Study on asynchronous injection and production of horizontal Wells in ultra-low permeability thin layer low abundance oil field

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Abstract: The ultra-low permeability, thin layer and low abundance GLN area is developed by water-injection with horizontal and straight combined well pattern. With the extension of development time, the water appears in multiple sections and directions in horizontal Wells, and the well area gradually enters the stage of medium and high water cut, which shows the characteristics of rising when water is injected, falling when liquid is stopped, and limiting the profile control pressure in multiple rounds of Wells. Therefore, developing the "note when mining, mining without note" asynchronous injection-production adjustment of horizontal well technology, make full use of the artificial fracture of high permeability channel and matrix suction effect between low permeable formation permeability, increase the crack near the matrix suction swept volume, to achieve the purpose of the horizontal well steady liquid water control, up to the level of the special low permeability thin layer low abundance wellblock improve recovery factor. Through the mechanism of injection-production, the use of pore throat boundaries, the respect such as injection-production timing and parameter optimization research, combined with the reservoir numerical simulation and theoretical formula, conduct asynchronous injection-production field practice, improved the development effect of horizontal well, and have achieved good economic benefits, for the next class of reservoir level wellblock middle and high water cut stage to explore a new way of governance.

Key words: ultra-low permeability oil field; Horizontal well; Asynchronous injection and production; Numerical simulation; Enhanced oil recovery

1. The introduction

The target reservoir in the peripheral GLN area is the Putaohua oil reservoir with an average buried depth of 1560m, which is a structure-lithologic reservoir. The reservoir is mainly composed of underwater distributary channel and mat sand deposits, with poor physical property and thin thickness. The reserve abundance is 12.8×104t/km2, the average porosity is 15.3%, and the average air permeability is 2.1mD. It is a low-porosity, ultra-low-permeability and low-abundance reservoir. In view of the fact that the vertical well development benefit is poor, the horizontal well is developed by water-injection combined with horizontal well pattern, and the horizontal well is completed by longitudinal zone-fracturing. The initial oil production per well is 10.6t, which is 3.0 times of the surrounding vertical well. However, with the prolongation of development time, the horizontal well is gradually exposed to water in multiple sections and directions, and the well area gradually enters the stage of medium and high water cut, showing the characteristics of rising when water is injected, falling when water is stopped, and limiting the profile control pressure of multiple rounds of Wells. Therefore, the asynchronous injection-production adjustment technology of "no injection at the time of injection, no injection at the time of production" was developed and perfected to make full use of the imbibition effect between the high permeability channel of artificial fractures and the low permeability layer of the matrix, increase the imbibition and volume of the matrix near the fractures, achieve the purpose of stabilizing fluid and controlling water, and improve the recovery efficiency. A new management method is explored for the middle and high water cut stage in horizontal well area of similar reservoir in the future.

2. Study on asynchronous injection and production

2.1 Study on injection and production mode and mechanism

The asynchronous injection-production adjustment technology is a special periodic water injection mode, which adopts the mode of "no injection at injection time and no injection at production time", which can be divided into three stages: water injection, stuffy well and oil recovery. In the stage of water injection, the injection well is opened and the horizontal well is closed. In the stuffy well stage, the injection well and the horizontal well are shut in simultaneously. In the production stage, the injection well is shut in and the horizontal well is opened [1-3].

In the stage of water injection, the injected water flows into the fracture sufficiently to achieve the initial oil-water displacement. With the increase of injection pressure, the formation energy is continuously replenished, and the injected water preferentially spreads to the matrix macropore throat which is far away from the fracture. At this time, the water driving force plays a dominant role. In the stuffy stage, the fluid velocity in the pore becomes slow, and the capillary force imbibition is enhanced, and the smaller the pore throat is, the stronger the capillary force is. In this case, the injected water is imbibed into the pore throat by the crack and the macropore throat, and the remaining oil in the matrix pore throat is replaced. Capillary force plays a leading role. During the production phase, imbibition displacement of remaining oil into large pore throats and fractures is more conducive to recovery as formation pressure increases and increases the differential production pressure, while reducing inefficient circulation. Therefore, from the perspective of microscopic oil displacement mechanism, asynchronous injection-production adjustment technology can play a role in improving displacement pressure difference, enhancing imbibition displacement and reducing inefficient circulation [4-7]

