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INNOVATIVE TECHNOLOGIES OF OIL AND GAS

FEASIBILITY ANALYSIS OF WATER INJECTION DEVELOPMENT BASED ON GEOLOGICAL RESERVOIR CHARACTERISTICS

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The characteristics of geological reservoirs are an important means to evaluate the feasibility of water injection development. The differences in reservoir characteristics in different regions make it difficult to scale up the promotion of water injection development parameters. A more effective way is to establish efficient water injection development methods and strategies suitable for the region. Therefore, based on the geological characteristics of the Wucangbao Chang 6 and Chang 9 oil reservoirs, the feasibility of water injection development in Wucangbao reservoir is analyzed from several aspects such as interstitial material content, reservoir hydrophilicity, and stress sensitivity. The water injection parameters of Wucangbao Chang 6 and Chang 9 single wells are calculated using methods such as apparent flow rate method, permeability and single well productivity regression method, and stratigraphic series curve regression method, respectively. The water injection parameters are obtained based on the single well production. The results show that the Wucangbao Chang 6 and Chang 9 reservoirs have good water injection feasibility and prospects in terms of sandstone cement, reservoir fluid properties, wettability, and water flooding efficiency; And the production of single well Chang 6 is 1.5-4.0 t/d, while the production of single well Chang 9 is 2.0-4.5 t/d; According to the injection production balance, the initial single well injection volume of the Wucangbao Chang 6 layer is 10 m^3, and the initial single well injection volume of the Chang 9 layer is 20 m^3, in order to maximize the recovery rate of the reservoir during the dry or low water cut period.

Keywords: water injection development, low permeability oil fields, single well production; recovery ratio.

1. Introduction

In recent years, the rapid development of the global economy has led to a growing demand for oil and gas resources [1-3]. Due to the widespread distribution of tight oil and gas around the world, its resource potential and exploration value have attracted widespread attention worldwide. Oil and gas exploration and development are taking great strides from conventional oil and gas fields to unconventional oil and gas fields [4-7]. The Wucangbao Reservoir is a typical tight sandstone reservoir with low porosity, low permeability, and complex pore structure. It belongs to a low porosity and low permeability reservoir and has significant

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characteristics of tight reservoir development. Its production is relatively high in the early stages of development, but it decreases rapidly, so the efficient and sustainable development of tight oil reservoirs has become a focus and difficulty in current research.

At present, horizontal well technology combined with segmented multi-stage fracturing technology is widely used worldwide to achieve efficient development of tight oil reservoirs, and to improve oil recovery by increasing the volume of modified reservoirs [8-12]. However, the expansion of fractures in tight oil reservoirs is influenced by their own geological conditions, and the situation varies greatly. Some reservoirs have strong heterogeneity, and there is a positive and negative rhythm in the vertical direction. During the development process, the influence of engineering factors superimposes two-phase or even three-phase seepage, making the seepage mechanism and development law of tight oil reservoirs very complex, and the dominant seepage channels are unclear [12-16]. At present, its development direction is shifting towards water injection. However, the successful water injection development of such reservoirs is also challenging due to their strong heterogeneity, well-developed barriers, and strong vertical heterogeneity [17-20]. The development plan for low-permeability reservoirs is still in the exploration stage and lacks mature experience. It is necessary to establish the optimal development plan for this type of reservoir as soon as possible.

This article conducts in-depth research on multiple developed low-permeability reservoirs in the northwest region, clarifies the common problems in water injection development of different reservoirs, and proposes efficient water injection development methods and strategies for low-permeability reservoirs.

2. Regional geological background

The Wucangbao block is located in the northern part of Wuqi Oilfield, adjacent to the Xin'an Border Area of Dingbian Oil Production Plant to the north, and surrounded by the Changqing Oilfield operation area on the east and west sides, with a total area of about 357 km^2 and an actual controlled area of about 252 km^2. 32 exploration wells have been drilled, with an average drilling depth of 240 3m. The total area of the research area is approximately 220 km^2. The combined oil bearing area of Yan'an Formation (Yan9~Yan10 Oil Formation) and Yanchang Formation (Chang4+5~Chang10 Oil Formation) is 160 km^2, with a calculated oil geological reserve of $10856.38 \cdot 10^4$ t and a dissolved gas geological reserve of $52.18 \cdot 10^8$ m^2.

