Research on Reasonable Vertical Well Injection Mode in Horizontal Well Area

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Abstract. Horizontal wells and vertical wells are used to jointly develop low permeability thin and poor oil layers, increasing the drainage area of horizontal wells to improve the initial production of single well, flexibly adopting different methods such as vertical well water injection and vertical well oil production to improve the degree of reserve control and production, and to realize the effective production of low permeability and difficult to recover reserves. However, due to the imperfect injection production relationship and insufficient formation energy supply in horizontal well area, the stable production period of horizontal well is short and the production decline is large, which affects the possibility of further enhancing oil recovery by joint development of horizontal well and vertical well. Combined with the characteristics of long horizontal section when drilling horizontal wells in a single oil layer plane and multiple oil layers when drilling conventional vertical wells vertically, the new concepts of connectivity ratio of both sides of horizontal section and connectivity coefficient of horizontal section length are proposed, and the corresponding relationship between injection and production and the degree of formation energy conservation in the combined development area of horizontal and vertical wells are systematically evaluated. Taking the horizontal well as the center, according to the position relationship between the horizontal well and the surrounding water injection wells (vertical wells), three kinds of injection production corresponding modes, namely symmetrical, triangular and quadrilateral, are innovatively defined. The numerical simulation method is applied to calculate the difference of formation pressure maintaining level and ultimate recovery factor of different injection production corresponding modes in Zhiping joint development well area under different reserves control degree, so as to optimize the mode of transferring vertical wells to injection, reasonably supplement formation energy, improve the formation pressure maintaining level, control the production decline rate of horizontal wells, and improve the recovery factor.

Keywords: Horizontal well · Vertical well to injection · Supplement formation energy · Different injection production corresponding ways · Enhanced oil recovery

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1 Preface

In recent years, the reserves quality of newly developed oil reservoirs in China is gradually getting worse. The conventional vertical well development is faced with the passive situation of low production and low economic benefit. Aiming at the outstanding characteristics of low permeability (below 10 mD), thin sand layer (below 2.5 m) and less oil layers (3–5 layers) in some oil reservoirs, the combined development mode of horizontal well and vertical well is innovatively applied and developed. According to the fault distribution and sand body development, a horizontal well is combined with 2–6 vertical wells for joint development. The horizontal well uses a long horizontal section to control 1–2 main oil layers, and all wells are production wells, so as to give full play to the advantage of large oil drainage area and improve the initial production of single well; the vertical well takes into account the main and non main oil layers, and flexibly deploys as injection wells and production wells. By injecting water into vertical wells and improving the corresponding relationship between injection and production with horizontal wells, the main reservoir can be developed efficiently, and the effective production of non main reservoir can also be considered. The joint development mode of horizontal well and vertical well has experienced three stages: experimental exploration, scale application and overall development. There are 453 horizontal wells in total. The number of wells accounts for only 2.1% of the total number of oil wells, but the annual oil production has reached 8.6% of the total production. The average single well production of horizontal wells is 3–5 times of that of vertical wells, achieving the goal of less wells and high production, and achieving good results.

2 Development Status of Horizontal Well Area

2.1 Current Development Status

The distributary channel and underwater distributary channel are mainly developed in the reservoir developed by horizontal and vertical wells. The sand body is scattered, the width of the channel is generally 200–300 m, and the average depth of the reservoir is 1750 m. The average number of oil layers drilled in horizontal wells is 2.2 layers, and the thickness of single layer is 2.6 m; the average number of oil layers drilled in vertical wells is 4.2 layers, and the thickness of single layer is 1.5 m. The average porosity is 16.8%, air permeability is 6.7 mD, oil saturation is 56.4%, and reserve abundance is 28.5 $\times$ 10^4 t/km^2. In the initial stage of horizontal wells, the daily fluid production is 10.4t, the daily oil production is 7.8t, and the water cut is 24.8%. In the initial stage of vertical wells in the same block, the daily fluid production is 1.9t, the daily oil production is 1.6t, and the water cut is 15.6%. The daily production level of horizontal wells is 4.9 times that of vertical wells. After five years of operation, the daily production of horizontal wells can still reach 2.7t (see Table 1), which is three times of that of vertical wells. Although the application of horizontal wells has achieved good development results, it still exposes the problems of rapid formation pressure drop and large production decline in the well area. It is necessary to study the reasonable formation energy supplement method to delay the production decline rate, so as to further improve the oil recovery.

