Research and application of gravel-packing flow-regulation water-control screen completion technique in horizontal wells

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Abstract. Horizontal well inflow control screen completion require packer to stage on the reservoir, however, the numbers of packer are limited to section of the reservoir, the reservoir sealing length is limited by packer rubber, effective sealing length is short, that restricts to the control precision of ICD in horizontal wells. In view of above, this paper presents a new horizontal well gravel packing inflow control screen completion technology, that uses gravel to replace the packer to seal the reservoir, resisting the transverse flow in the wellbore, making the inflow control screen can control water directly on formation in which the position is located, to realize the dynamic adjustment the flow profile in the whole horizontal well section. From the technological principle and characteristics, key implemental technology, gravel and supporting tools, construction technology and other aspects of horizontal well gravel filling, the gravel packing inflow control screen completion technology were studied. The technology was applied in adjustment horizontal well completion in the xinjiang A oilfield. After application, the oil production increased by 5.1 times, the water content decreased by 13.5%, and achieved a good effect of controlling water coning and increasing oil. The application results suggest that horizontal gravel inflow control screen pipe completion technology can improve the effect of inflow control screen completion, that could be applied in the new wells and old wells second completion.

1. Introduction
Flow-regulation water-control screen completion in horizontal wells is a completion technology developed in the 1990s. It has been applied extensively at home and abroad and has achieved good results [1-3]. With deeper study and promotion of the completion technology, increasingly high requirements have been proposed for this technology. How to maximize the water-coning and oil-stabilizing function of flow-regulation water-control screen to realize the full-interval dynamic control in horizontal wells has gradually become a research hotspot. In the conventional horizontal well flow-regulation water-control screen completion, packers are required to divide the reservoir into several sections to achieve the subsection control over the pay zone, thereby deceasing production in high-permeability sections, improving liquid production in low-permeability sections, and balancing the horizontal inflow profile [4]. However, the packer used to divide the reservoir will limit the number of reservoir sections; the length of the pack position is limited by the length of the packer barrel. Small effective packing length inhibits the regulation accuracy of flow-regulation water-control screen in horizontal wells. In addition, for the secondary completion of horizontal wells, the completion method using a packer combined with flow-regulation water-control screen cannot meet the completion
operation of adjustment wells with multiple complicated conditions coexisting. The problem is more prominent in the application of deep horizontal wells in secondary completion during water-blocking and oil recovery operations. Therefore, this paper proposes a new type of gravel-packing flow-regulation water-control screen completion in horizontal wells. Through tool and design optimization, secondary flow-regulation water-control screen completion in horizontal wells under difficult and complex geological conditions was successfully implemented in deep wells of A Oilfield in Xinjiang.

2. Gravel-packing flow-regulation water-control screen completion technique in horizontal wells

2.1. Technical principles and features

The gravel-packing flow-regulation water-control screen completion technique in horizontal wells is to replace the traditional packer with gravel to isolate the reservoir. In horizontal section, gravel was placed in the annulus between the flow-regulation water-control screen and well wall, and the gravel packing is used to block the lateral fluid flow entering the wellbore, so that the flow-regulation water-control screen directly block water and stabilize oil in the located section, realizing the dynamic adjustment of inflow profile at whole horizontal wellbore with unlimited water controlling stages. The whole set of completion string of gravel-packing flow-regulation water-control screen completion in horizontal wells is shown in the following figure:

![Schematic diagram of integral completion string of gravel-packing flow-regulation water-control screen completion in horizontal wells.](image)

1. Packing string, 2. Casing, 3. Packing packer, 4. Packing converter, 5. Flow-regulation water-control screen, 6. Flushing tube, 7. Packed gravels, 8. Guide shoe

Figure 1. Schematic diagram of integral completion string of gravel-packing flow-regulation water-control screen completion in horizontal wells.

