An optimization method of horizontal well completion control water and sand

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Abstract. With the development and maturity of horizontal well drilling and completion technology, horizontal wells are widely used in various reservoirs and have achieved good development results. Due to horizontal wells in the reservoir through a long distance, horizontal section of the reservoir physical property heterogeneity, water avoidance height difference and horizontal wellbore flow with toe effect, leading to production pressure difference and water breakthrough time in all parts of the shaft is different, the level of sand and bottom water cresting is strong heterogeneity, oil well early water breakthrough and local a large amount of sand production, the serious influence of horizontal well production and development of comprehensive benefits. In this paper, based on the prediction model of critical production pressure difference of sand production in horizontal wells and the prediction model of water appearance time of horizontal Wells in bottom water reservoir, the critical production pressure difference and water appearance time of sand production in each micro-element section are quantitatively determined along the horizontal well section, so as to form a design method of horizontal well completion that takes water and sand control into account. And ICD horizontal well completion method as the research object, water breakthrough time, yield as the optimization goal, control sand as constraint conditions, with each section down into the number of ICD string and nozzle sizes as design variables, the ICD horizontal well completion parameters established multi-objective optimization model, obtained the comprehensive consideration of water control sand control effect of the optimal ICD completion program.

1. Introduction

With the development and maturity of horizontal well drilling and completion technology, horizontal wells are widely used in various reservoirs and have achieved good development results. Compared with vertical wells, horizontal well has expanded the wellbore and reservoir of contact area, improve the efficiency of the drainage, and bottom water can complement the energy of the reservoir damage in the development process, can make the horizontal well in smaller to earn relatively high yield production pressure difference, significantly improve the single well production and recovery factor, at the same time, reduce the risk of horizontal section of the store are sand [1-4]. Therefore, horizontal well technology is widely used in bottom water sandstone reservoirs.

However, in the actual production process of oil fields, especially in the horizontal wells with high production or long horizontal sections, bottom water often breaks through from the heel end or high permeability section first, causing early water appearance of oil Wells or even forced shut-in due to full well flooding. At the same time, horizontal well development of unconsolidated sandstone reservoir is also faced with serious sand production problem, which will not only cause surface and
underground equipment abrasion, casing damage, oil and gas separator sand, but also reduce the production of oil wells or even force oil and gas wells to stop production, seriously affecting the normal production of oil and gas wells. At present, uneven ridging of bottom water and sand release from reservoir have become major obstacles to the production performance of horizontal wells [5-8].

Studies show that both water appearance and sand production in horizontal wells show strong heterogeneity [8-12]. The main reasons for the heterogeneity of water and sand production in horizontal wells are:

1. There is a heel toe effect in the production section of horizontal wells. The pressure of variable mass flow in the wellbore increases gradually from the toe end to the toe end, and the pressure difference in the production at the heel end is obviously greater than that at the toe end, leading to the bottom water ridge and sand release occurring at the heel end. When the horizontal section has strong reservoir physical heterogeneity, the well section in the hyper permeability zone will produce liquid at a fast rate, and the bottom water will break through in the hyper permeability zone first. Meanwhile, the well section with weak rock cementing strength will produce sand seriously. (3) For some special water-sensitive reservoirs, such as loose sandstone reservoirs with high shale content, early water appearance will reduce the rock strength and intensify the sand production in local well segments.

Therefore, comprehensive consideration of sand production and water breakthrough nonhomogeneous factors, the level of sand and evaluate the bottom water cresting conditions, set up horizontal well completion segmentation method, and according to the needs of water control sand control, and to extend the horizontal water breakthrough time, control, storage with sand and ensure production, for the purpose of optimizing the piecewise ICD completion parameters, forming a set of horizontal well completion water control method for the optimization design of sand control, the use of horizontal well development of bottom water loose sandstone reservoir has the very vital significance.

2. The main problems existing in horizontal well development at present
At present, the research and application of horizontal well completion with segmented water control and sand control have developed rapidly, and a lot of work has been carried out successively, and some achievements have been made. However, there are still some deficiencies in the theoretical research and production practice of horizontal well completion design method in the following aspects: Most of ICD horizontal well completion optimization research mainly focus on improve the recovery efficiency of horizontal well or in the net present value of single objective optimization, the ICD horizontal well completion optimization design, the objective function to select a single, water control and stable oil cannot very good combination, optimization of the result is often only get higher yield, but at the same time, high yield water breakthrough time is short, horizontal well in horizontal well water flooded soon even shut-in, also did not consider sand control and water control of ICD horizontal well completion parameters optimization design method.

