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Research Article

Numerical Simulation Study on the Development Effect of Gravity Fire Flooding by Vertical Well Sidetracking

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As a development method to replace steam stimulation of heavy oil, in situ combustion often faces many problems in thick reservoir, such as low vertical sweep efficiency and channeling combustion. According to the characteristics and development history of this kind of reservoir, a method of changing plane fire flooding to gravity fire flooding is proposed by using the existing steam stimulation development well pattern and sidetracking horizontal section of vertical production wells. The influence of different factors on sidetracking gravity fire flooding production effect is analyzed from the aspects of reservoir geology and development engineering. The internal stimulation mechanism of this method is further studied, and the evaluation model between recovery factor and main control factor is established by using multiple linear regression equation. The results show that vertical sidetracking gravity fire flooding can improve the recovery of thick heavy oil reservoir by 42%; the better recovery effect can be obtained when the sidetracking length is about 1/2 of the well spacing; the coincidence degree between the established recovery evaluation model and the results of numerical simulation is more than 85%. The research results of this paper can help the mine fire flooding development to change the mining mode and provide some guidance for the medium- and long-term planning.

1. Introduction

The steam stimulation benefit and economic benefit of the reservoir become worse obviously [1–3]. The blocks are extremely limited, which can use steam flooding [4, 5] or steam-assisted gravity drainage flooding [6, 7] as the replacement method. In situ combustion technology has the characteristics of wide application range and high oil displacement efficiency [8, 9], which is often used as the replacement method after steam injection thermal recovery [10]. In a thick reservoir, conventional fire flooding often faces the problems of fire line early breakthrough [11] and channeling combustion [12]. In order to improve fire flooding development effect in thick reservoir, the horizontal well is applied to fire flooding to form gravity fire flooding, which can use gravity-assisted oil discharge to improve the affected volume of fire flooding [13].Top-down fire flooding and Toe-to-heel air injection (THAI) fire flooding are main gravity fire flooding [14]. With complex well pattern, top-down fire flooding needs to drill new injection wells in the upper part of the oil layer, which is only suitable for undeveloped reservoirs [15]. With a simple well pattern, THAI fire flooding only needs one injector and one productor, which can be used in both new and old reservoirs [16, 17]. Comprehensive consideration, THAI fire flooding is more suitable as a replacement method after steam stimulation. In the actual production of the mine, reverse nine point well pattern is mostly used for steam stimulation. The initial well spacing is generally 150~200 m, and the later period is mostly 70~100 m after repeated infill [18, 19]. When fire flooding is adopted as the development mode after steam stimulation, the existing well pattern should be used as much as possible to obtain higher recovery factor and lower production cost.

Combining the characteristics of steam stimulation well pattern and fire flooding technology, a production method is proposed by using vertical well sidetracking to form gravity fire flooding. The numerical simulation software is used to comprehensively analyze the production effect of conventional fire flooding and vertical sidetracking gravity fire flooding, clarify the main reservoir geological factors and development engineering factors of vertical sidetracking gravity fire flooding, and reveal the internal stimulation mechanism. On the basis of theoretical research, the relationship between main control factors and recovery factor is studied, and the comprehensive prediction recovery evaluation model is established.

In this paper, firstly, a fire flooding model is established to compare the effect of ordinary fire flooding with that of gravity fire flooding in vertical well sidetracking, highlighting the advantages of the latter. Secondly, the influence factors of gravity fire flooding in vertical well sidetracking are analyzed, the influence of each factor on the final effect of fire flooding is shown, and a better lifting scheme is put forward. Finally, based on the above theory, a multiple linear regression model is established to analyze the error and help predict the development effect of gravity fire flooding in vertical well sidetracking.

2. Fire Flooding Model Establishment and Effect Comparison

2.1. Establishment of Fire Flooding Model. A gravity fire flooding model of a heavy oil reservoir is established with a grid of $29 \times 29 \times 12$ is based on the reservoir parameters of Liaohe oil field in the STARS module of CMG numerical simulation software (Figure 1). The reservoir length is 140 m, width is 140 m, thickness is 60 m, top depth is 500 m, porosity is 0.2, permeability is 500 mD, oil saturation is 0.6, and crude oil viscosity is 536 mPa·s under oil formation conditions. The thermal conductivity of the rock is 3.00×10^5 J/(m·d·°C). The thermal conductivity of oil, gas and water is 1.20×10^4, 3.2×10^3, and 5.35×10^4 J/(m·d·°C).