The figure above shows the overall string structure of the gravel-packing flow-regulation water-control screen completion in horizontal wells. The quantity and completion parameters of flow-regulation water-control screen are optimized according to the horizontal well production and reservoir geological characteristics[5][6], and then determine the combination of the completion pipe string and the specific throttling parameters of the screens; the oil tubing or drilling pipe were used as the feeding pipe to carry the flow-regulation water-control screen completion string to the horizontal completion interval. The packing converter and the packing packer are placed at the heel end of the horizontal section or the inclined well section of the horizontal well (the specific position is
determined based on the well type characteristics). After the completion string is in place, the pressurized ball is dropped down to set and seal the packing packer, sealing the entire annular space of completion string and the upper casing annular space. After the packer is sealed, pull out the feeding pipe and run in the gravel-packing string to start the gravel-packing operation. The water is used as the sand-carrying liquid to carry the gravel through the gravel-packing string and then by packing converter to the annular space between the flow-regulation water-control screen and well wall. After the water carries the gravel in place, the packed gravel will stay in the horizontal section of the annulus due to the filter function of flow-regulation water-control screen. The water enters into the flow-regulation water-control completion string through the screen, and then flows through packing converter into the casing annulus between the feeding string on the upper part of the packer and the inner wall of the casing, and finally flows through the casing annulus into the circulation tank outside the wellhead, the complete packing cycle is finished. The above cycle is repeated throughout the gravel-packing process until the horizontal section is fully packed by gravel [7][8]. Since the flow-regulation water-control screen is used as the completion string, the channel connecting the horizontal section annulus and the inner tube of completion string is an flow-regulation water-control throttle, whose space is relatively small compared to ordinary screens. Therefore, it is not possible to carry out high pressure and large capacity sand carrying operations. In order to improve the gravel-packing effect in the horizontal section, the packing process maintains a small pumping displacement. The displacement rate of water for the packing is less than 0.3 m³/min, and the ultra-low density high molecular gravel that can be carried by the oilfield water is selected as packing gravel. On the other hand, the throttling function of flow-regulation water-control screen also increases the inflow resistance of oilfield water in each screen, forcing the oilfield water to carry the gravel to the horizontal toe end in the horizontal section to improve the packing effect. In addition, in the secondary completion operation of new wells or wells with large wellbore space, the flow-regulation water-control screen of larger inner diameter can be run in hole, and flushing pipes and fittings for packing can be run into the flow-regulation water-control screen of larger inner diameter to ensure that the oilfield water is recirculated at the toe end of the horizontal wells, thus improving the ability of the oilfield water of carrying sand to the horizontal toe end and enhancing the packing effect[9].

The completion string of the gravel-packing flow-regulation water-control screen completion technique has the advantages of simple structure, which can be used for water-control completion in new wells, and be used for secondary water-control and oil-stabilizing completion in horizontal wells with open hole completion, perforation completion and slotted liner completion. In addition, when the whole set of flow-regulation water-control screen completion technique has to be pulled out, the string shall be run to release he packing packer, and then the packing converter shall be closed. Then oilfield water is injected into the string, and finally flows out of the horizontal completion section annulus and casing annulus. Hence, a positive circulation system is established, which is composed of the pipe column—horizontal completion section string—horizontal section annulus—casing annulus—flush the sand at the bottom of well outside the well. After gravels are flushed out, the entire completion string can be pulled out of hole.

2.2. Keys for technology implementation
Horizontal well completion has relatively high costs and risks, especially for deep complex horizontal wells. Main principles for the completion operation are to ensure safety and high efficiency. Key difficulties in the implementation of horizontal well gravel packing flow-regulation water-control screen completion technique are listed as follows:

1) Flow-regulation water-control screen completion string, upper packing packer and packing converter should be tripped in hole and set together, which proposes higher requirements for well through, scraping, and selection of proper OD of completion string.

2) In order to ensure the effects of gravel packing, gravels are used as separating material to separate reservoirs, and its packing results determine the water controlling and oil stabilizing effects of the whole technology; for the throttling feature of flow-regulation water-control screen, this technique
is not suitable for high pressure and large displacement packing. The small displacement tight packing in annulus space of lower horizontal interval put forward higher requirements on selection of packing gravels, packing method and relevant parameters for packing completion.

3) The whole completion string in horizontal well faces the risk of being buried and plugged by sands during gravel packing. Meanwhile, the whole completion string has a weak point at the connection part between upper feeding string and packing packer, with high leakage risk. Therefore, special requirements are put forward on selection of string, packing technique and outer shape of completion string at horizontal interval.

4) Flow-regulation water-control screen is the core part for controlling water and stabilizing oil of horizontal well gravel packing flow-regulation water-control screen completion technology; after reservoirs are separated infinitely by gravel packing, flow-regulation water-control screen can be used to control fluid in formation, inhibit water production interval or control production volume at high production fluid interval, and enhance output of oil production interval or low fluid production interval. Flow-regulation water-control screen should be designed to meet demands of earlier packing displacement rate and later fluid controlling. There are high demands for selection of proper completion parameters.