The main oil bearing series in the oil area are Yan'an Formation Yan9, Yan10, Yanchang Group 4+5, Chang6, Chang8 and 9 oil layers. Among them, Yan'an Formation Yan9 and Yan10 are only sporadically distributed, and Chang6 and Chang9 oil layers are the main oil bearing layers in the study area. Based on the analysis of surface crude oil properties from 7 wells including Wu 1 and Wu 13, as well as high-pressure crude oil properties from Wu 3, Wu 5, and Wu 9 wells, the average surface crude oil density of Yan 10, Chang 4+5, Chang 6, Chang 8, Chang 9, and Chang 10 reservoirs is 0.835 g/cm^3, viscosity is 5.22 mPa·s, gum asphalt is 4.89%, solidification point is 21.6°, sulfur content is 0.02%, and wax content is 10.1%. The average formation crude oil density is 0.798 g/cm^3, viscosity is 6.50 mPa·s, volume coefficient is 1.122, and the original gas oil ratio is 36.47 m^3/t. The chloride ion content in the formation water is 23179.6 mg/L, and the total mineralization degree is 35209.8 mg/L; Belongs to the $CaCl_2$ water type.

3. Reservoir characteristics

Chang 6 oil group. Chang6 oil reservoir with a depth of 1985m and a permeability of $0.54 \cdot 10^{-3}$ μm^2, porosity of 8.7%, original formation pressure of 14.66 MPa, saturation pressure of 2.48 MPa, pressure coefficient of 0.80, formation temperature of 65.64°C, pressure gradient of 0.738 MPa/100 m, and geothermal gradient of 2.09°C/100 m. It belongs to a low-pressure oil reservoir and a normal formation temperature system. As the main oil bearing layer in the Wucangbao block, the reservoir has poor physical properties and severe heterogeneity within and between layers. Overall, it can be evaluated as an heterogeneous layer, belonging to an ultra-low permeability, low porosity, and structurally lithologic oil reservoir. According to the sensitivity analysis data of the reservoir, the Chang 6 oil formation is a weak salt sensitive, medium weak water sensitive, and weak velocity sensitive reservoir.

All 65 wells in the work area have encountered oil layers during drilling, with a total effective thickness of 1762.9 m. Although oil layers are distributed in each well area, on the plane, the distribution of oil layers is mainly influenced by lithological factors, followed by structural control. That is, in the same part of the structure, the thickness of oil layers varies greatly, and even there is a phenomenon of thin oil layers in high parts and thin oil layers in bottom parts. For example, in the higher part of the structure, the effective thickness is 10-20 m in the Wu 7-Wu 1 well area; The Wu 13~Wu 33 well area, which is located in the lower part of the structure, has an effective thickness of 20-84 m. The effective thickness of the single well interpretation of this oil formation is 4.6-83.8 m, with an average of 27.2 m per well.

The planar distribution characteristics of the oil layers in each sub layer of the oil formation are also mainly influenced by lithological factors, followed by structural conditions.

Chang 9 oil group. Chang9 oil reservoir with a depth of 2250 m and a permeability of $0.99 \cdot 10^{-3}$ μm^2, porosity of 9.7%, original formation pressure of 18.10 MPa, saturation pressure of 9.391MPa, pressure coefficient of 0.76, formation temperature of 72.80°C, pressure gradient of 0.804 MPa/100 m, and geothermal gradient of 3.23°C/100 m. It belongs to a low-pressure oil reservoir and a normal formation temperature system. The reservoir characteristics are basically similar to those of the Chang 6 oil formation, and the overall evaluation can be classified as an heterogeneous layer, belonging to an ultra-low permeability, low porosity, and structurally lithologic oil reservoir. In addition, according to the sensitivity analysis data of the reservoir, the Chang 9 reservoir is classified as a weak salt sensitive, weak water sensitive, no to weak velocity sensitive, moderately strong acid sensitive, and moderately weak alkali sensitive reservoir.