Table 1. Comparison of production classification of horizontal wells after five years of production

Yield classification (t)	Number of horizontal wells (well)	Proportion(%)	Initial stage			Five years after putting into operation			Production decline range		Average single well	
			Nissan liquid (t)	Daily oil production (t)	Water cut in oil well (%)	Nissan liquid (t)	Daily oil production (t)	Water cut in oil well (%)	Total range (%)	Annual average(%)	Cumulative oil production (10^4t)	Cumulative water production (10^4t)
≤2	196	40.9	10.2	6.6	35.3	5.2	1.4	73.1	78.8	15.8	0.89	0.71
(2–5)	171	35.7	10.2	8.6	15.7	5.4	2.6	51.9	69.8	14.0	0.91	0.43
≥5	86	18.0	11.3	9.1	19.5	6.4	5.8	9.4	36.3	7.3	1.77	0.35
合计	453	100.0	10.4	7.8	24.8	5.5	2.7	51.2	65.7	13.1	1.06	0.54

2.2 Main Problems

According to the daily production level of horizontal wells after five years of production, it is divided into three levels for dynamic characteristics analysis: compared with the initial production situation, the three levels show the change characteristics of daily fluid decline, daily oil decline and water cut rise. The daily oil production decreased from 7.8t to 1.4t in the initial stage, with an average annual decline rate of 13.1%, much higher than the average annual decline rate of 8.8% in vertical wells. The daily fluid production of horizontal wells decreased from 10.4t at the initial stage to 5.5t (see Table 1), indicating that the reservoir is affected by poor reservoir physical properties and low permeability, with limited conductivity and no obvious effect of water injection.

Affected by the scattered development of sand body and relatively developed faults, the number of vertical wells around horizontal wells is not fixed, the distribution of connected vertical wells is irregular, the corresponding relationship between injection and production is not perfect, and the horizontal wells generally lack of injection wells, which leads to production without injection or under injection in horizontal well area, and the formation energy can not be replenished in time, resulting in poor oil production.

Table 2. Comparison table of formation pressure change in horizontal well area

Yield classification (t)	Number of piezometric wells in horizontal wells (well)	Number of vertical wells around (Well number)			Formation pressure in well block (MPa)		Keep the pressure level (%)
		Water injection well	Production well	Subtotal	Initial stage	Five years later	
≤2	39	86	148	234	15.33	9.96	65.0
(2–5)	24	60	74	134	15.81	11.07	70.0
≥5	10	29	7	36	14.86	11.65	78.4
合计	73	175	230	404	15.42	10.56	68.4

For 39 wells with daily oil production ≤2 t, the formation pressure drop is the largest. After five years of production, the pressure level is only 65.0% (see Table 2), and the daily fluid drop is the largest, reaching 78.8% (see Table 1). It is necessary to optimize the vertical well injection mode to improve the injection production well pattern in the horizontal well area, supplement the formation energy, and further develop the production potential of horizontal wells.

3 A New Method for Evaluating Injection Production Relationship in Horizontal Well Area

In the past, the concepts of water drive control degree and the connected thickness percentage of unidirectional, bidirectional and multidirectional oil and water wells were

generally used to describe the injection production relationship of vertical well development. The higher the degree of water drive control, the greater the percentage of multi-directional connected thickness, which indicates that the more water drive reserves in the well area, the more perfect the injection production relationship, and the better the development effect. However, these conventional concepts are used to describe the thickness correspondence of oil and water wells in multiple oil layers vertically, and cannot describe the length correspondence of oil and water wells in a single oil layer plane. In order to better describe the injection production perfection degree of the joint development area of horizontal well and vertical well, two new concepts, namely the water drive control degree of vertical well development and the percentage of connected thickness in different directions, are proposed by fully considering the separation characteristics of the long horizontal section from the well block in a single reservoir plane To evaluate the injection production perfection of horizontal well block.

3.1 Length Connectivity Coefficient of Horizontal Section

Referring to the concept of water drive control degree in the development of vertical wells, the sum of the lengths of the oil bearing sand sections connected between the horizontal section and the adjacent water injection wells and the percentage of the total length of the oil bearing sand sections in the horizontal section are defined as the length connection coefficient of the horizontal section (see Formula 1), which describes the water drive reserves control degree of the horizontal section in the well block.

$$R = \frac{\sum_{i=1}^{n} L_i}{L} \times 100\% \tag{1}$$

In the formula, R—Length connectivity coefficient of horizontal section, percentage;

Li—The length of the perforated sandstone section connecting the horizontal section and the adjacent water injection well, i = 1, 2, 3…, Unit of measurement: m;

L—Total shooting length of horizontal section, Unit of measurement: m.