Horizontal well section completion at present is mainly focused on the elimination of horizontal wells with toe effect caused by bottom water coning too rapidly, its segmentation strategy is to divide the interval of permeability, porosity, close to the same completion unit, only considering the permeability of reservoir physical parameters, the determination of permeability and threshold, strong subjectivity of piecewise rely more on experience. At present, there are few researches on the design of horizontal well completion for sand control in heterogeneous reservoirs. At the same time, there is no comprehensive consideration on the two cases of sand control and water control, and there is no relevant subsection method to determine the location and section number according to wellbore flow and formation characteristics.

3. Horizontal well water control sand control completion section method
Sand production and bottom water ridge are the main reasons that restrict the productivity of horizontal Wells in unconsolidated sandstone bottom water reservoir. Segmental completion is to divide the well section with similar sand production level and bottom water ridging condition into the
same completion unit, and to control water and sand by implementing a targeted completion plan in the unit. This chapter based on horizontal well sand production and water breakthrough characteristics of inhomogeneous, the dividing principle, establishes the horizontal well completion and sanding critical production pressure difference and water breakthrough time as the segmentation index, the horizontal section as the order of infinitesimal section, the introduction of multidimensional orderly clustering algorithm, set up horizontal well completion segmentation method, for water control for horizontal well sand control completion design laid a foundation.

3.1 Horizontal well water control sand control completion segmentation principle
Horizontal well completion segmentation is the first step in the optimization design of horizontal well water control and sand control. The horizontal well sections with sand production and bottom water ridging into similar conditions are considered as a whole. Packer is used to separate different sections to form non-interfering completion units. Setting corresponding completion parameters according to sand production and water appearance of different completion units can not only improve the specificity of the completion, but also facilitate the production stimulation measures such as staged acidizing and staged fracturing in the later stage of production, so as to meet the requirements of refined completion. However, improper completion segmentation of horizontal wells can also lead to production decline or more serious sand production and water intrusion problems.

At present, there is no scientific subsection standard or strictly referential horizontal well completion subsection method. In the construction site, the reservoir permeability and porosity of the horizontal section are usually taken as subsection indexes, and the location and number of sections are determined according to the project experience of the engineers and technicians. The segmentation results depend heavily on personal experience, so it is difficult to accurately reflect the differences between reservoir layers in horizontal sections, and there is no completion segmentation method that comprehensively considers sand control and water control. In view of this problem, according to the completion requirements of horizontal well water control and sand control, the segmented principle of horizontal well water control and sand control is proposed:

(1) Well segments with similar sand production and water appearance characteristics are divided into the same completion unit to ensure the common adaptability of each completion unit to the completion mode and improve the pertinence of the completion.

(2) The completion unit shall meet certain length requirements to ensure the normal operation of the water and sand control completion string.

(3) To the extent that the segmented completion technology can solve, the number of segments should not be set too many, so as to reduce the complexity of completion construction and improve economic benefits.

3.2 Selection of segmented indexes of horizontal well completion with water control and sand control
Whether the segmented completion results are reasonable or not depends largely on the selection of segmented indicators. If there are too many segmented indicators, there may be correlation and repetitiveness between the indicators in the evaluation of horizontal section sand production and bottom water ridging, making the calculation more complicated. If the segmented index is too little, the sand production and bottom water ridging in horizontal well section cannot be evaluated comprehensively and truly. In order to select representative, sensitive and easy to calculate indexes from as many indexes as possible, the optimization of segmented indexes should generally follow the following requirements:

(1) Objectivity principle: In order to truly reflect the sand production and bottom water ridging in the horizontal well segment, the characteristic indexes with strong objectivity that can be quantitatively analyzed should be selected as far as possible to minimize subjectivity, so that the segmented completion results can be more reasonable and credible.

(2) Principle of completeness: There are many factors involved in the process of sand production and bottom water ridging in horizontal wells, and a single factor only reflects a certain characteristic.
Therefore, the segmenting index should cover the main factors that cause the heterogeneity of sand production and bottom water ridging in horizontal wells, so as to accurately reflect the sand production risk and bottom water ridging rule.