Chemical reactions in heavy oil reservoirs include the following:

$$\text{Heavy oil} \longrightarrow \text{light oil} + \text{coke}(\text{cracking reaction}) \quad (1)$$

$$\begin{aligned}\text{Heavy oil} + O_2 \longrightarrow \text{Co}/N_2 + \text{water} + CO_2 \\ + \text{coke}(\text{oxidation of heavy components})\end{aligned} \quad (2)$$

$$\text{Light oil} + O_2 \longrightarrow CO_2 + \text{water}(\text{light component oxidation}) \quad (3)$$

$$\text{Coke} + O_2 \longrightarrow CO_2 + \text{water}(\text{high temperature oxidation}) \quad (4)$$

In the fire flooding model, the reverse nine point pattern is used for production with 70 m well spacing, and the gas injector well is in the middle. The shut-in condition of productor well is set as the wellbore temperature reaches 200°C or the oxygen content in the wellbore is higher than 0.05. The longest production years is set as 10 of the model. In the upper part of the oil layer, the gas injector well is perforated in the 1st, 2nd, 3rd, and 4th layers. Air at 50°C is injected, and the maximum injection pressure is 20 MPa. Using artificial ignition with 450°C, the heating time is 60 days. Constant rate gas injection scheme is adopted, the gas injection rate is kept at 10 000 m^3/d for production after the successful ignition of oil layer. In the conventional fire flooding, the productor wells are perforated in the vertical section. In the gravity fire flooding, the product or wells are not shot in the straight section but sidetracked horizontal section with a length of 30 m at the bottom of the formation (12th layer).

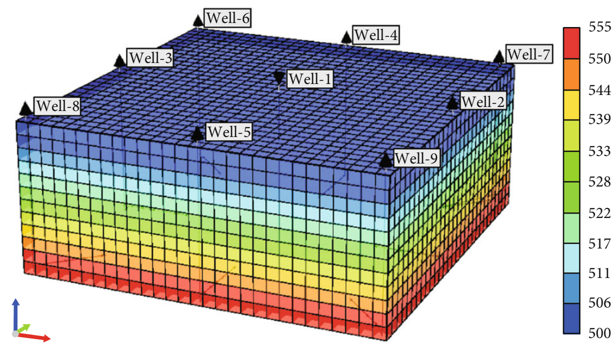


Figure 1: CMG model map.

2.2. Comparison of Fire Flooding Effect. Comparing oil production rate between conventional fire flooding and vertical sidetracking gravity fire flooding (Figure 2), the oil production rate of the two development methods gradually increased from the 570th day. The analysis shows that the cracking of heavy oil into coke burns and releases a lot of heat which makes the reservoir temperature rise rapidly after the successful ignition of crude oil. It leads to a significant decrease in viscosity and a significant increase in fluidity due to the heating of crude oil. The conventional fire flooding reaches the peak of oil production speed in 2700 days, while the oil recovery speed of vertical sidetracking gravity fire flooding in 1000 D of direct drilling has been the same with it. From the initial stage of production to 3500 days, the oil recovery speed of the vertical sidetracking gravity fire flooding in the direct well side drilling is always higher than conventional fire flooding. Compared with conventional fire flooding, vertical sidetracking gravity fire flooding can obtain higher oil recovery rate and higher crude oil production in a shorter time. Vertical sidetracking gravity fire flooding has the characteristics of short production cycle, rapid economic benefits, and reduced production risk.

From the comparison of the air to oil ratio by the conventional fire flooding with the vertical sidetracking gravity fire flooding by drilling on the straight well side (Figure 3), it can be found that the peak value of the air to oil ratio of the conventional fire flooding is up to 4000 m^3/m^3, while

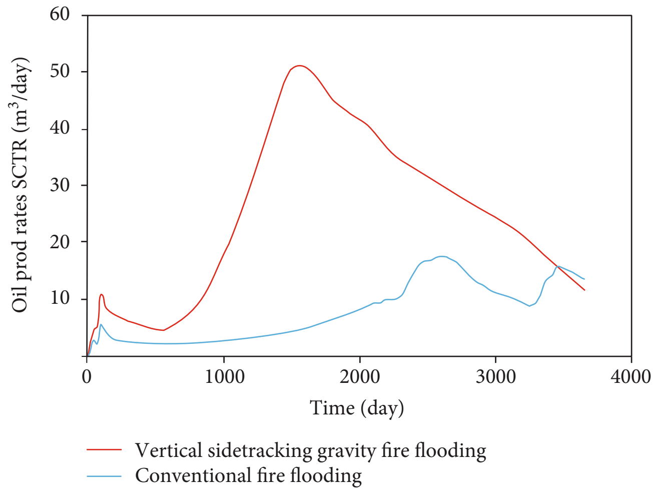


Figure 2: Comparison of oil production rate between conventional fire flooding and vertical sidetracking gravity fire flooding.