Table 3. Parameter table for calculating the length connectivity coefficient of horizontal section in a horizontal well

Category		Reservoir number encountered during drilling in horizontal section						Length connectivity coefficient of horizontal section (%)
		P12	P13	P141	P142	P15	小计	
Horizontal section (m)	Shooting length	8	66	132	34	6	246	86.2
	Connected length	8	66	132	0	6	212	

For example, in a horizontal well, five sedimentary units are drilled in the horizontal section, and the total length of sandstone is 246 m. Among them, the length of Pu 142 layer is 34 m, and there is no well connection around. The length of sandstone connected in this horizontal section is 212 m, and the calculated horizontal section length connection coefficient is 86.2% (see Table 3). The water drive reserves in the well area are highly controlled.

3.2 Connection Ratio of Different Sides in Horizontal Section

In the development of vertical wells, the thickness percentages of unidirectional connectivity, bidirectional connectivity and multidirectional connectivity are usually used to reflect the water drive equilibrium in the well area. In the joint production area of horizontal wells and vertical wells, the length of horizontal section is usually more than 300m, which has a certain separation effect on the well area on the plane, and the oil and water wells on both sides of the horizontal section do not interfere with each other According to the water drive situation of the horizontal well, five connection modes are designed, including unilateral unidirectional connection, unilateral bidirectional connection, unilateral multidirectional connection, bilateral bidirectional connection and bilateral multidirectional connection (see Fig. 1).

Unilateral unidirectional connection of horizontal wells: water injection wells are distributed on the same side of the horizontal section (regardless of the location relationship of water injection wells on the same side), when there is only one water injection well, it is unilateral unidirectional connection; when there are two water injection wells, it is unilateral bidirectional connection; when there are more than three water injection wells, it is unilateral multidirectional connection.

Bilateral bidirectional connection of horizontal wells: the water injection wells are distributed on both sides of the horizontal section (regardless of the position relationship between the two sides of the water injection wells), when there is one water injection well on each side, it is bilateral bidirectional connection; when there are more than three water injection wells on both sides, it is bilateral multidirectional connection.

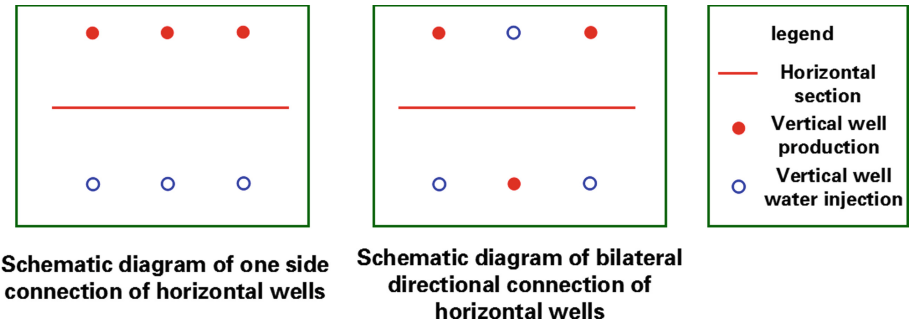

Fig. 1. Schematic diagram of directional connection at different sides of horizontal well

3.3 Evaluation Results of Injection Production Relationship in Horizontal Well Block

The horizontal wells are divided into three categories according to good, medium and differential development effects, and the injection production relationship is evaluated respectively (see Table 4). There are 185 horizontal wells with good development effect. The injection production relationship in the well block is relatively perfect, the bilateral connection ratio is 68.6%, and the length connection coefficient of the horizontal section reaches 90.5% (see Table 4), which indicates that the injection wells are basically connected in the perforated sandstone section, and the formation energy supplement is relatively sufficient. There are 106 horizontal wells with poor development effect. The unilateral connection ratio is 28.7%, and the length connection coefficient of horizontal section is only 72.0%. It shows that nearly one third of the horizontal section's shooting length is not connected with water injection wells, and the formation energy supply is seriously insufficient. It is necessary to transfer the surrounding vertical wells reasonably to improve the formation liquid supply capacity.

4 Establish Ideal Model by Numerical Simulation

In order to give full play to the advantages of horizontal wells in low permeability reservoir and extend the stable production time of single well, it is necessary to redefine the injection production pattern in horizontal well area and improve the corresponding relationship between injection and production in combination with the number and distribution of vertical wells in the well area.

4.1 Innovative Definition of Injection Production Mode in Zhiping Well Area

In order to further optimize the injection and production system of horizontal well area, three injection and production modes of horizontal wells are defined based on the location relationship and quantity of horizontal wells and surrounding injection wells.