(3) Principle of independence: The selected sub-indicators should be independent of each other, and there should be no conversion relationship between each other. Avoid the repeated consideration of a factor, resulting in inaccurate evaluation.

(4) Practical principle: Data that is easy to obtain in production should be selected for segmented indicators. In the condition of the evaluation conclusion is comprehensive and objective. Simplify as much as possible to avoid triviality.

Horizontal bottom water cresting is with toe effect, reservoir heterogeneity, and avoid the result of joint action of many factors such as water height, horizontal section along the distribution of water breakthrough time is the most intuitive reflect the status of horizontal bottom water cresting indicators, through the calculation of reservoir seepage and bobbin horizontal well flow coupling under the condition of water breakthrough time, can accurately reflect the horizontal section along the water invasion situation; Critical production pressure difference (CDP) is an important quantitative index to judge formation sand production, which includes not only rock strength factors but also well stress factors. Therefore, in this paper, the critical production pressure difference and water appearance time of the sand taken out are selected as the indicators reflecting the sand production and bottom water ridge along the horizontal section.

3.3 Time of horizontal Wells in bottom water reservoir

In the original state of the reservoir, the oil-water interface maintains a pressure balance under the action of gravity and viscous forces. With the exploitation of crude oil, pressure drop occurs in the reservoir, and gravity is gradually offset by viscous forces. When the viscous force is greater than gravity, the oil-water interface deforms and rises. This phenomenon of bottom water inrush to horizontal wellbore is called bottom water ridge. Horizontal wells in bottom water reservoir water ridge forms by the reservoir physical property and fluid property, well track and other factors, according to the laws of the horizontal well water cut rising can be divided into three kinds of watered-out mode: dot see water flooded, dot see water and local water flooded and linear water overall watered-out mode, accurate analysis of horizontal section along the water breakthrough time distribution, by using horizontal well completion segmentation method and profile control technology, makes the model of horizontal well water flooding development towards more conducive to recovery, for horizontal well bottom water reservoir has important practical significance.

The water appearance time of horizontal wells is mainly affected by water avoidance height, horizontal section length, residual oil saturation, vertical permeability and other parameters. The higher the residual oil saturation and vertical permeability is, the earlier the water will appear in horizontal Wells. The longer the height and length of the horizontal section are, the later the water will appear in horizontal wells. According to the coupled model of reservoir seepage and horizontal well bobbin flow, the fluid production profile of horizontal well can be obtained. By substituting the formula of water appearance time, the water appearance time of horizontal section can be obtained to guide segmenting.

3.4 Horizontal well water control sand control completion section design process

Firstly, input the basic parameters required for the prediction model of critical production pressure difference of sand production in horizontal wells and the calculation model of water appearance time in horizontal wells with bottom water reservoir. Secondly, according to the segmented index model, the segmented index matrix of each micro-segment of horizontal well is generated. Thirdly, the multi-dimensional ordered clustering operation is performed, which mainly includes the calculation of segment diameter and loss function, and the segmented scheme is generated under different segments until the number of segments is specified. Finally, the optimal segmenting scheme is determined by combining horizontal well economics and technology.
4. Downhole inflow controller
The downhole inflow controller (ICD) can create a pressure drop in each section of the horizontal well through the nozzle, flow passage or hole, and adjust the production pressure difference in each section, so as to control the release of sand and balance the production profile. So this chapter selected ICD horizontal well completion method as the research object, water breakthrough time, yield as the optimization goal, control sand as constraint conditions, with each section down into ICD nozzle size and quantity of the tubing string as optimization variables, ICD horizontal well completion parameters established multi-objective optimization model, using fast non dominated sorting genetic algorithm (NSGA-II) is solved, by comprehensive consideration of water control sand control effect of the optimal ICD completion parameters.

4.1 ICD structure and types
Inflow Control Device (ICD) is a passive downhole fluid flow Control Device. By changing the size and direction of the fluid flow or both, it interferes with the normal movement of the fluid and produces impingement, separation and detachment, vortex and other phenomena. It creates a supplementary pressure drop between the annular space and the tubing, regulates the distribution of the production pressure difference in the horizontal section, and realizes the balanced injection and production in the horizontal section. At present, ICD devices commonly used at home and abroad can be divided into the following three types according to their structural characteristics and the principle of generating pressure drop.