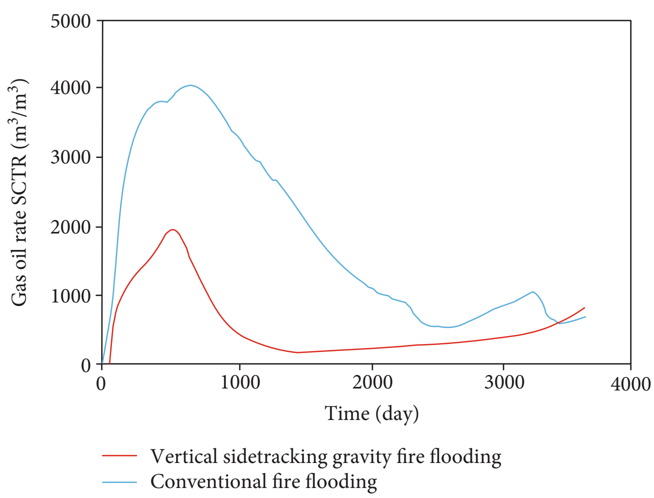
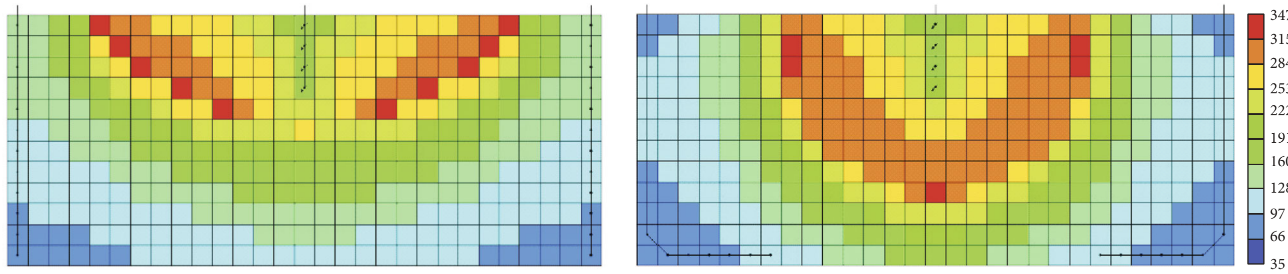


Figure 3: Comparison of air oil ratio between conventional fire flooding and vertical sidetracking gravity fire flooding.

the peak value of the vertical sidetracking gravity fire flooding is lower than 2000 m^3/m^3 when drilling on the straight well side. The air-to-oil ratio of the conventional fire flooding is always higher than that of the vertical sidetracking gravity fire flooding before 3500 days. In the process of fire flooding oil recovery, the daily operation cost is mainly concentrated on air compression [20]. Therefore, vertical sidetracking gravity fire flooding has more cost advantage than conventional fire flooding. After 3500 days, the ratio of gravity fire flooding air to oil in the side drilling of the direct well is higher than that of conventional fire flooding. It is analyzed that in the later stage of the gravity fire flooding production, most oil-bearing areas in the reservoir are affected, and the oil content in the reservoir is less, and the existence of horizontal section of sidetracking makes the gas in the reservoir easier to enter the production well. Therefore, it is suggested that in the later stage of vertical sidetracking gravity fire flooding production, the air injection amount of gas injection well can be appropriately reduced.

From the comparison of temperature field between conventional fire flooding and vertical sidetracking gravity fire flooding (Figure 4), it can be seen that at the same time, the vertical sweep of conventional fire flooding is poor, the combustion only occurs in the upper part of the oil layer, and the horizontal overlap is serious. Because of the traction effect of the horizontal segment for vertical sidetracking gravity fire flooding, the live wire vertically waves well and the plane is used relatively evenly, capable of slowing the live wire overcoverage. The heavy oil can flow only after the viscosity is reduced by heating. The advancing direction of the fire line is the flow direction of the liquid, so the oil saturation in front of the fire line is also higher. The traction of the production well to the fire line is equivalent to the traction of the liquid flow direction. The three directions tend to be the same. Therefore, only the temperature fields of the two fire drive modes are compared and analyzed here. The analysis shows that the existence of sidetracking horizontal section reduces the distance between the main well section



(a) Conventional fire flooding

(b) Vertical sidetracking gravity fire flooding

Figure 4: Comparison of temperature field between conventional fire flooding and vertical sidetracking gravity fire flooding.

and the gas injection vertical well, which can make full use of gravity assisted oil drainage. The problems of serious horizontal overlap and small vertical sweep area of conventional fire flooding can be alleviated by pulling down the fire line and adjusting the sweep direction of fire line, so as to achieve better mining effect.

It can be seen from the comparison of recovery degree between conventional fire flooding and vertical sidetracking gravity fire flooding (Figure 5) that after 10 years of operation of the model, the recovery degree of the two mining methods reaches the maximum, the recovery degree of conventional fire flooding is 19%, the recovery degree of vertical sidetracking gravity fire flooding is 61%, and the improved recovery degree is 42%.

The above analysis shows that the plane fire flooding after horizontal section of the drilling side of the straight well is transformed into gravity fire flooding, which can effectively inhibit the gas overburden, improve the air utilization efficiency, and expand the spread area of fire flooding, thus obtaining higher oil production speed, lower air oil ratio, and higher production degree.

