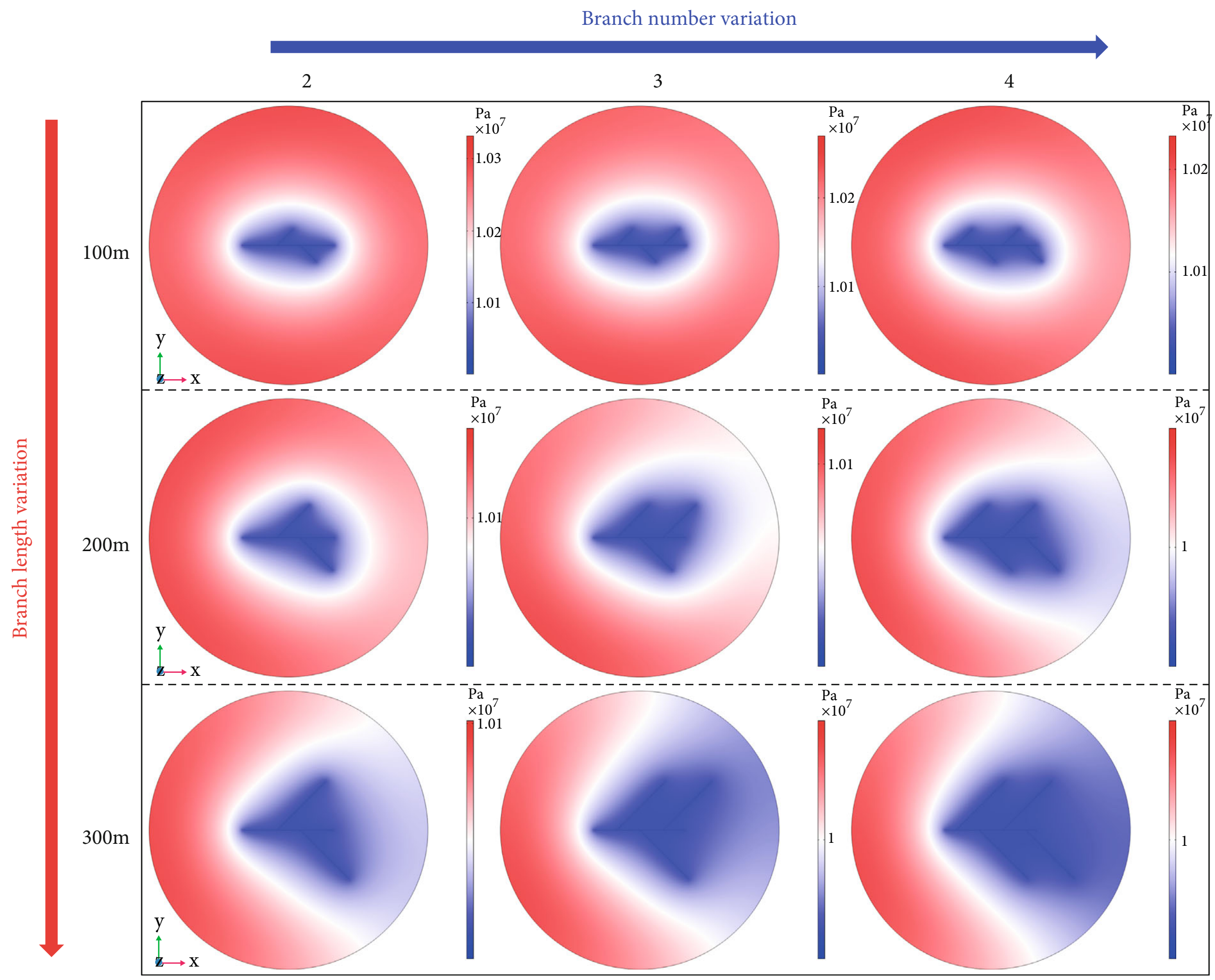


Figure 18: Effect of branch numbers on transient pressure distribution at 5000 d.

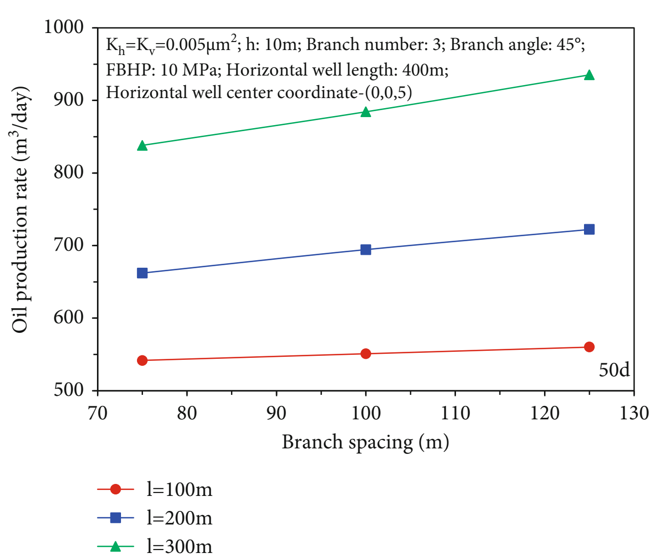


Figure 19: Effect of branch spacing on production rate.