4.1.1 Frictional ICD
Friction-type ICD is used to control the flow of fluid through a pre-designed curved or spiral channel by adjusting the diameter, length and number of the channel, which will cause flow loss due to the wall friction of the channel during the flow process. In this way, the corresponding attached pressure drop can be generated to control the inflow of fluid and balance the production profile of horizontal wells. According to different channel types, frictional ICD can be divided into spiral channel ICD and curved ICD. Baker Hughes Equlizer ICD is a typical spiral channel ICD. Frictional ICD restricts fluid flow by increasing fluid friction resistance. It slows the flow velocity of fluid in the channel and
reduces the risk of erosion and blockage of ICD string. However, the pressure drop generated by such an ICD structure is closely related to the fluid viscosity. With the increase of water content, the formation fluid viscosity changes, and the attached pressure drop generated by frictional ICD also changes greatly. Especially when the viscosity of oil and water is very poor, once the bottom water breakthrough, the friction-type ICD will play a very weak role in limiting current.

4.1.2. Throttling ICD
According to different throttling devices, the throttling ICD can be divided into nozzle ICD and orifice plate ICD. This type of ICD produces attached pressure drop by reducing the fluid overflow area. Among them, Schlumberger's Res Flow ICD combines water control and sand control functions by installing multiple throttling nozzles at the connection of the screen. During production, the reservoir fluid generates the corresponding attached pressure drop through the throttling effect of the nozzle, so as to balance the fluid production profile along the horizontal well. The attached pressure drop of the nozzle-type ICD can be adjusted by changing the size and number of the throttling nozzle. The attached pressure drop generated by throttling ICD is greatly affected by the density and flow velocity of the fluid and is not sensitive to the fluid viscosity, so it can be used in heavy oil reservoirs. However, the risk of erosion and blockage is relatively high due to the fast flow velocity of the fluid with a small overcurrent area.

4.1.3. Mixed ICD
The hybrid ICD combines the characteristics of nozzle type and spiral channel type, and adopts the principle of decentralized stepped-throttling to produce pressure drop. This type of ICD installs the baffle in the flow tank to form a labyrinth diversion tank, and the reservoir fluid flows through a series of continuous Chambers formed by the baffle, generating corresponding attached pressure drop. Compared with nozzle-type or orifice plate type ICD, the mixed ICD diversion channel has a larger flow area, which significantly reduces the flow velocity of the fluid in the device, so it is not easy to occur erosion damage.

4.2 Working principle of ICD string
Application of ICD in heterogeneous reservoir with horizontal well completion, usually used with packer and blind pipe, packer is used to change the water breakthrough time and the critical production pressure difference is large in sand hole packer, form independent of pressure and flow unit, blind pipe can sustain annulus between tubing and high pressure difference, thus ensuring annular part of reservoir fluid flow from the unit after ICD nozzle into the tubing, enhance the capacity of the regulation of ICD

In a horizontal well with an ICD completion, the flow of reservoir fluid from formation to tubing is driven by the production differential pressure, and the flow from formation to annulus is driven by the net production differential pressure. When the fluid flows from annulus to tubing, the attached pressure drop is generated through the ICD unit, and the fluid enters the tubing through the ICD unit. The net production pressure difference, ICD attached pressure drop and production pressure difference have the following

\[ \Delta p_e = \Delta p_r + p_{ICD} \]

4.3 Principle of pipe string controlling water and sand
When using constant pressure horizontal well production system, by adjusting the interval down to the number of ICD string and nozzle size, made in bottom water cresting faster interval larger pressure drop, reduce the interval of produced fluid rate, at the same time improve the annulus between tubing and casing pressure, make this net production differential pressure drop to the sand under the critical production pressure difference (CDP); The dual purpose of water control and sand control is to ensure that the net production pressure difference in this section is less than the critical production pressure
difference (CDP) in this section by using a smaller pressure drop or no ICD completion in the section with a slower bottom water ridge.