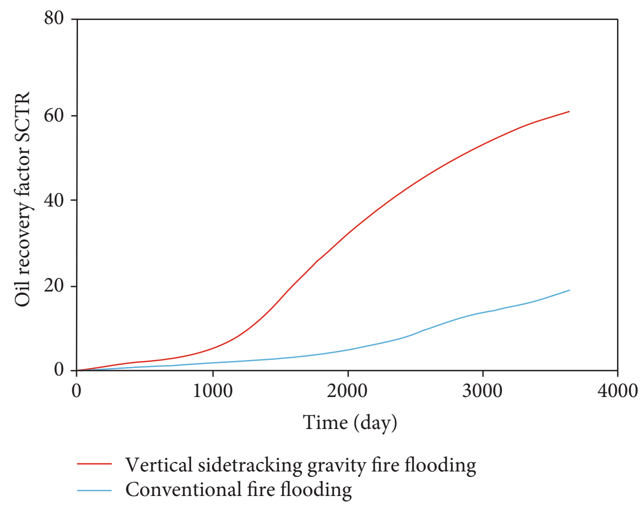


Figure 5: Comparison of recovery degree between conventional fire flooding and vertical sidetracking gravity fire flooding.

3. Analysis on Influencing Factors of Vertical Sidetracking Gravity Fire Flooding

In the process of vertical sidetracking gravity fire flooding, the combustion front usually breaks through in the horizontal section at the bottom of the oil layer. Once oxygen breaks through from the horizontal segment, combustion occurs, causing the well cylinder to damage, at which point there is still a large area in the formation that is not waved by the combustion belt, thus forming a dead oil [21]. In order to further study the influence of various factors on the recovery factor in the process of vertical sidetracking gravity fire flooding, the parameter sensitivity analysis is carried out from two aspects of reservoir geological factors and development engineering factors.

3.1. Reservoir Geological Factors. Based on the field data and field experience, the screening [22] criteria of in situ combustion reservoir development mode are obtained, and the boundaries of fluid parameters and geological parameters such as crude oil viscosity, crude oil density, reservoir thickness, oil saturation, and permeability are determined, respectively. Among them, CHU adopts statistical reliability limit method to get the screening standard and considers viscosity is not a parameter to distinguish the success of the pyrolytic oil layer [23]. Based on the parameter statistics of fire flooding field projects, Ning and others analyzed the influencing factors of fire flooding by using the difference confidence limit method and found that the reservoir depth and crude oil viscosity are not the key factors [24] for the success of fire flooding projects. The density and viscosity of crude oil are closely related. Therefore, considering the selection criteria of in situ combustion reservoir, the sensitivity analysis is only conducted on the geological parameters such as porosity, permeability, reservoir thickness, and oil saturation and the fluid parameters such as density and viscosity of crude oil are not considered.

The research on the main parameters of in-situ combustion reservoir selection criteria assumes that the success of the fire flooding project only depends on the characteristics of the reservoir and crude oil and does not consider the influence of external factors such as field construction and operation conditions. Obviously, in the actual mine project, in addition to considering reservoir geological factors, development engineering factors are also important for fire flooding projects.

3.2. Development Engineering Factors. The development engineering factors that affect the vertical sidetracking gravity fire flooding production effect mainly include gas injection rate, perforation location of gas injection well, vertical well sidetracking length, and well spacing [25, 26].

3.2.1. Gas Injection Rate. In the process of in situ combustion, the amount of air injected directly reflects the increased heat in the in situ combustion reservoir. Increasing gas injection rate can expand the range of fire line and enhance oil recovery. But too high gas injection rate is easy to form gas channeling channel, which leads to unstable combustion in the reservoir. In a certain range, increasing the gas injection rate can improve the oil recovery, but beyond the optimal gas injection rate, the production time will be shortened sharply, and the oil recovery will not increase but decrease. Therefore, the gas injection rate is not the greater the better.

3.2.2. Perforation Location of Gas Injection Well. When the perforating position of the injection well is located in the upper part of the reservoir, the distance between the perforating position and the horizontal section can be increased, the time of the fire line reaching the horizontal well can be delayed, and the gravity effect of the crude oil can also be used. When it is located in the lower part of the reservoir, it can slow down the low degree of vertical production caused by gas overlap and prevent the air overlap seriously affecting the development effect in the development process. Therefore, for different reservoirs, the perforation location of injection wells will also change.