increase of the numbers of branch well, the total production rate of multibranched well increases approximately linearly, but the effect of increasing branch numbers varies greatly under the condition of different branch lengths. When the branch length is 100 m, the increase of the branch numbers causes a slight increase in total production rate, while when

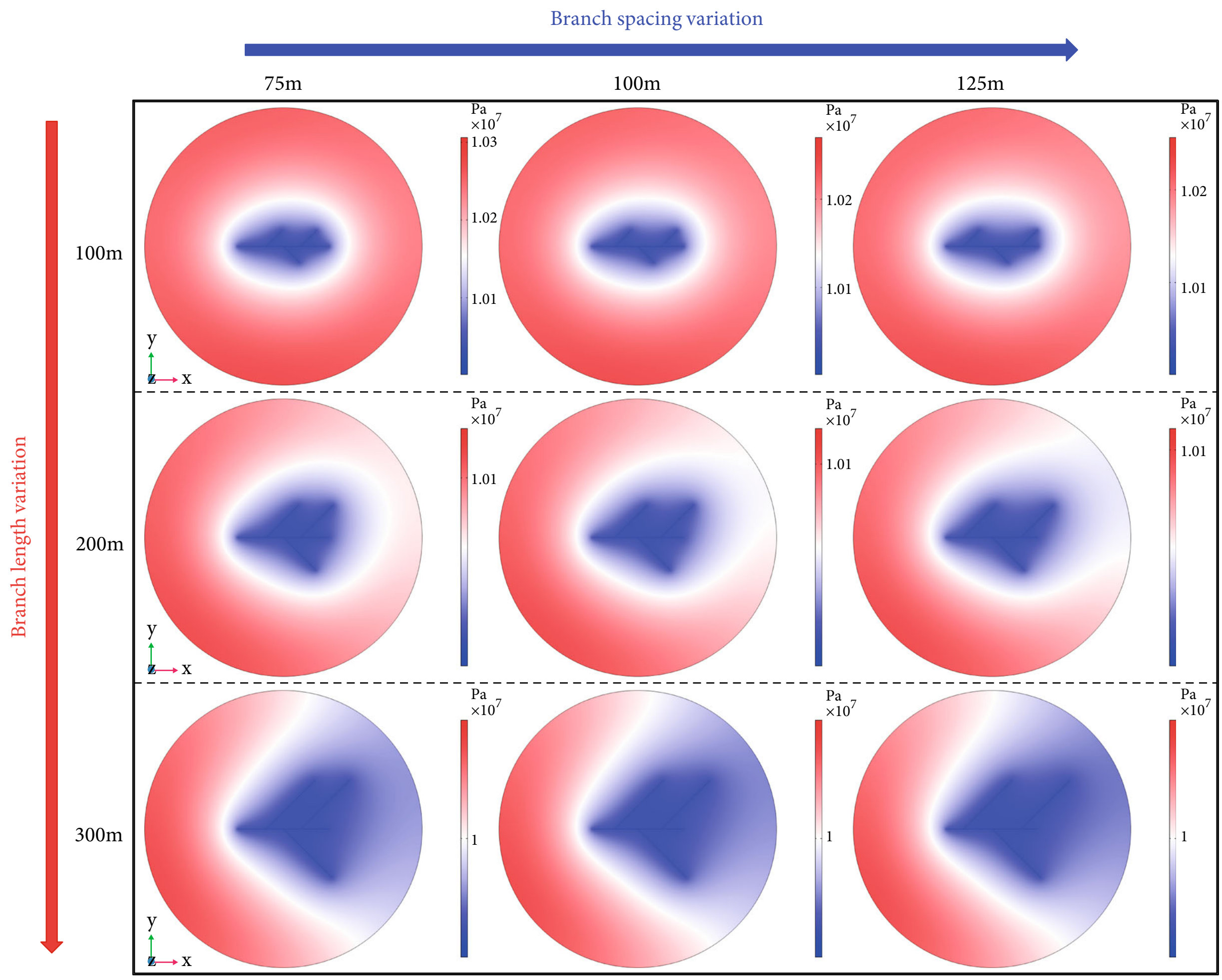


Figure 20: Effect of branch spacing on transient pressure distribution at 5000 d.

the branch length is 300 m, the increase of branch numbers can significantly increase the total production rate of the multibranched horizontal well.