4.4 ICD completion parameter multi-objective optimization model

After the horizontal well completion segmentation scheme is determined, matching design should be carried out for the number of ICD completion string to be inserted into each section and the nozzle size, so that the horizontal well can be:

1. It can generate enough pressure drop between the open hole wall and the tubing, and the net production pressure difference of each section is less than the critical production pressure difference of sand production, which meets the requirements of horizontal Wells without sand production;

2. Limit the liquid yield rate in the high-permeability zone, so that the liquid yield profile is balanced, the oil-water interface is promoted uniformly, and the water appearance time is prolonged;

3. Downhole installation of ICD increases the flow resistance of oil to the bottom hole, resulting in a decrease in production. Therefore, under the constant pressure production system, the horizontal well production should meet the economic benefit requirements of the oilfield. In order to ensure the economic benefits of horizontal wells in oil field production, the larger the yield is, the better. Under the condition of the same yield, the longer the water duration is, the better. However, these two objective functions are in conflict with each other, and the water exposure time is usually short when the yield is high. Therefore, the objective of ICD parameter optimization for horizontal wells is to control the rapid rise of bottom water while maintaining high production.

4.5 The objective function

4.5.1. Objective function of maximum output

In order to meet the economic benefits of horizontal well production, horizontal well production is selected as one of the objective functions in this paper.

\[
\min _{x} f_1(x) = \max Q = \min \sum_{i=1}^{n} (-q_i L_i)
\]

\( f_1(x) \) or \( Q \) refers to the horizontal well production, \( m^3/d \); \( n \) is the number of horizontal well segments; \( Q \) is the fluid production rate of horizontal wells at each stage, \( m^3/d/m \). \( L_i \) is the segmented length of horizontal well, m.

4.5.2. The objective function of the minimum water time variation coefficient

When optimizing the horizontal well completion with water control, we expect the bottom water to ridge evenly to ensure the same water appearance time at each stage to achieve the maximum recovery factor. The variation coefficient of water appearance time reflects the degree of heterogeneity of water appearance time along the horizontal segment. The greater \( CV \) is, the greater the dispersion degree of water appearance time will be, the more serious the phenomenon of heterogeneous ridging of bottom water will be. Therefore, in this paper, the variation coefficient of water appearance time is selected as another objective function. The objective function of the variation coefficient of water appearance time is expressed as follows:

\[
\min _{x} f_2(x) = \min CV(t) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (t_i - t)/t}
\]

Where, \( CV \) is the variation coefficient; \( n \) is the number of horizontal well segments; \( t_i \) is the water appearance time of each section of the horizontal well, day; \( t \) is the average water appearance time of horizontal wells, day.

4.6 Design variables and constraints

The design parameters of horizontal ICD completion mainly include the selection of packer type, the installation location and number of packer, the selection of ICD type, the current limiting strength of
ICD and the number of installation. The installation location and the number of the packer can be determined according to the horizontal well water control and sand control completion segmentation method. The current limiting strength of the packer is mainly affected by the number of string and nozzle size. Therefore, the design variables for determining the multi-objective optimization model are: the number of string and nozzle size of ICD. In addition, when NSGA-II algorithm is applied to multi-objective optimization problems, some parameter ranges, namely constraints, need to be set. In the optimization of ICD completion parameters, the following constraints are specified according to the requirements of completion string process restriction and sand production control:

1. Since horizontal Wells are divided into multiple completion units and each completion unit is composed of a number of ICD string, the maximum number of ICD string allowed into each completion unit number of ICD string ≤ (completion unit length - packer length) / ICD string single length
2. ICD nozzle diameter: 0.5~3mm;
3. After installing The ICD in each section, the net production pressure difference from the reservoir to the open hole wall shall be less than the minimum critical production pressure difference of the well section to ensure no sand production in the well section. Therefore, the adducted pressure drop generated by the ICD string shall meet the following:

\[ p_{ICD} > p_e - p_{wf} - CDP \]

4.7 The realization of the optimal scheme
Selected when the NSGA-II algorithm of evolution to the algebra is specified, all the alternatives to form the Pareto optimal solution set. Theoretically, all solutions in Pareto's optimal solution set can be regarded as the optimal solution, but in order to meet the weight difference of production demand and optimization goal, the optimal solution needs to be further optimized. Topsis method can sort samples in Pareto solution set according to the distance from the ideal optimal solution to the ideal worst solution, and the sample that is closest to the optimal solution and farthest from the worst solution is the optimal solution. Therefore, Topsis method is selected in this paper for the scheme decision problem after system optimization

The basic steps are as follows:
1. The original decision matrix was established and the evaluation index was homogenized;
2. Based on the normalized initial matrix, the optimal scheme and the worst scheme of the finite scheme are found.
3. Calculate the distance between each evaluation object and the optimal solution and the worst solution respectively;
4. The relative proximity of each evaluation object to the optimal solution is calculated and sorted to obtain the optimal scheme.