3.2.3. Sidetracking Length of Vertical Well. In conventional fire flooding, when the gas injection well and production well are both vertical wells, it is difficult to ensure sufficient oxygen supply at the combustion front. Although it can be achieved by increasing the gas injection rate, increasing the gas injection rate will lead to gas channeling and high air-oil ratio. When the horizontal section of sidetracking is too short, the improvement of gas channeling or air-oil ratio is not obvious. Short horizontal section of side-drilling in production straight well will not significantly improve gas channeling or high air-oil ratio. However, when the horizontal section is too long, due to the short distance between the gas injection vertical well and the horizontal production well, air is easy to enter the horizontal production well, resulting in fire channeling, causing reburning of crude oil in the well bore and burning the horizontal well bore, which has serious potential safety hazards. It is necessary to determine an appropriate sidetracking length of vertical well, which can ensure production safety and obtain better development benefits.

3.2.4. Well Spacing. Well spacing directly limits the sidetracking length of vertical wells. Different well spacing corresponds to different sidetracking length of vertical wells. The larger the well spacing, the longer the sidetracking length of vertical wells. The ratio of the length of the vertical sidetrack to the spacing through the normalization treatment method is used to consider the length and spacing of the vertical sidetrack. Dimensional expressions are transformed into dimensionless expressions. This breaks the limitation that only suitable side-drilling length for straight wells can be studied at a single spacing. The appropriate sidetracking length of the vertical well can be obtained in reverse. When the well spacing is known, after obtaining the appropriate ratio of the sidetracking length of the vertical well to the well spacing, which highlights the essential meaning of sidetracking length of vertical well.

Combined with literature research and field experience, it can be determined that the main development engineering factors affecting the development effect of vertical well sidetracking gravity fire flooding are gas injection rate, perforation location of gas injection well, and the ratio of vertical well sidetracking length to well spacing.

3.3. Sensitivity Analysis. Combined with in situ selection criteria and field experience, the values of reservoir geological factors can be set at three levels as shown in Table 1 (Table 1). The value of development engineering factors usually depends on reservoir geological factors. In order to get the value range of development engineering factors under different reservoir geological factors, the value levels of different reservoir geological factors are comprehensively considered. The reservoir geological factors, including porosity of 0.2, permeability of 500 mD, reservoir thickness of 42 m, and oil saturation of 0.6, are selected as the parameters in the fire flooding model. The upper perforating is adopted in the gas injection wells, and the gas injection rate and sidetracking length of vertical wells are changed, respectively, to obtain the variation law between the gas injection rate and the recovery factor (Figures 6 and 7).

It can be seen from Figure 5 that when the gas injection rate changes from 5000 m^3/d to 15000 m^3/d, the recovery first increases and then decreases, with the minimum recovery rate of 56.5%, and the maximum recovery rate of 64% when the gas injection rate is 10000 m^3/d. The overall fluctuation of recovery is not large in the range of injection rate change. In order to comprehensively study the influence of the gas injection rate on recovery, the gas injection rate is assigned to 5000, 10000, and 15000 m^3/d in the fire flooding model. It can be seen from Figure 6 that the recovery rate is basically maintained at 64% when the sidetracking length of vertical well is short (10, 20, and 30 m). The recovery rate drops sharply when the sidetracking length of vertical well is long (40, 50, 60, and 70 m). The recovery is even less than 15% at 60 and 70 m, which has no development and economic benefits.

According to the change law of recovery, the abnormal high value and abnormal low value of gas injection rate and sidetracking length of vertical well are eliminated, respectively, and the value range of gas injection rate and sidetracking length of vertical well is determined. Perforation location of gas injection well can be divided into upper perforation, middle perforation, and lower perforation. Considering the convenience of data processing, 1/3, 2/3, and 1 are used to represent upper perforation, middle perforation, and lower perforation, respectively. The value level of development engineering factors is obtained (Table 2).

In the fire flooding model, sidetracking of vertical well is realized by formation perforation, and the length of sidetracking corresponds to different perforation numbers. The

Table 1: Value level of reservoir geological factors.

Factor	Porosity	Permeability (mD)	Reservoir thickness (m)	Oil saturation
1	0.2	500	24	0.4
2	0.3	1 000	42	0.5
3	0.4	1 500	60	0.6

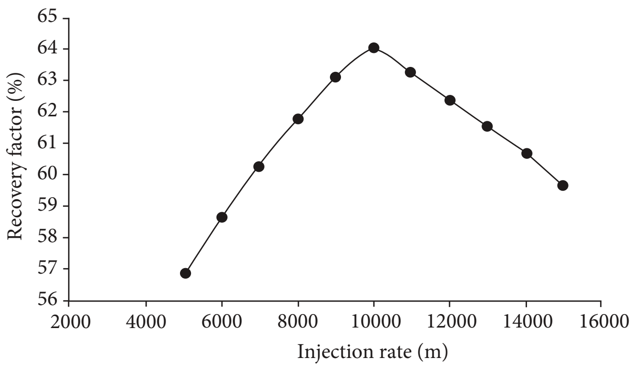


Figure 6: Relationship between gas injection rate and recovery factor.