Symmetrical injection production mode: there is one water injection well on each side of the horizontal section, and the water injection wells are symmetrically distributed around the horizontal section (see Fig. 2);

Triangle injection production mode: there are three water injection wells on both sides of the horizontal section, and the water injection wells are basically distributed in a triangle around the horizontal section (see Fig. 2);

Quadrilateral injection production mode: there are 4 injection wells on both sides of the horizontal section, and the location of injection wells is basically quadrilateral around the horizontal section (see Fig. 2).

Table 4. Evaluation results of injection production relationship in horizontal well area

Development effect	Number of wells (well)	Proportion (%)	Unilateral connectivity				Bilateral connectivity			Length connectivity coefficient of horizontal section (%)
			One-way(%)	Two-way(%)	Multidirectional(%)	Subtotal(%)	Two-way (%)	Multidirectional (%)	Subtotal(%)	
Good	185	40.8	14.4	6.7	0.8	21.9	25.6	43	68.6	90.5
Moderate	162	35.8	28	0.5	0	28.5	46.3	11.5	57.8	86.3
Poor	106	23.4	23.9	4.1	0.7	28.7	10.2	33.1	43.3	72.0
Total	453	100.0	21.2	4	0.7	25.9	29.3	30.3	59.6	85.5

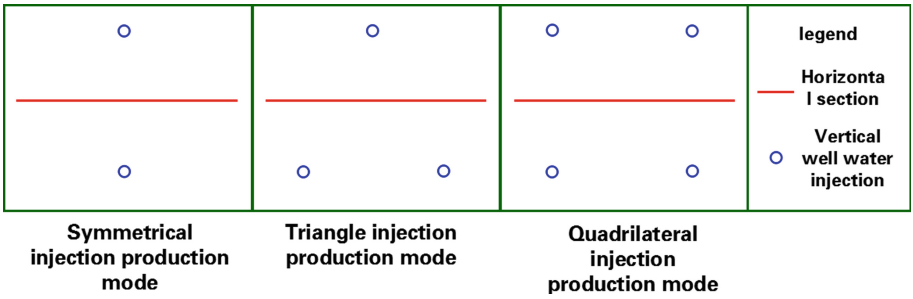

Fig. 2. Schematic diagram of three injection production corresponding modes in horizontal well area

4.2 Optimization of Injection Production Mode in Different Well Areas by Numerical Simulation

The ideal mathematical models of three injection production modes (symmetrical, triangular and quadrilateral) in three vertical horizontal joint development well areas are established. According to the respective pressure drop formulas of vertical wells and horizontal wells, the streamline diagram and pressure gradient field diagram of different injection production modes are drawn by using superposition principle and streamline tracing method (see Fig. 3).

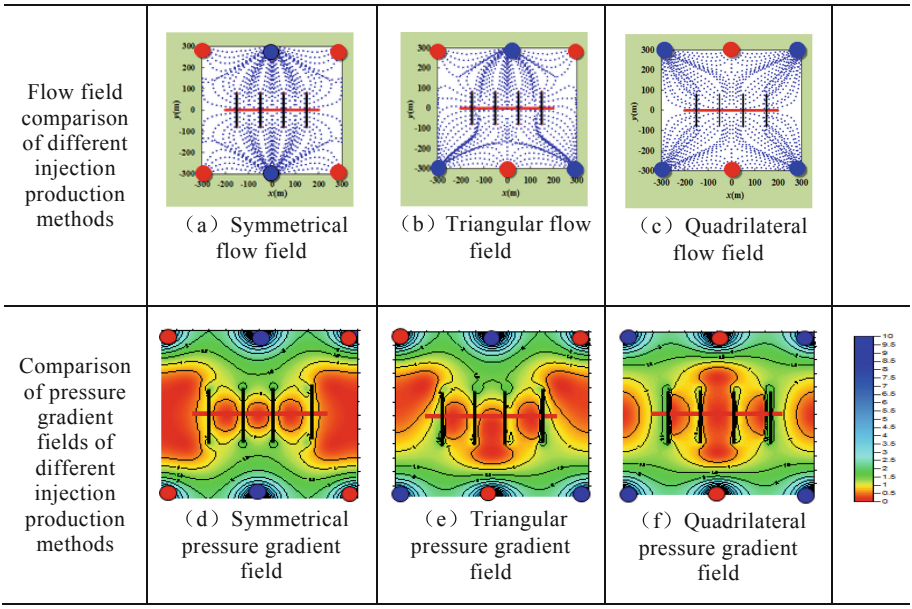

Fig. 3. Flow field and pressure gradient field of different injection production modes in horizontal well area

Combined with the reserve ratio of different oil layers in different well areas, the final recovery differences of different injection production methods are quantified by numerical simulation (see Table 5), and the standard chart is established.