There are 52 wells in the work area that have encountered oil layers during drilling in this oil formation, with a total effective thickness of 764 m explained. On the plane, the distribution of oil layers is controlled by dual factors such as lithology and structure. The oil layers are mainly distributed in a sheet-like pattern in the Wu 8~Wu 17~Wu 31 well areas, followed by sporadic distribution in the Wu 3 and Wu 35 well areas. The effective thickness of a single well is 1.4-38.0 m, with an average of 14.7 m per well.

This oil formation has a total of 6 sub layers, and the distribution of its oil layers is also influenced by dual factors such as lithology and structure.

4. Analysis of "Dessert Zones" based on reservoir characteristics

The Chang4+5 and Chang6 oil reservoirs in the southern Wu 420 well area have submitted a total of 91.028 million tons of proven reserves, with a proven oil bearing area of 101.86 km^2. By the end of 2008, 30 exploration wells and 3 trial production wells had been completed in the northern extended oil area; In 2009, 8 exploration wells were deployed, with 2 completed and 1 currently being drilled. The average completed drilling depth is 2403 m, and the length of the drilling layer is 10. The research results indicate that the Chang-9 reservoir has a large scale and exploration potential.

As of the end of August 2009, a total of 56 wells have been tested in Wucangbao, including 9 wells in Yan'an Formation, 17 wells in Yanchang Team 6 (19 layers), 8 wells in Chang8 (10 layers), and 24 wells in Chang9. Yan 9 and Yan 6, Chang 8, and Chang 9 of the Yan'an Formation in the entire region all obtained industrial oil flow during oil testing. Among them, Yan 9 has 5 wells that obtained industrial oil flow, but the distribution is scattered and the effective thickness is small. Chang 6 has 3 wells that obtained industrial oil flow, Chang 8 has 2 wells that obtained industrial oil flow, and Chang 9 has 16 wells that obtained industrial oil flow. It can be seen that Chang 9 has high potential in Wucangbao.

From the oil testing situation, there are 3 wells in Yan 9 that have been tested with full water, and another 3 wells have a water content exceeding 70%. The average liquid production of 9 test wells is 13.10 m^3/d, with an average oil production of 5.73 m^3/d and an average water content of 60.44%; There are 3 wells in Chang6 that have undergone oil and water testing, and 8 wells have a water content exceeding 60%. The average liquid production of 19 test wells is 2.29 m^3/d, with an average oil production of 1.28 m^3/d and an average water content of 63.89%; Three wells were tested for oil and water in Chang8, with an average liquid production of 3.24 m^3/d and an average oil production of 1.05 m^3/d, with an average water content of 52.9%; Only one well, Wu 1, was tested for full water in Chang9, while the water content in the other wells was generally below 10%. The average liquid production and oil production of 24 test wells (layers) were 4.37 m^3/d, 4.14 m^3/d, and 9.82%, respectively, fully demonstrating that Chang9 has good development prospects.

During the initial trial production of Chang9, there were 3 wells with an average daily liquid production of 6.97m3/d and an average daily oil production of 5.27 m^3/d, with a comprehensive water content of 23.67%. The production capacity of 3 wells was around 5 m^3/d. As of the end of August, there were 3 wells in production with an average daily liquid production of 1.7 m^3/d and an average daily oil production of 1.7 m^3/d, with a comprehensive water content of 2%. One well had a production capacity of around 3 m^3/d, indicating that the Chang9 oil reservoir has a high production capacity.

In addition, from the trial production curve of the Chang9 oil group in the demonstration area (initially believed to be the Chang8 oil group and reinterpreted as the Chang9 oil group), the average daily oil production in the initial stage was 6 t/d without water content. After half a year of trial production, the average daily oil production gradually decreased to 3 t/d, indicating that the production decreased rapidly due to insufficient liquid supply, but the initial production capacity was high and without water content, indicating that the Chang9 layer has good production potential.