The effects of branch numbers and length on transient pressure distribution at 5000 d are presented in Figure 18. We can find that at a given branch length, with the increase of branch numbers, the control area of fishbone multibranched horizontal well increases, but the interference between branch wellbore and main wellbore increases. Similarly, at given branch numbers, with the increase of branch length, the control area increases, and the interference between branch wellbore and main wellbore decreases. It can also be seen that the increase of branch numbers has different effects on the shape and area of control area of fishbone multibranched horizontal well under different branch lengths. The longer the branch length, the greater the influence of branch numbers on the shape and area of control area.

(4) Effect of the Spacing between Two Branch Wells (d). The effect of d on production behavior is discussed in this section. Basic parameters of branch well to be paid attention to are $n = 3$ and $\alpha = 45°$. The initial production rate at production time of 50 d was taken as the comparison target. The effect of the branch spacing on the production rate of multibranched horizontal well is shown in Figure 19. With the increase of the branch spacing, the total production rate of multibranched well increases linearly, but the effect of increasing branch spacing varies greatly under the condition of different branch lengths. When the branch length is 100 m, the increase of the branch spacing causes a slight increase in total production rate, while when the branch length is 300 m, the increase of branch spacing can significantly increase the total production rate of the multibranched horizontal well.

On the one hand, the reason is that when the branch length is small, the effect of the main wellbore on the branch wellbores decreases slowly with each additional spacing, and the contribution of the branch well to production rate increases slowly. On the other hand, when the branch spacing is large, the interference between branch wellbores becomes less obvious, and the contribution of the branch well to the production rate is relatively big. Therefore, the influence of branch length should also be considered when choosing proper branch spacing.

The effects of branch spacing and length on transient pressure distribution at 5000 d are presented in Figure 20. We can find that at a given branch length, with the increase of branch spacing, the control area of fishbone multibranched horizontal well increases, and the interference between branch wellbore and main wellbore decreases. Similarly, at a given branch spacing, with the increase of branch length, the control area increases, and the interference between branch wellbore and main wellbore decreases. It can also be seen that the increase of branch length has different effects on the shape and area of control area of fishbone multibranched horizontal well under different branch spacing. The larger the branch spacing, the greater the influence of branch length on the shape and area of control area.

5. Conclusions

In this paper, we investigated the production behavior and transient pressure distribution characteristics of fishbone multibranched horizontal well in an oil reservoir by numerical simulation considering different reservoir and well-type factors. From the above analysis, the following conclusions can be drawn:

(1) The numerical model of fishbone multibranched horizontal oil well is established. The mathematical model is numerically solved by finite element method, and oil production rate is calculated using material balance method. The different transient pressure distribution characteristics and production behavior are caused by various reservoir and well-type factors

(2) The reservoir properties, as well as FBHP, have important effect on the production behavior and transient pressure distribution. With the increase of effective thickness, oil reserves increase and multibranched well recovery capacity increases. With the increase of heterogeneity, vertical seepage resistance increases and productivity decreases. Different heterogeneity has different effect on area and shape of control area, and the vertical permeability has an important influence on the productivity. Lower FBHP results in greater elastic productivity. The pressure drop propagation is slowly due to the large FBHP

(3) The length and location of the main wellbore have an important effect on the production behavior and transient pressure distribution. The large length of the main wellbore results in the increase of the production capacity. When the horizontal section of the multibranched well is located in the middle of the reservoir, the daily production and cumulative oil production of the multibranched well are the largest under any circumstances. In addition, at the horizontal plane, deviating from the middle of the reservoir perpendicular to the main well has a greater impact on productivity

(4) The branch well structure which is an important factor affecting the productivity of fishbone multibranched horizontal well includes branch length, branch numbers, branch angle, and branch spacing. With the increase of branch length, the production rate increases more obviously with large branch angle, and the increase rate gradually increases. With the increase of branch angle, the production rate increases more obviously with large branch length, but the increase rate gradually decreases. With the increase of branch numbers, the production rate increases more obviously with large branch length. With the increase of branch spacing, the production rate increases more obviously with large branch length. The increase of branch length has a greater effect on the increase of production rate and control area than the effect of other factors. Hence, a longer branch length should be selected under the premise of drilling technology and drilling safety

(5) The analysis results show that the new method and model in this study have important significance to production behavior analysis for practical application. The new method not only enriches production analysis of fishbone multibranched horizontal well in reservoir considering different influencing factors and provides some valuable advice for drilling but also provided a useful tool in performance analysis of other multibranched well with complex structure in two-region composite reservoirs

Data Availability

The data in this study are available. If you need to obtain the data in this study, please contact "z19020014@s.upc.edu.cn" by email.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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