4.8 Optimization design process
The optimization process of horizontal well ICD completion parameter optimization was determined by integrating the objectives and constraints as shown in the figure 3-1.
First of all, the input ICD horizontal well completion flow coupling model and objective function of the basic parameters for calculation model and the NSGA-II run configuration parameters; Secondly, according to the process constraints of ICD string and the production constraints of controlling sand production, the initial population is generated. Thirdly, population genetic evolution operation is carried out, which mainly includes selection, crossover and variation, generation of sub-population and sorting, until the iterative algebra is specified, Pareto optimal solution set is obtained. Finally, Topsis method is used to optimize the design scheme of completion parameters.

5. Example application and analysis
This chapter carries out completion optimization design for a production well in S oilfield and analyzes its application effect.

5.1 Basic data
S oilfield is a typical unconsolidated sandstone bottom water reservoir, characterized by shallow burial depth, high shale content and loose cementation.

At present, all the 16 horizontal wells that have been put into production in this block have serious sand production problems. At the same time, affected by reservoir heterogeneity, the oil well sees water quickly and bottom water ridge is relatively serious. well A1 is a production well and is produced at a constant pressure of 3MPa. Its designed vertical depth is 1420m A target vertical depth 1418m, B target vertical depth 1420m. Taking this well as an example, the optimized design of horizontal well completion with water control and sand control is carried out by using the established method.

Reservoir parameters of S oilfield and wellbore parameters of well A1 are shown in Table 1. The horizontal logging interpretation of Well A1 is all reservoir, oil-free and water-free homogeneous layer and tight layer.

Table 1 Main reservoir and wellbore parameters of Well A1

| parameter                      | The values | parameter                      | The values |
|--------------------------------|------------|--------------------------------|------------|
| Reservoir thickness            | 32m        | Formation water density        | 1010kg/m³  |
| Reservoir pressure             | 223MPa     | Crude oil density              | 926kg/m³   |
| Shaft diameter                 | 0.1397m    | Avoid water height             | 13m        |
| Crude oil viscosity            | 18mpa.s    | Formation crude oil volume     | 1.013      |
| Relative wellbore roughness    | 0.01       | Residual oil saturation        | 0.283%     |
| Azimuth of maximum horizontal principal stress | N130E | porosity                       | 27.1%      |
| Bound water saturation         | 0.27%      | Maximum horizontal principal stress | 24.31 MPa |
Due to the heterogeneity of reservoir physical properties, fluid production in horizontal wells is uneven, and wall friction, acceleration, gravity and other factors in the horizontal wellbore will cause pressure drop loss in the wellbore, aggravating the difference of fluid production rate at each point, thus affecting the fluid production profile. The minimum liquid production rate of Well A1 was 0.27 m³/d/m, appearing at 140m. The maximum liquid production rate was 1.18 m³/d/m, appearing at the 70m; The average fluid production rate of the whole well was 0.629 m³/d/m.

5.2 Horizontal well completion section design

The initial length of each ICD pipe (10m) forming the completion string is a micro segment, and the horizontal segment is divided into 30 micro segments. The multi-dimensional ordered clustering algorithm is used for segmentation and the optimal segmentation results under different segmentation numbers are obtained.

| Number of segments | Loss function | Segmentation results |
|--------------------|---------------|---------------------|
| 2                  | 37.97         | 0-70,70-300         |
| 3                  | 16.09         | 0-70,70-140,140-300 |
| 4                  | 11.11         | 0-70, 70-140,140-220, 220-300 |
| 5                  | 8.64          | 0-70, 70-140,140-220,220-250,250-300 |
| 6                  | 6.91          | 0-70, 70-90,90-140,140-220,220-250,250-300 |
| 7                  | 5.65          | 0-70, 70-90,90-110,110-140,140-220,220-250,250-300 |

| segments | Block length (m) | Wellbore variable mass flow pressure (MPa) | Average liquid yield rate | Water breakthrough time (day) | Critical pressure difference of sand production (m³/d) |
|----------|------------------|------------------------------------------|--------------------------|-----------------------------|------------------------------------------------------|
|          |                  |                                          |                          |                             |                                                      |
| 1        | 0-70             | 10.458                                   | 0.863                    | 35.8                        | 2.28                                                 |
| 2        | 70-140           | 10.476                                   | 0.334                    | 98.4                        | 1.74                                                 |
| 3        | 140-300          | 10.488                                   | 0.656                    | 47.4                        | 2                                                     |