2.2 Study on pore-throat boundary of asynchronous injection and production

In the tight well stage of asynchronous injection-production development mode, capillary force is the main controlling factor of oil-water interpermeability, and its size determines the strength of impibition displacement. It is particularly important to study the production performance of different capillary forces in the reservoir. Combined with the laboratory core experiment in GLN area, numerical simulation is applied to observe the development effect of different injection and production development methods by changing different capillary forces [8]. Meanwhile, according to the capillary force formula, different capillary forces were transformed into corresponding pore-throat radii, and the relationship between different pore-throat radii and recovery degree was obtained.

Capillary force formula:

$$Pc=\frac{2\sigma\cos\theta}{r} \quad (1)$$

Type in the: σ—The interfacial tension, mN/m; θ—Wetting Angle; r—The pore radius, mm; Pc—Capillary force, Pa.

According to the research results in Table 1, at the initial stage of capillary force increase, the recovery degree of asynchronous injection and production is similar to that of synchronous injection and production. At this time, the development effect of asynchronous injection and production is not different from that of synchronous injection and production when capillary force is smaller in the reservoir. However, when the capillary force is greater than 0.3MPa, that is, the pore throat radius is less than 2.35μm, the capillary force imbibition is enhanced and plays a leading role. The recovery degree of synchronous injection and production decreases sharply, and the development effect becomes worse. However, the recovery degree of asynchronous injection and production rebounded, and then decreased, but the overall development effect was better than that of synchronous injection and production. However, the pore-throat radius in ultra-low permeability GLN area is less than 2.35μm, accounting for up to 73.8%, which is suitable for asynchronous injection and production to excavate the remaining oil in fine pore-throat [9-10].

Table 1 Quantitative characteristics of capillary force and pore-throat radius in different injection and production methods

Capillary force /MPa	The pore throat radius (μm)	Asynchronous injection and production /t	Asynchronous injection production degree /%	Simultaneous injection and production of cumulative oil production /t	Degree of synchronous injection and production /%
0.01	52.0	34005.6	12.12	33513.2	12.03
0.03	17.3	32585.3	11.93	32123.2	11.87
0.05	10.4	32020.3	11.86	31456.3	11.78
0.08	6.5	31456.3	11.78	30456.3	11.64
0.1	5.2	31254.2	11.75	30216.2	11.61
0.3	2.35	34611.1	12.20	29232.2	10.72
0.5	1.04	34201.3	12.15	26554.2	10.39
0.7	0.74	32013.2	11.85	21565.3	9.76
1.0	0.52	18652.4	9.39	15658.3	9.02
2.0	0.26	15331.1	8.98	10645.3	8.39
3.0	0.17	14023.3	8.81	9321.5	8.22

2.3 Study on timing of asynchronous injection and production

In view of the fact that the pore structure in GLN area is highly heterogeneous and the water in horizontal Wells is fast, it is considered to establish well groups with different pore throat structures to optimize the timing of asynchronous injection and production. The reservoir numerical simulation model is established according to the actual geological parameters of the reservoir, and the timing of asynchronous injection and production is optimized for reservoirs with different pore structures.

Table 2 Classification of different pore-throat structures

Pore types	Throat category	Throat radius /μm
A	Large throat	2.0-4.0
B	In the throat	1.0-2.0
C	Small throat	0.5-1.0

Nine asynchronous injection and production timing schemes are designed for reservoirs with pore structures of class A, B and C. The recovery degree and water cut at the end of 10 years of asynchronous injection and production of horizontal Wells are taken as evaluation indexes to optimize the asynchronous injection and production timing of horizontal Wells.