3. Packing gravel and associated tools

3.1. Optimal selection of packing gravel
Select lower density gravels as the packing gravels, and their density are from 1.0g/cm³ to 1.03g/cm³ which are similar with water density. Ensure that the packing gravels can be carried by oilfield water. Small displacement and fine filling should be executed. Under high temperature and high pressure operating condition, completeness of gravels should be maintained and compression strength of the gravel should be over 60MPa and temperature rating should be over 200 ℃. On the other hand, particle size of the gravel should be between 40 mesh and 100 mesh, and degree of sphericity should be over 0.95. Smaller gravel size and higher sphericity can be applied to guarantee the compactness after gravel accumulation, reduce the permeability of the gravel after filling, and block the lateral flowing of fluid significantly to pack off intervals.

3.2. Flow-regulation water-control screen
Flow-regulation water-control screen is the core for stabilizing oil production and controlling water of horizontal well gravel-packing flow-regulation water-control screen completion technique. Traditional flow-regulation water-control screen are all passive mode which regulate water by controlling fluid. This traditional screen has three types including nozzle type, flowing pipe type and spiral channel type. Nozzle type flow-regulation water-control screen is extensively applied for its simple structure and high reliability. As the development of technologies, the new type screen has active flow regulation and water controlling mode, which can adjust resistance automatically in accordance with the situation of production fluid and realize self-adjusting flow-regulation water-control. It has two types, namely streamlined type and floating plate type [10-12]. From perspective of water controlling and oil stabilizing effect, the horizontal well gravel-packing flow-regulation water-control screen completion technique selects to use self-adaptive flow-regulation water-control screen for better performance. The early gravel packing technique requires flow-regulation water-control screen to have some flowing capacity and relatively high reliability under pressurized packing. Therefore, it is recommend to use nozzle type flow-regulation water-control screen or “flow channel type” self-adaptive flow-regulation water-control screen without moving parts.

3.3. Packing converter
The function of the converter is mainly to convert filling flow channel, ensure packing gravels and sand-carrying fluid in wellhead feeding string (tubing or drilling stem) can enter into the annular spaces between the flow-regulation water-control screen in horizontal interval and the formation
through packing converter. Sand-carrying fluid will flow into the completion well bore through the flow-regulation water-control screen after gravels are carried to the spaces between the screen and the formation, then the fluid enter into the annular spaces between feeding string (tubing or drilling stem) and the casing through the converter in completion well bore; finally the fluid can be discharged out of well bore, and enter into sand-carrying fluid again, and a complete circulation operation is finished.

3.4. Packing packer
The main function of the packing packer is listed as following: to pack and fill intervals and upper well-bore; prevent fluid in the packing intervals or packing gravels entering into upper spaces of well-bore; guarantee well-bore fluid flow along with the designated passage; ensure the formation fluid can only flow out of well-bore through completion string; meanwhile, gravels should be maintained in the horizontal interval during packing; and sand-carrying fluid can be discharged out of well through completion string, and then normal circulation can be established for the whole packing procedure.

4. Completion optimization

4.1. Preparation in wellbore
In order to successfully run flow-regulation water-control screen completion string assembly in hole and set upper packing packer, firstly miscellany and silt in well-bore should be cleaned; washing mill & scraper should be tripped in to scrape and wash the casing, and setting position of the packer should be scraped and washed for about 3 to 5 times. In accordance with the different completion programs, drifting & special milling string should be used in horizontal intervals to simulate drifting; in secondary completion operation, make wiper trips for more than three times to ensure completion string can be tripped in later. Casing, silt and miscellany at the well bottom should be cleaned with large displacement with the displacement rate as high as possible up to surface pump pressure or the upper limit of displacement. In addition, formation inhalation test should be carried out before tripping in completion string to ensure the safety of well bore during filling, flow rate of three pressure points should be tested under 1MPa, 3MPa and 5 MPa.

4.2. RIH of completion string
Install the base of the hanger and lifting standpipe at the wellhead after cleaning well-bore, and establish a closed circulation system. Then assemble completion string assembly at well head: guide shoe + flow-regulation water-control screen + blind pipe + flow-regulation water-control screen + blind pipe + packing converter + packing packer. Secondary flow-regulation water-control screen completion string should be run into hole according to the designed sequence, and tubing & drilling pipe should be drifted before tripping in. These pipes should be checked carefully to avoid disqualified tubing and pipe being run into hole. Speed should be controlled for tripping in tubing and drilling pipes, and percussion drill and drilling string not well braked are prohibited. After the string reaches the designed position, packer should be set by normal pressurizing stepwisely. Mark gravel packing position and backwashing position after setting the packer, and then open the filling point to start gravel packing.