5. Feasibility of water injection development based on reservoir characteristics

Characteristics of sandstone filling materials. The filler material includes impurities and binders, with an average total content of 24.7%. Among them, the impurities are composed of chlorite, illite, mud iron, etc., with an average content of 6.9%; The main components of cementitious materials are calcite, dolomite, quartz, and feldspar, with common siderite, pyrite, and asphaltene. The content of cementitious materials is 17.8%. Asphalt often fills microcracks and is heavily contaminated with sheet-like minerals such as illite, chlorite, mica, etc., as well as rock debris such as cryptocrystalline rocks. The low content of sensitive minerals in the filling material is beneficial for water injection development.

Hydrophilicity. According to the displacement experiment of two core blocks in Block 9, it is shown that this layer is a weakly hydrophilic reservoir, which is conducive to water injection (**Table 1**).

Weak water sensitivity and no to weak speed sensitivity. According to the sensitivity analysis of the block reservoir, the results show that the Chang 9 reservoir is weakly salt sensitive, weakly water sensitive, no to weak velocity sensitive, moderately strong acid sensitive, and moderately weak alkali sensitive, which is conducive to water injection.

Stress sensitivity. According to the results of the Wucangbao Chang9 rock overlying pressure pore permeability test (**Table 2**), it is shown that the Wucangbao Chang9 layer has strong stress sensitivity, and the formation permeability will greatly decrease with the increase of overlying pressure. The overlying pressure increases from 5 to 20, and the average permeability decreases by 70.3%. However, when the pressure drops to the original level, the permeability only recovers to 50% of the original level. Therefore, it is necessary to maintain a high formation pressure during development to prevent the permeability from decreasing and becoming irreversible. The experimental results also indicate the necessity of advanced water injection.

Properties of crude oil. Compared with other low-permeability oil fields in the Ordos Basin, the geological and surface fluid properties of the Wucangbao oil reservoir are basically equivalent to those of the Chang 6 oil field, while the Chang 9 oil field has slightly better properties, which is beneficial for water injection development.

Water driven oil efficiency. From the relative permeability curve of the oil-water phase of the core sample, it can be seen that the oil-water in Wuqi has two characteristics of seepage. As the water saturation increases, the relative permeability of the oil phase rapidly decreases, while the relative permeability of the water phase slowly increases, exhibiting typical characteristics of low permeability reservoir permeability curves. The oil-water ratio has a low permeability point. From the oil-water relative permeability curve, as the water saturation increases, the relative permeability of the oil phase decreases rapidly, while the

Table 1. Wettability analysis of Wucangb

Well No.	Depth/m	Air Permeability ($10^{-3}um^2$)	Porosity /%	Moisture index	Oil moisture index	Wettability
W34	2117.76	0.024	6.76	0.37	0.54	Slightly water-wet
W34	2119.41	0.154	7.62	0.34	0.64	Slightly water-wet

Table 2. Results of overpressure porosity and permeability test in Wucangbao oilfield

Core No.	Experimental result						
W34 7 4/8-4	Overburden pressure (MPa)	5	8	11	14	17	20
	Permeability (mD)	0.024	0.017	0.012	0.009	0.007	0.006
	Porosity (%)	6.76	6.73	6.70	6.69	6.67	6.67
W34 9 4/16-8	Overburden pressure (MPa)	5	8	11	14	17	20
	Permeability (mD)	0.154	0.112	0.087	0.069	0.060	0.053
	Porosity (%)	7.62	7.57	7.55	7.51	7.50	7.59