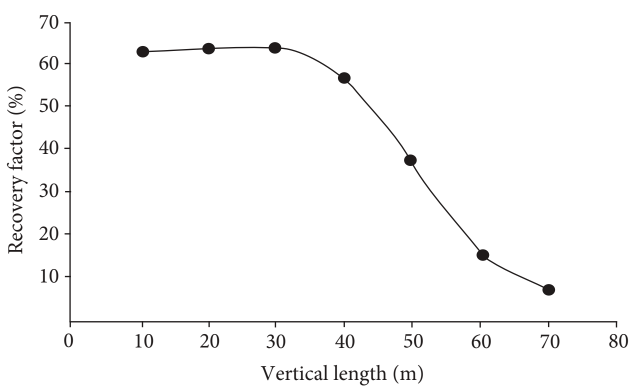


Figure 7: Relationship between vertical sidetrack length and recovery factor.

Table 2: Value level of development engineering factors.

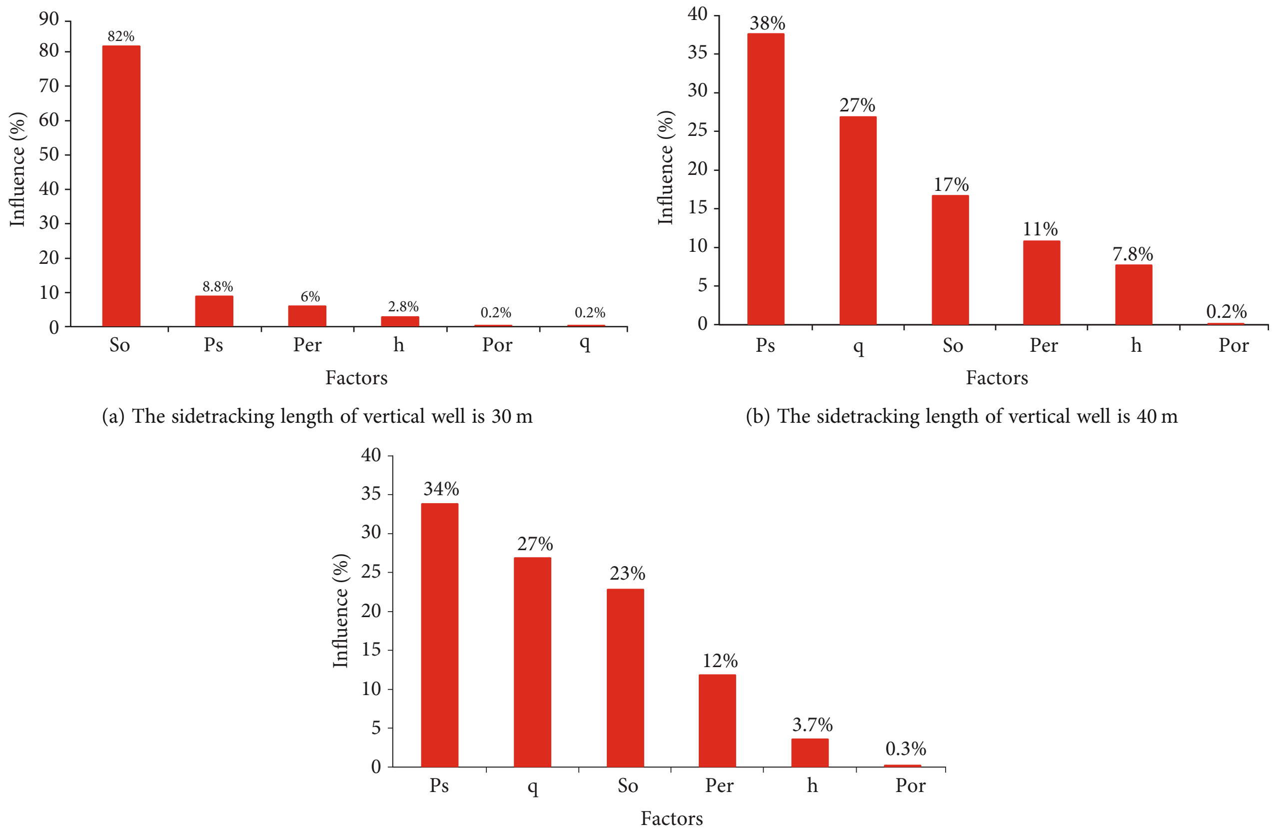
Factor	Gas injection rate (m^3/d)	Perforated position of injection well	The length of sidetracking in vertical wells (m)
1	5000	1/3	30
2	10000	2/3	40
3	15000	1	50

number of perforations per well in each fire flooding model is a fixed value, which can not reflect the change of the length of side drilling in straight wells. Therefore, the sensitivity of other factors to recovery is analyzed based on the proxy model in the CMOT module in case of 30, 40, and 50 m vertical sidehole lengths, respectively. It can be seen from the analysis results (Figure 8) that when the sidetracking length of vertical well is short (30 m), the oil saturation has the greatest impact on the recovery factor, with the value of 82%, occupying an absolute dominant position. At this time, other reservoir geological factors and development engineering factors have little influence on recovery factor. With the increase of sidetracking length of vertical wells, the most important factor affecting recovery is the perforation location of gas injection wells instead of oil saturation, but other factors such as gas injection rate and oil saturation still have great influence on recovery.