5.3 Horizontal well completion section design

Different completion program application effect analysis of ICD after completion, A1 well sand production and water breakthrough are improved to a certain extent, plan A, B and C are different extent, limits the production of high yield liquid with liquid rate, improve the balance of liquid producing profile, but at the same time led to the decrease of the horizontal well production. The
optimal completion plan B is 54.6 m³/d, which is about 70% lower than the open-hole completion. ICD completion has a great impact on bottom water break out time. When an open hole completion is used, the bottom water breakthrough time is 35 days; When option B was used, the bottom water breakthrough time was 171 days, 136 days more than when the open hole was completed.

In scheme A, B and C, the net production pressure difference of each section is less than the critical production pressure difference of each section. This indicates that after the ICD completion, all sections of horizontal wells can ensure no sand production and meet the requirements of horizontal well sand control.

### Table 4 Objective functions under different completion parameters

| plan position | The number of ICD | ICD nozzle diameter (mm) | Attached to the pressure drop (MPa) | Water breakthrough time (day) | Water time variation coefficient | Production (m³/d) |
|---------------|-------------------|--------------------------|-----------------------------------|-------------------------------|---------------------------------|------------------|
| A 0-70        | 3                 | 2.21                     | 1.532                             | 85                           | 0.169                           | 100.46           |
| 70-140        | 3                 | 1.52                     | 1.325                             |                              |                                 |                  |
| 140-300       | 6                 | 2.77                     | 1.348                             |                              |                                 |                  |
| 0-70          | 2                 | 2.35                     | 2.147                             |                              |                                 |                  |
| B 70-140      | 2                 | 1.46                     | 1.982                             | 171                          | 0.178                           | 54.6             |
| 140-300       | 5                 | 1.19                     | 2.157                             |                              |                                 |                  |
| 0-70          | 1                 | 0.63                     | 2.816                             |                              |                                 |                  |
| C 70-140      | 1                 | 0.51                     | 2.788                             | 746                          | 0.187                           | 12.22            |
| 140-300       | 2                 | 0.62                     | 2.801                             |                              |                                 |                  |

### 6. Conclusion

1. Based on the above model, the characteristics of the horizontal well's fluid production profile are analyzed, and the sensitivity of the factors affecting the equilibrium of the horizontal well's fluid production profile is analyzed. The results show that the distribution of the fluid production profile in the horizontal section is not uniform due to the influence of the flow pressure drop in the horizontal wellbore and reservoir heterogeneity. In homogeneous reservoirs, the horizontal section shows an asymmetric U-shaped fluid production profile, with a higher fluid production rate near the heel, and the bottom water is more likely to break through the heel end. The pressure difference between the heel end and the toe end is greater than the pressure difference between the toe end and the horizontal well, and the sand production risk at the heel end is more serious.

2. Under the condition of constant pressure production, the fluid production profile of horizontal Wells becomes more uniform with the increase of crude oil viscosity and wellbore diameter; With the increase of reservoir thickness, horizontal permeability, horizontal section length and production pressure difference, the fluid production profile of horizontal Wells becomes more and more uneven. Permeability anisotropy has little influence on the yield profile.

3. Put forward "location adjacent, risk of sand and water breakthrough time close to" principle of sand control section water control in horizontal well completion, considering horizontal heterogeneity reservoir property and horizontal wellbore flow with toe effect caused by sand production risks and
water breakthrough time, building sand critical production pressure difference (CDP) and water breakthrough time segmentation index vector matrix (T), introducing multi-dimensional orderly clustering mathematical method, forms the comprehensive consideration of water control sand control of horizontal well completion segmentation method.

(4) ICD horizontal well completion method as the research object, established the aims to realize the maximization of the horizontal well balanced water breakthrough and yield at the same time to ensure that the reservoir sand not multi-objective ICD completion parameter optimization model, and uses the rapid and command sequence genetic algorithm (NSGA-II) get to ICD string number and nozzle size for variables of Pareto optimal solution set, the order of the Pareto solutions using Topsis method to determine the best completion program, formed a comprehensive consideration of water control sand control of ICD horizontal well completion parameters optimization method.

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