Table 3. Comprehensive data of water drive oil

Well No.	Geologic horizon	Oil displacement efficiency during waterless period (%)	Water cut 95%		Water cut 98%		Final	
			Oil displacement efficiency (%)	Injection multiple Pv	Oil displacement efficiency (%)	Injection multiple Pv	Oil displacement efficiency (%)	Injection multiple Pv
Qi 26-30	$C6_1$	38.0	52.0	1.04	57.9	2.85	65.9	10.53
	$C6_1$	41.5	50.9	0.88	56.4	2.45	64.7	11.67
	$C6_1$	41.0	50.2	0.86	53.8	1.91	58.6	7.38
	$C6_1$	42.3	53.0	0.95	56.7	2.1	64.2	10.83
Qi 24-34	$C6_1$	36.4	48.7	1.29	53.6	2.93	65.7	19.57
	$C6_1$	32.1	48.8	1.19	52.8	2.78	64.7	26.89
Average		38.6	50.6	1.0	55.2	2.5	64.0	14.5
Wu421	$C4+5_2$	34.05	44.05	1.1	46.06	1.84	48.54	9.92
	$C4+5_2$	31.76	43.22	0.95	45.63	1.78	51.36	11.15
	$C4+5_2$	37.16	46.15	1.2	48.63	2.14	49.79	11.78
	$C4+5_2$	39.59	48.97	0.93	51.16	1.61	52.2	8.72
Average		35.6	45.6	1.0	47.9	1.8	50.5	10.4

relative permeability of the water phase increases slowly. The relative permeability of the water phase is small when residual oil is present (**Table 3**).

The indoor water flooding test shows that the oil displacement efficiency of the Wucangbao Gaochang 6 reservoir during the anhydrous period is 35.6%, and the oil displacement efficiency is 45.6% when the water content is 95%; When the water content is 98%, the oil displacement efficiency is 47.9%; The final oil displacement efficiency is 50.5%. It can be seen that adopting water injection development can improve the oil recovery rate of the reservoir in this area.

The Wucangbao Chang 6 and Chang 9 reservoirs have good water injection feasibility and prospects in terms of sandstone cement, reservoir fluid properties, wettability, and water flooding efficiency. In addition, compared with the statistical results of water flooding experiments in other oil fields in the Ordos Basin, combined with nearly 20 years of water injection development in the Wangyao old area of Ansai Oilfield, good results have been achieved. The natural decline rate is controlled within 7%, and the predicted final recovery rate can reach 25.1%. It can be predicted that the water injection development effect in Wucangbao is good .

Compatibility between injected water and formation water. According to the analysis data of the produced water from the Wu 28 and 49-31 oil wells, their iron content and sulfate reducing bacteria did not meet the minimum standard water quality (C3), while saprophytic bacteria and iron bacteria reached the C1 standard; The water sample from the water source well meets the A1 standard for iron, TGB, and iron bacteria, while the SRB meets the A3 standard.

The water produced by the Wu 28 oil well and the 49-31 oil well are both calcium chloride water type. The total mineralization degree of the water sample from the source well is 3909 mg/L, which is sodium sulfate water type. The water produced by the oil well and the water from the source well are different types, and there is a possibility of incompatibility after mixing the two types of water.

The observation results of the appearance of the mixed water after heating are shown in **Table 4**. From the experimental results, it can be seen that the produced water from the oil well is mixed with the water from the source well, causing turbidity and sedimentation in the mixed water. It is preliminarily believed that the produced water from the oil well is not compatible with the water from the source well. Among them, 1# is a water sample produced by the Wu 28 oil well; 2# is a water sample produced by oil wells 49-31; 3# is a water sample from the water source well.

From the changes in turbidity after mixed heating, it can be seen that the turbidity of the two types of water has increased compared to before mixing, and mixed heating has a promoting effect on the increase in turbidity. Mixing two types of water results in turbidity and precipitation, and the two types of water are not compatible.

By analyzing the changes in the content of calcium, magnesium, and sulfate ions in mixed water before and after heating, it can be concluded that after mixed heating of 1# and 3#, the scaling ions calcium, magnesium, and sulfate ions in the water decrease

Table 4. Turbidity of Wucangbao produced water and source well water samples before and after heating

Turbidity	Mixing ratio				
	1:0	3:1	1:1	1:3	0:1
1#:3#					
Before heating	2.51	3.25	5.38	2.91	0.31
After heating	4.62	4.7	6.32	4.94	0.49
1#:3#					
Before heating	8.92	6.17	9.79	3.76	0.31
After heating	22.56	20.17	19.79	18.76	0.49

compared to before mixed heating. This indicates that after mixed heating, the scaling ions combine with each other to form precipitates, reflecting the incompatibility between the produced water of Wu 28 oil well and the water sample of the water source well; After mixed heating of 2 # and 3#, the scaling ions calcium, magnesium, and sulfate ions in the water decreased compared to before mixed heating, indicating that after mixed heating, the scaling ions combined with each other to form precipitates, reflecting the incompatibility between the produced water from the 49-31 oil well and the water from the source well.