Analysis shows that horizontal wells are far away from gas injection wells, development engineering factors have little influence on recovery, reservoir geological factors play a dominant role on recovery, when the length of sidetracking in vertical wells is short, it is shown that when the ratio of length of sidetracking in vertical wells is 3/7. At this time, the influence of reservoir geological factors on the recovery factor is still dominant. When the length of sidetracking in vertical wells is long, the ratio of the length of the drilling to the distance is 4/7 and 5/7, and the distance between the horizontal well and the injection well is close. The influence of development engineering factors on the recovery rate increases rapidly, which is equally important as the geological factors of the reservoir. It is concluded that the better mining effect can be obtained when the length of the sidetracking in vertical wells is about 1/2 of the well distance between the production well and the injection well. In order to reduce the influence of other geological factors and development engineering factors on oil recovery, the length of sidetracking in vertical wells can be reduced appropriately when vertical sidetracking gravity fire flooding is carried out, if the reservoir has high oil saturation. The length of sidetracking in vertical wells can be appropriately increased if the oil saturation is low. In order to reduce the importance of oil saturation and expand the influence of development engineering factors such as perforation position and gas injection rate of gas injection well and in order to obtain better mining effect, the poor geological conditions can be overcome by adjusting development policies.

4. Solving Multiple Linear Regression Equation

4.1. Pretreatment of Simulation Results. Because there are many reservoir geological factors and development engineering factors studied and the number of factors involved is more, if the numerical simulation is used, a large number of model parameters need to be manually adjusted for permutation and combination, and the workload is huge. When the CMOST polynomial model is used to calculate, only the range of the value of the research factors is input. The software will arrange and combine the main control factors



(a) The sidetracking length of vertical well is 30 m

(b) The sidetracking length of vertical well is 40 m

(c) The sidetracking length of vertical well is 50 m

Figure 8: Recovery sensitivity analysis results. Among them, the meanings of the abbreviated letters in the figure are as follows: Ps: perforation location of gas injection well; So: oil saturation; Perm: permeability;h: reservoir thickness; Por: porosity;q: gas injection rate.

Table 3: Recovery factor under different combination of main control factors.

The length of sidetracking in vertical wells	Perforated position	$S_o\phi$	Kh	q/h	Recovery ratio (%)
3/7	1/3	0.18	60 000	250.00	55.87
3/7	2/3	0.1	63 000	357.14	53.74
3/7	1	0.24	36 000	416.67	54.78
4/7	1/3	0.2	90 000	250.00	46.36
4/7	2/3	0.18	90 000	83.33	45.45
4/7	1	0.2	24 000	625.00	42.25
5/7	1/3	0.12	42 000	357.14	33.62
5/7	2/3	0.18	21 000	238.09	25.73
5/7	1/3	0.2	9 000	83.33	37.32

freely under different values to get the recovery ratio under each combination mode.

After determining the main control factor and its value range, the corresponding parameters are assigned in the fire flooding model, and the proxy model of CMOST module is used for calculation. Because there are many parameters studied, there are many recovery results under different combination methods, and some recovery results are too low, which is not in line with the actual situation of the reservoir. The simulation results are screened based on the relationship between sidetracking length and recovery factor of vertical well obtained in Figure 7. When the length of the drilling is 30 m, the recovery ratio is 64%, while the recovery ratio is 50% when the length of the drilling is 40 m, and 30% is taken as the benchmark when the length of the side drilling is 50 m, up and down float not more than 10%, 29 sets of simulation results were obtained. Considering the influence of various factors on oil recovery and simplifying the

Table 4: Comparison of numerical simulation results and calculation results.

Number	The length of sidetracking in vertical wells	Perforated position	$S_o\phi$	Kh	q/h	Recovery ratio (%) Analog value	Estimated value	Error
1	3/7	1/3	0.18	60000	250	55.87	63.30	13.29
2	3/7	1	0.24	36000	416.67	54.78	56.48	3.10
3	4/7	2/3	0.18	90000	83.33	45.45	43.76	3.72
4	4/7	1	0.2	24000	625	42.25	44.04	4.24
5	5/7	1/3	0.12	42000	357.14	33.62	32.41	3.60
6	5/7	2/3	0.18	21000	238.09	25.73	23.29	9.48

complexity of the final multiple linear regression equation, the relationship between various factors is established according to the actual situation. Among them, the product of oil saturation and porosity is the reserve coefficient ($S_o\phi$). Permeability and reservoir thickness are expressed by the product of the two, i.e., formation coefficient (Kh), and gas injection ratio and reservoir thickness are expressed by the ratio of the two, i.e., gas injection intensity (q/h). Since there are too many groups, only 9 of them are listed here (Table 3).