Table 3 Numerical simulation and prediction results of extraction degree and water cut at the end of 10 years with different injection timing

plan	Injection-production plan	Class A Recovery degree (%)	Class A The moisture content (%)	Class B Recovery degree (%)	Class B The moisture content (%)	Class C Recovery degree (%)	Class C The moisture content (%)
1	Continuous injection	21.18	87.23	20.27	89.23	18.39	87.56
2	When the moisture content is 10%, it is transferred to asynchronous injection and production	20.95	89.25	19.35	90.25	17.64	89.64
3	When the moisture content is 20%, it is transferred to asynchronous injection and production	21.86	91.13	19.16	90.13	18.86	85.13
4	When the moisture content is 30%, it is transferred to asynchronous injection and production	22.19	90.75	21.52	87.75	19.39	84.62
5	When the moisture content is 40%, it is transferred to asynchronous injection and production	23.15	89.43	22.15	85.43	19.94	84.43
6	When the moisture content is 50%, it is transferred to asynchronous injection and production	24.87	91.45	22.85	84.45	20.88	82.17
7	When the moisture content is 60%, it is transferred to asynchronous injection and production	24.45	89.13	23.39	79.68	21.53	80.29
8	When the moisture content is 70%, it is transferred to asynchronous injection and production	23.18	90.12	22.97	81.27	22.78	79.15
9	When the moisture content is 80%, it is transferred to asynchronous injection and production	22.98	91.28	21.45	90.22	20.31	83.57

According to the numerical simulation results, the smaller the throat, the later the suitable time for asynchronous injection and production. The optimal asynchronous injection and production rate was 50% for large pore throat (2.0-4.0μm), 60% for medium pore throat (1.0-2.0μm), and 70% for small pore throat (0.5-1.0μm).

Table 4 Results of asynchronous injection and production time with different pore-throat structures

The pore structure	Throat radius (μm)	Capillary force (MPa)	Optimal timing of asynchronous injection and production
Large pore throat	2.0-4.0	0.12	water 50%
The pore throat	1.0-2.0	0.21	water 60%
Pore throat	0.5-1.0	0.40	water 70%

2.4 Optimization of asynchronous injection and production parameters

2.4.1 Optimization of injection and production cycle

The injection-production period is optimized according to the reservoir conductance coefficient and stage injection-production balance. In the aspect of optimizing the water injection cycle, in order to ensure the water injection sweep within the distance between injection and production Wells, the formula of reservoir conductivity coefficient is applied to optimize the water injection cycle of 2 months. In terms of optimizing oil production cycle, combined with field tests, when the optimized oil production cycle is 4.2 months, the cumulative injection-production ratio of the stage is 1.0 to maintain the injection-production balance.
Reservoir conductivity coefficient formula:

$$T=\frac{\mu\cdot Ct\cdot\Phi\cdot L^2}{2K} \quad (2)$$

Type in the: T—Half cycle of water injection, s; μ—Fluid viscosity, mPa•s; Ct—Integrated coefficient of compression, Pa-1; Φ—porosity, %; L—Injection-production well spacing, m; K—Permeability of air, mD
At the same time, according to the actual situation of the oil field, 12 different injection and production cycles are designed for numerical simulation, so as to optimize the injection and production cycle reasonably. According TO the numerical simulation results, the recovery degree of 60 injection and 120 production period is the highest, the water content is the lowest, and the development effect is the best. Therefore, based on the above two methods, in order to ensure the development effect, the optimal injection and production cycle is February injection and April production.

2.4.2 Stuffy well cycle optimization

According to the fluid flow velocity formula from fracture to matrix:

$$V=\frac{K_m}{\mu}\left(\frac{P_1-P_2}{L}-G\right) \quad (3)$$

Type in the: V—Mean seepage velocity, m/s; Km—Permeability of matrix, mD; μ—Fluid viscosity, mPa·s; P1—Fracture pressure, Pa; P2—The matrix stress，Pa；L—The distance between the fracture and the substrate，m；G—Formation initiation pressure，M Pa/m.