In addition, according to the analysis of other blocks in the Ordos Basin, it can be concluded that the mixed scaling amount between the Luohe Formation water and the Chang10 Formation water under ground conditions is greater than 100mg/L, and the compatibility is not good. When using the Luohe Formation water as the water source for injection, it is necessary to optimize the addition of anti $CaCO_3$ scale inhibitors and surfactants.

The compatibility analysis of the water from the Chang 6 formation and the Chang 10 formation shows that the mixed scaling amount of the Chang 6 formation water and the Chang 10 formation water under ground conditions is less than 100mg/L, indicating good compatibility. Therefore, reinjection of the Chang 6 formation water is feasible, which not only ensures the water source for injection, but also benefits environmental protection and cost reduction.

6. Optimization of water injection parameters

6.1. Single well production

Visual flow method. According to the actual data statistics of 19 development blocks in the Jurassic system of the Ordos Basin and the Triassic oil reservoir in the Ansai Oilfield, the relationship between the oil recovery index and fluidity is as follows:

$$LgI_{oh} = 0.473\lg\left(\frac{K}{\mu_o}\right) - 1.077,$$

where, I_{oh} is oil recovery index per meter (t/(d·m·MPa)); K is Median probability of air permeability ($\times 10^{-3}\mu m^2$); μ_o is formation crude oil viscosity (mPa·s).

The viscosity of crude oil in the Wucangbao Chang 6 formation is 2.39mPa·s, with an average permeability of $0.54\cdot 10^{-3}$ μm^2, according to the above formula, the oil recovery index of Chang 6 is 0.042 t/(d·m MPa). Based on the reasonable production pressure difference (11.664 MPa) and effective thickness (13.6 m) of Chang 6 mentioned above, the single well production of Chang 6 layer is calculated to be 6.66 t/d; The viscosity of crude oil in the Chang 9 formation is 1.93mPa·s, and the average permeability is $0.99\cdot 10^{-3}\mu m^2$ .According to the above formula, the oil recovery index of Chang 9 is 0.061 t/(d· m·MPa). Based on the reasonable production pressure difference (9.701 MPa) and effective thickness (9.3 m) of Chang 9 mentioned above, the single well production of Chang 9 layer is calculated to be 5.5 t/d.

Regression method between permeability and single well productivity. Due to the fact that the permeability of Wucangbao is comparable to that of Longdong Chang3 and Ansai Chang6, the relationship curve between the air permeability of Longdong Chang3 and Ansai Chang6 exploration wells and the initial single well production capacity of the oil well is regressed to obtain the single well production capacity.

$$Q_o = 1.7116\ln x + 4.1686,\ Q_o = 2.1251x^{0.6261},$$

where, Q_o is initial production capacity, t/d; x is formation permeability, $10^{-3}\mu m^2$.

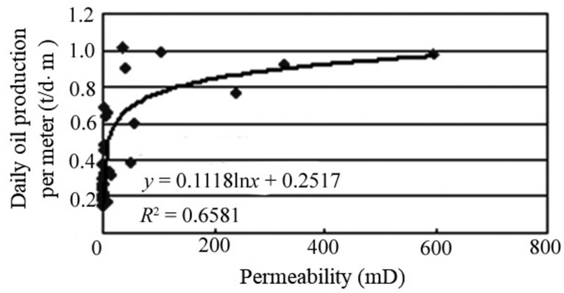

Fig. 1. Relationship curve between permeability and daily oil production per meter

According to the above formula, the single well production capacity of the Chang 6 oil layer can reach 1.46-3.12t/d. The single well production capacity of Chang9 oil reservoir can reach 2.11-4.15t/d.