4.2. Establishment of Regression Equation. Suppose that the dependent variable y and the independent variables $x_1, x_2, \cdots, x_m$ has N groups of actual observation data. Assuming that there is a linear relationship between the dependent variable and the independent variable, the mathematical model is as follows:

$$y_j = a_0 + a_1 x_{1j} + a_2 x_{2j} + \cdots + a_m x_{mj} + e_j. \tag{5}$$

The simulation results are imported into excel, and the parameter data are further processed according to the existing relationship between the main control factors and the normalization method; through the data analysis tool of Excel, the multiple linear regression equation between recovery factor and main controlling factors is obtained. The data analysis function of Excel is to use the least square method to obtain a very accurate multiple linear regression equation. Select "regression" in the data analysis window to call up the multiple regression model. Select the region where the sample data is located to the corresponding sub window; the system will calculate the model immediately and give the corresponding calculation results report. By using the data analysis function, the main controlling factors and recovery factor are linearly regressed, and the multiple linear regression equation is obtained as follows:

$$\begin{aligned} y = {} & 108.99888 - 114.50704 l/L - 9.03421 P_s \\ & - 26.45259 S_o\phi + 1.03784 \times 10^{-4} Kh \\ & - 1.96902 \times 10^{-2} q/h. \end{aligned} \tag{6}$$

The regression analysis results show that the coefficient of the model is 0.942, indicating the recovery ratio y and l/L, P_s, $S_o ø$, the correlation between Kh and q/h is high. The P value of F significance statistic is 5.64×10^{-12}, far less than the significant level of 0.05, indicating that the regression effect of the established model is significant.

In addition, for the values of several groups of main control factors, the accurate recovery values are obtained by using numerical simulation software and compared with the predicted recovery values calculated by regression equation (formula (2)). It can be seen from the prediction results (Table 4) that the recovery rate obtained by the numerical simulation software is highly consistent with that predicted by the regression equation. The error percentage is less than 15%, which indicates that the multiple linear regression equation can effectively predict the development effect of vertical sidetracking gravity fire flooding and guide the actual production.

5. Summary and Conclusion

(1) Timely conversion of development mode can improve the effect of fire drive

In the later stage of steam stimulation development, especially for thick reservoirs, when the development mode is changed to fire flooding, the existing well pattern can be used to sidetrack the horizontal section of vertical wells, and the horizontal fire flooding can be changed from plane fire flooding to gravity fire flooding, which can effectively avoid the problem of plane fire flooding and significantly improve the effect of fire flooding.

(2) Increasing the sidetrack length of vertical well can obtain better production effect under certain well spacing

The sensitivity analysis of recovery factor is carried out from two aspects of reservoir geological factors and development engineering factors. The main geological factors of reservoir are porosity, permeability, reservoir thickness, and oil saturation. The main development engineering factors are gas injection rate, perforation location of gas injection well, and the ratio of the length of sidetracking in vertical wells spacing. It is considered that when the length of sidetracking in vertical wells is about 1/2 of the well spacing between production well and injection well, better production effect can be obtained, and when the reservoir condition is poor, the length of sidetracking in vertical wells can be increased appropriately.

(3) The multiple linear regression model based on the above theory has high accuracy

The multiple linear regression model is obtained from the relationship between the main control factors and the recovery factor. The predicted recovery factor is in good agreement with the recovery factor obtained by the numerical simulation software. It can effectively predict the development effect of vertical well sidetracking gravity fire flooding and has certain practicability for guiding the actual production of the mine.

Abbreviation

a_0: Regression coefficient, dimensionless
a_m: Regression coefficient, dimensionless
e_j: They are independent and all obey the normal distribution of the standard, $j = 1, 2, \cdots, n$
h: Reservoir thickness, m
K: Permeability, mD
Kh: Formation coefficient, mD·m
l: Sidetracking length of vertical well, m
L: Well spacing, m
m: The number of independent variables
n: The number of simulation results group obtained by different main control factors
P_s: Perforation location of gas injection well
q: Gas injection rate, m^3/d
q/h: Gas injection intensity, $m^3/(d \cdot m)$
S_o: Oil saturation
$S_o ø$: Reserve coefficient
$x_1, x_2, \cdots, x_m$: One set of variables that can be observed, which indicates the main control factors affecting recovery
y: The value of the observed random variable changes with the change of $x_1, x_2, \cdots, x_m$ and is affected by the test error; here is the recovery ratio
$ø$: Porosity.

Data Availability

The data in this paper are all from the software application in the author's research process (for details, see the description in the article).

Conflicts of Interest

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

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