The time of fluid seepage from the fracture to the matrix rock is：

$$t=\frac{L}{V} \tag{4}$$

You can get it by combining the two equations：

$$t=\frac{L^2\mu}{K_m(P_1-P_2-GL)} \tag{5}$$

Combined with oilfield development experience, L is 8m, fluid viscosity is 1mPa•s, matrix permeability is 2.1md, P1 is 14.9mpa when fracturing, P2 is 10.21mpa when developing formation pressure before measures, G is 0.6mpa /m when starting pressure, and the theoretical soaking time is 33D. At the same time, according to the actual situation of the oil field, seven different stuffy well cycles are designed for numerical simulation to optimize the stuffy well cycle reasonably. According to the numerical simulation results, the stuffy well has the highest recovery degree, the lowest water content and the best development effect in 30 days. Therefore, by integrating the above two methods, the stuffy well period is optimized to be 1 month in order to ensure the development effect.

Table 5 Prediction results of development indicators at the end of 10 years for different injection and production cycles

Soak period /d	Recovery degree /%	The moisture content /%
0	30.15	73.24
15	30.36	72.77
30	31.28	71.58
45	30.25	72.88
60	30.95	73.15
75	29.98	75.36
90	29.68	73.99

3. Field test effect

According to the idea of "theoretical support, trial first and scale promotion", 24 Wells were promoted in the GLN area from 2018 to 2019, and the daily oil production per well increased by 1.8T, with an additional 156T in the cycle. From 2020 to 2021, it was gradually promoted to 60 injection and 36 production in GLN area, and achieved good results: First, the formation pressure was gradually recovered. The formation pressure increased from 9.9MPa to 10.09MPa, and the injection-production ratio increased from 0.9 to 1.8. The second is to increase the production of individual Wells. The oil per day per well increased by 1.5t, the average oil per round increased by 126T, and the cumulative oil increased by 9293T. The third is to reduce the invalid cycle. Oil change rate per thousand tons of water increased from 15T to 73T; Fourth, better economic benefits have been achieved. Without increasing the input, the efficiency is 23.06 million yuan, and good economic benefits have been achieved. The final recovery efficiency is estimated to increase by 3.58 percentage points.

4. Conclusion

(1) Asynchronous injection and production can make full use of the full imbibition effect between high and low permeability layers through the adjustment mode of no injection at the time of injection and no injection at the time of production, achieve the purpose of stabilizing the liquid and controlling the water of the horizontal well, achieve the role of improving the recovery efficiency, and explore a new treatment method for the horizontal well in the middle and high water cut stage.

(2) In the asynchronous injection and production stage, the injected water fully flows into cracks and matrix macropore throat, and the water driving force plays a dominant role; In the stuffy stage, the fluid velocity in the pore slows down, and the injected water imbibs into the pore throat, and the capillary force plays a leading role. In the stage of oil recovery, the remaining oil of imbibition displacement will be more favorable to be recovered due to the increase of production pressure difference.

(3) At the initial stage when the pore throat radius gradually decreases, the water driving force plays a dominant role, and the development effect of asynchronous injection and production is similar to that of synchronous injection and production. However, when the pore throat radius is less than 2.35μm, capillary force imbibition is enhanced and plays a leading role. The development effect of asynchronous injection and production is better than that of synchronous injection and production.

(4) The smaller the throat, the later the time for asynchronous injection and production, the best asynchronous injection and production of large pore throat (2.0-4.0μm) is 50%, the best asynchronous injection and production of medium pore throat (1.0-2.0μm) is 60%, and the best asynchronous injection and production of small throat (0.5-1.0μm) is 70%.

(5) The optimization of asynchronous injection and production parameters is injection in February, stuffy in January, and production in April. The development effect of asynchronous injection and production is better than that of synchronous injection and production, and the final recovery degree is expected to increase by 3.58 percentage points.

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