Permeability statistics method. Collect the average permeability, effective thickness, and daily oil production data of 31 blocks in Changqing low-permeability oilfield, and fit the established relationship curve between permeability and daily oil production (**Figure 1**). The permeability of Wucangbao Chang 6 reservoir is $0.54 \cdot 10^{-3} \mu m^2$ .Based on the relationship between permeability and daily oil production per meter in the graph, it is determined that the daily oil production per meter in the Chang6 reservoir in this area is 0.183 t/d.m, and the effective thickness of the reservoir is 13.6 m. Based on this, the average daily oil production of the Wucangbao Chang6 reservoir is 2.49 t/d; The permeability of Chang 9 reservoir is $0.99 \cdot 10^{-3} \mu m^2$ .Based on the relationship between permeability and daily oil production per meter in the graph, it is determined that the daily oil production per meter in the Chang9 reservoir in this area is 0.251 t/d.m, and the effective thickness of the reservoir is 9.3 m. Based on this, the average daily oil production of the Wucangbao Chang9 reservoir is 2.33 t/d.

Regression method of stratigraphic coefficient curve. When the fluid properties and pressure systems are similar to similar reservoirs, an empirical formula is regressed based on the relationship curve between the formation coefficient of the developed area and the initial single well productivity (**Figure 2**):

$$Q_o = 0.1367x + 1.0388.$$

According to the above formula, the single well production capacity of the Chang 6 oil layer can reach 2.05-3.98 t/d; The single well production capacity of Chang9 oil reservoir can reach 2.30-4.16 t/d.

Calculation method for oil testing yield reduction. According to the statistical relationship between the trial production and oil production of developed blocks in the Ordos Basin, the production of oil wells is about 1/3 to 1/4 of the trial production.

At present, Wucangbao has completed 56 well tests, including 12 oil tests in the long 6 layers, with an average oil production rate of 2.29 m^3/d, and a calculated average oil recovery index of 0.63 m^3/(d·m) per meter; 24 oil tests were conducted on the 9

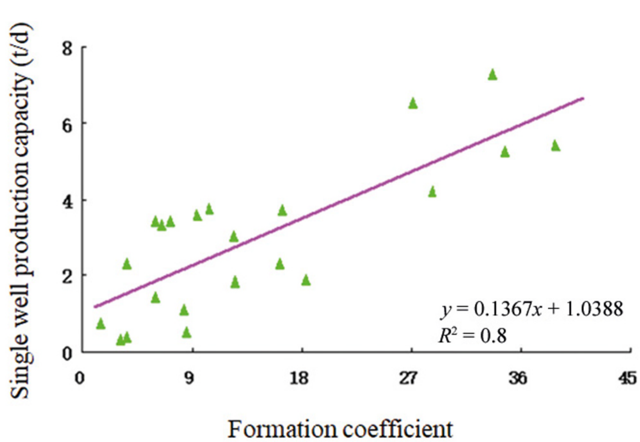

Fig. 2. Relationship curve between permeability and daily oil production per meter

layers, with an average oil production of 4.9m3/d and an average oil recovery index of 1.13 $m^3/(d·m)$ per meter. According to the above standards, the single well liquid production of the Chang6 and Chang9 oil layers is 2.1-2.9 m^3/d and 2.63-3.5 m^3/d, respectively. Considering that the initial water content of the Chang6 and Chang9 oil layers is 10% and 5%, the single well production capacity of the Chang6 and Chang9 oil layers is 1.9-2.6t/d and 2.5-3.33 t/d, respectively.

Trial procurement statistical method. At present, the exploration and development wells of Wucangbao Chang 6 and Chang 9 have an average daily liquid production of 4.05 m^3/d, daily oil production of 1.94 m^3/d, water content of 48.8%, and an average oil recovery index of 0.36 $m^3/(d.m)$ in the early stage of production of the Chang 6 oil reservoir group; In the initial stage of the Chang 9 oil reservoir group, the average daily liquid production was 3.13 m^3/d, the daily oil production was 3.1 m^3/d, the water content was 1.89%, and the average oil recovery index per meter was 0.52 $m^3/(d·m)$. Considering that the initial water content of the Chang 6 and Chang 9 reservoirs is 10% and 5%, respectively, the single well production capacity of the Chang 6 and Chang 9 reservoirs is 4.4 t/d and 4.6 t/d, respectively.