4.3. Gravel pack operation
Connect filling equipment at well head, and pressure test should be conducted to be ok; fill gravels in accordance with pumping procedure, and keep the continuous filling; once the pump stops suddenly, start the spare pump immediately, and pump the water into the well; circulate slurry to well bottom, and ensure the smooth flow passage. The maximum working pressure should be lower than 10MPa, and sand ratio should be controlled between 5% and 8%. Initial flow rate about filling operation is 0.3m³/min, and filling pressure should be increased to keep flow constantly when flow rate decreases; until the pressure is raised to 6MPa, keep the pressure at the fixed value; when the flow rate is lower than 0.3m³/min, stop filling and then open backwashing channel to backwash until no sand is at the
outlet. Working pressure should be observed at all time; if the designed sand volume has not been increased to screen-out pressure (which is higher than working pressure 5MPa), stop the pump and replace pipe fluid to wash well by reverse circulation.

5. Field application and benefit evaluation

5.1. Effects of field application
For one horizontal well in A oil field, with well depth of 4970 meters and horizontal section about 300 meters, perforating completion is used in early stage; after 6 years’ production, water cut was 95% and daily oil production was 1.7t/d. The reservoir parameters are given in table 1. Then, the well faces challenges of shutdown due to high water cut. Secondary completion was conducted by horizontal well gravel-packing flow-regulation water-control screen completion technique for controlling water cut and increasing oil production, and the operation was successful; secondary flow-regulation water-control screen completion string was assembled and gravel packing operation achieved success in one time. This technology is the first application of this technique in secondary completion in China.

| Parameter                              | Symbol | Unit  | Value  | Parameter                              | Symbol | Unit  | Value  |
|----------------------------------------|--------|-------|--------|----------------------------------------|--------|-------|--------|
| Ground oil density                     | ρₒ     | g/cm³ | 0.84   | Salinity of formation water             | mg/l   |       | 21.27×10⁴ |
| Oil volume factor                      | Bₒ     | Rm³/Sm³ | 1.147⁷ | Original formation pressure             | Pₒ     | MPa   | 49.21  |
| Formation oil viscosity                | µₒ     | mPa/s | 1.955  | Bubble pressure                        | Pₙ     | MPa   | 9.97   |
| Formation water density                | ρₚ     | g/cm³ | 1.150  | Thickness of oil bearing layer          | h      | m     | 9      |
| Formation water viscosity              | µₚ     | mPa/s | 0.26   | Original GOR                           | Rₛ     | m³/m³ | 57     |

5.2. Benefit evaluation
After operation, run production string into hole to acquire new productivity of oil well. Productivity of the horizontal well is listed in table 2.

| Stage                          | Production pressure difference | Oil production per day | Water production per day | Fluid production per day | Water cut |
|--------------------------------|-------------------------------|------------------------|--------------------------|--------------------------|-----------|
| Before operation               | 2.0                           | 1.7                    | 39                       | 41                       | 94.7      |
| After operation                | 3.2                           | 8.7                    | 37.7                     | 46.4                     | 81.2      |
| Theory analysis                | 3.2                           | 2.7                    | 62.4                     | 72.5                     | 96.3      |

If only production pressure difference increasing is required, gravel packing flow-regulation water-control screen is not recommended for stabilizing oil and controlling water.

As shown in the table, the total fluid volume did not change obviously, and the daily oil production was increased by 5.1 times from 1.7t/d to 8.7t/d, and water cut was decreased by 13.5% from 94.7% to 81.2%. Good effects of controlling water cut and increasing oil production of the completion technology was achieved. In order to further analyze the effects of whole set techniques, Calculated productivity and changes of water cut are listed in table 2. As shown by the table 2, comparing with simulation by only increasing production pressure difference, the daily oil productivity was increased by 3.2 times from 2.7t/d to 8.7t/d, and water cut was decreased by 15.1% from 96.3% to 81.2%; the above two comparisons prove that horizontal well gravel packing flow-regulation water-control screen
completion technology can be used to increase oil productivity in horizontal wells and decrease water cut of oil wells, thus infinite water cut controlling and oil productivity increasing can be realized.

6. Conclusions
1) This paper proposed the horizontal well gravel packing flow-regulation water-control screen completion technology, which can be used for new well completion, early openhole completion, slotted liner completion and secondary completion of perforated horizontal wells.
2) Ultra low density gravels are packed to separate reservoir in completion well by using flow-regulation water-control screen. Comparing with conventional packer, this new packer can be used to separate layers infinitely and realize water control infinitely.
3) Flow-regulation water-control screen can be used to control formation water production dynamically; water at any position can be controlled automatically with high efficiency of controlling water cut and increasing oil production.
4) Field application indicates that gravel packing flow-regulation water-control screen completion technology in horizontal well is feasible; this technique can improve production of oil wells, reduce water cut in horizontal wells, and control water and stabilize oil production of horizontal wells.

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