The triangle injection production method is the best when the reserve ratio of horizontal well target layer is less than 70%; the quadrilateral injection production method is the best when the reserve ratio of horizontal well target layer is more than 70%; the recovery rate of symmetric injection production method is always low.

It is suggested that when the theoretical research results of injection production system adjustment are used to guide the field application, the optimization and adjustment of injection production system should be carried out flexibly in combination with the actual vertical well type, number and well point position.

Table 5. Recovery calculation results of different injection production methods in horizontal well area

Reserves proportion of target layer in horizontal well (%)		60	65	70	75	80	85	90	95	100
Recovery ratio (%)	Symmetric	29.92	30.08	30.24	30.4	30.56	30.72	30.88	31.04	31.2
	Triangle	30.61	30.83	31.05	31.26	31.48	31.7	31.92	32.13	32.35
	Quadrilateral	30.26	30.78	31.3	31.82	32.35	32.87	33.39	33.91	34.43

5 Application Examples in Guiding Oil Field

In order to match the geological characteristics such as fault strike and sand body development scale, the actual injection production mode in horizontal well area is more complex, mostly in the form of asymmetric, oblique triangle and irregular quadrilateral. Therefore, the adjustment principle of injection production system in horizontal well area is to improve the injection production from one side to both sides, and improve the injection production mode from asymmetric and symmetric injection production to triangle and quadrilateral, so as to form a relatively stable injection production mode Perfect corresponding relationship between injection and production, give full play to the production potential of target layer and non target layer of horizontal well, and facilitate the later adjustment and tapping potential.

5.1 Example of Single Well Adjustment

The water drive direction is increased by oil well injection. For example, there are three water injection wells around Zhao60-Ping54 well block, forming a triangle injection production mode. In order to improve the injection production relationship, the injection production mode of Zhao58-55 well block around Zhao60-Ping54 well block is quadrilateral. The formation pressure in the well block increased by 8.2%, and the daily oil production of this well increases by 1.1t, which shows obvious adjustment effect.

Table 6. Adjustment of injection production system in Zhiping joint development well area

Number of horizontal wells (well)	Before transfer					After transfer				
	Injection production mode	Water injection vertical well (well)	Vertical injection well (well)	Unilateral unidirectional connectivity ratio (%)	Daily production of single horizontal well(t)	Injection production mode	Water injection vertical well (well)	Unilateral unidirectional connectivity ratio (%)	Daily production of single well affected by horizontal well (t)	Added value of daily oil production (t)
4	Irregular	2	8	86.2	1.2	Irregular	10	23.4	3.6	2.4
3		4	6	75.2	1.8	Symmetric	10	0	4.2	2.4
5		10	5	30.2	1.9	Triangle	15	0	3.1	1.2
4		6	6	35.5	1.8	Quadrilateral	12	0	3.5	1.7
6	Symmetric	12	12	0	1.9	Quadrilateral	24	0	2.8	0.9
22	Total	34	37	45.4	1.8	–	71	4.6	3.2	1.4

5.2 Overall Adjustment Effect

Under the guidance of the new injection production system adjustment method in Zhiping joint development well area, 37 vertical wells have been reinjected in 9 blocks. The injection production mode in the original well area has been improved, the proportion of unilateral unidirectional connection has decreased from 45.4% to 4.6%, and the formation pressure maintenance level has increased from 65% to 72.4%. There are 22 horizontal wells in the well area, and the average daily oil production of single horizontal well has increased from 1.8t before reinjection to 3.5t after effect 2t, increased by 1.4t (see Table 6).

6 Conclusion

The first is the joint development of horizontal wells and vertical wells. The injection production system is quite different from that of conventional vertical wells. The two new concepts, the length connectivity coefficient of horizontal section and the connectivity ratio of different sides of horizontal section, can properly reflect the corresponding relationship between injection and production in horizontal well area, and can be used to describe the injection production perfection degree of horizontal wells;

The second is the innovative definition of symmetrical, triangular and quadrilateral injection production mode in horizontal well area, which is in line with the current situation of injection production well pattern in Zhiping joint development well area, and can be applied to other reservoirs with medium and high permeability, such as horizontal well combined with vertical well joint development;

The third is the standard chart of the optimal injection production mode corresponding to different reserves ratio obtained by numerical simulation, which can guide the adjustment practice on site with high reliability and effectively improve the daily oil production level of single horizontal well;

Fourth, larger length connectivity coefficient of horizontal section and higher bilateral multi-directional connectivity ratio of horizontal section are conducive to establishing a more perfect corresponding relationship between injection and production in horizontal well area, better improving formation pressure maintenance level, controlling production decline rate of horizontal well and improving ultimate recovery.

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