Taking into account the various options mentioned above, the production capacity of Chang6 single well is 1.5-4.0 t/d, and that of Chang9 single well is 2.0-4.5 t/d.

6.2. Selection of water injection parameters

According to the principle of injection production balance, the daily injection rate formula for injection wells during the production period is:

$$Q_w = \frac{1000MN_oQ_o}{N_w\rho_o}\left(\frac{B_o}{B_w} + \frac{S_w}{1-S_w}\right),$$

where N_o is number of oil production wells; N_w is number of water injection wells; Q_o is daily oil production of oil wells, t/d; Q_w is daily injection volume of water injection wells, m^3/d; B_o is volume coefficient of crude oil; B_w is volume coefficient of water; ρ_o is the density of surface crude oil, kg/m^3; ρ_w is water density, kg/m^3; S_w is the initial water content of the oil well, decimal; M is injection sampling ratio.

According to the development experience of the Triassic ultra-low permeability reservoir in Changqing Oilfield, when the injection production ratio is 1.0-1.2, it can ensure sufficient production capacity and reasonable extraction speed. The surface crude oil density of Wucangbao Reservoir is $0.835·10^3$ kg/m^3, the density of water is 1000 kg/m^3, and the volume coefficient of water is 1. The volume coefficients of crude oil in the Chang 6 and Chang 9 oil layers are 1.1175 and 1.2153, respectively.

According to the formula for daily injection volume of water injection wells above, when the production capacity of Wucangbao Chang 6 single well is 4 t/d, the water content is 10%, and the injection production ratio is 1.0, the injection volume of a single water injection well is 17.66 m^3; When the single well production is 1.5 t/d, the water content is 10%, and the injection production ratio is 1.0, the single well injection volume of the injection well is 6.62 m^3; When the production capacity of Wucangbao Chang 9 single well is 4.5 t/d, the water content is 5%, and the injection production ratio is 1, the single well injection volume of the injection well is 20.5 m^3; When the single well production is 2 t/d, the water content is 5%, and the injection production ratio is 1, the single well injection volume of the injection well is 9.11 m^3.

From the dynamic analysis of water injection wells in the Linqu area, the reservoir has a strong water absorption capacity, with a daily water injection volume of 35-51 m^3 per well, an apparent water absorption index of 3.5-6.9 m^3/d, and an average of 4.4 m^3/d. Moreover, the water injection pressure is stable. Therefore, the above injection allocation plan for Wucangbao Oilfield is feasible.

In summary, the initial injection volume of a single well in the Chang6 layer of Wucangbao is 10m3, and the initial injection volume of a single well in the Chang9 layer is 20 m^3. For the combined production and injection wells, the initial injection volume of a single well is 25 m^3. During the implementation process, monitor the formation pressure at any time to ensure that it remains near the original formation pressure. Adjust the water injection parameters according to changes in formation pressure.

7. Conclusions

Based on the geological reservoir characteristics of the Chang6 and Chang9 oil formations in Wucangbao, the feasibility of water injection development in Wucangbao reservoir is analyzed. The single well production of Wucangbao reservoir is calculated, and the water injection parameters are obtained through the injection production balance formula.

The Wucangbao Chang 6 and Chang 9 reservoirs have good water injection feasibility and prospects in terms of sandstone cement, reservoir fluid properties, wettability, and water flooding efficiency.

The production of Chang6 single well is 1.5-4.0 t/d, and the production of Chang9 single well is 2.0-4.5t/d.

Finally, based on the injection production balance, it is determined that the initial single well injection volume of the Wucangbao Chang 6 layer is 10 m^3, and the initial single well injection volume of the Chang 9 layer is 20 m^3, in order to maximize the recovery rate of the reservoir during the dry or low water cut period.

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