IOP Conference Series: Earth and Environmental Science

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To cite this article: Zhou Xiaofeng *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **459** 042069

IOP Conf. Series: Earth and Environmental Science **459** (2020) 042069 doi:10.1088/1755-1315/459/4/042069

Concurrent-Separate Constant Pressure Water Injection Design Optimization Technique Considering the Threshold Pressure Gradient

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Abstract. A new complex technique for optimizing the design of concurrent-separate constant pressure water injection (CSI), considering the threshold pressure gradient, is proposed. First, the regularity of the each production unit water omnidirectional movement was determined based of the constructed 3D-geological model of the studied field object, and then the critical values of the inefficient water injection into multilayer formations process indicators were calculated based on the obtained data. Second, using an intelligent borehole monitoring and control system, the threshold pressure of water injection into the productive reservoir was determined and CSI special blanks were constructed under constant pressure, taking into account the threshold pressure gradient in injection wells. Third, a procedure has been developed for determining the optimal water injection pressure of each production facility into the productive reservoir during the development of multilayer oil fields. The application of the proposed technique for optimizing the CSI design under constant pressure is by an example of field data from the Daqing oil field of the People’s Republic of China (PRC). The calculation results show that the injected under the constant pressure water efficiency factor value increased significantly by 8.6% due to the sensible separation of the volume of water injected into the productive reservoir. The proposed technique may be useful for CSI designing optimization on other oil fields.

1. Introduction

Reservoirs become more heterogeneous when they are flushed with injected water at the late stage in the oil fields development. The individual design of the oil refinery is required in the development of multilayer oil fields, taking into account the influence of zonal and layer-by-layer reservoir heterogeneities. The main task of the CSI designing is a more detailed description of the studied reservoir characteristics and the exact elements separation of fluid motion in it [1]. Currently, the method of injecting water with a specific volume does not guarantee the implementation of a certain amount of water injection through the layers in injection wells due to the reservoirs' volumetric filtration properties (VFP) changes over time. This phenomenon is explained by the fact that the injection and production wells system is in a nonequilibrium state. In addition, the injected water efficacy factor is gradually decreasing due to the complex connectivity characteristics description of the pore space in the studied layer. For the balanced production of oil reserves from each productive reservoir, it is necessary to create an efficient water injection pressure in the reservoirs and control its change, according to the results of which SCI is carried out across reservoirs under the specific pressure. At the same time, we take feasible measures to control the impact on the reservoirs in order to increase the reserves utilization and the efficiency of oil field development [1, 3].

We propose a methodology for optimizing the CSI design under constant pressure, taking into account the threshold pressure gradient. The aim of our work is the balanced development of oil reserves from each reservoir during the development of multilayer oil fields. The application of the proposed methodology for determining the water injection pressure for each reservoir is illustrated by field data using the example of the Datsin oil field, China. The value of the injected under constant pressure water efficacy factor has significantly increased due to the sensible separation of the water volume injected into the productive reservoir.

2. Inefficient water injection process indicators identification method

After the long-term reservoir flushing with injected water, the physical properties of the reservoir have changed significantly compared to the initial stage of multilayer oil fields development. The dominant channels of water entering the well have gradually formed in some production facilities or local areas, which leads to a deterioration in the efficiency of oil field development with WF. As a result, there is an inefficient circulation of injected water, therefore, there is an urgent task to develop a method for identifying the process indicators of inefficient water injection [4-8].

A method is proposed for identifying the process indicators of inefficient water injection based on mathematical modeling and statistical determination of the cumulative probability, which helps to determine the dominant channels through which water enters the well. The method proposed in this paper allows to identify the dominant channels in the system of injection and production wells and take feasible measures to adjust the water injection mode. The procedure for identifying technical indicators of inefficient water injection is presented as follows:

1) Building a 3D-geological model. The regularity of the omnidirectional water movement at each operational object is determined based on the constructed 3D-geological model of the studied field object.

2) Determination of dominant channels., The oil saturation distribution in the studied system of injection and production wells is determined based on mathematical modeling., The dominant channels feeding the well with water are identified based on the obtained results of oil saturation distribution.

3) Identification of technical indicators of inefficient water injection. Production data of the entire history of field development are analyzed and the technical parameters of inefficient water injection in the studied unit are determined based on the Statistical Determination of Aggregate Probability method. The limiting values of inefficient water injection process indicators are calculated based on the dominant canals results at the second stage.

4) Determination of feasible control measures to increase the of water injection efficacy in each production unit of an injection well, considering the actual conditions of field development.

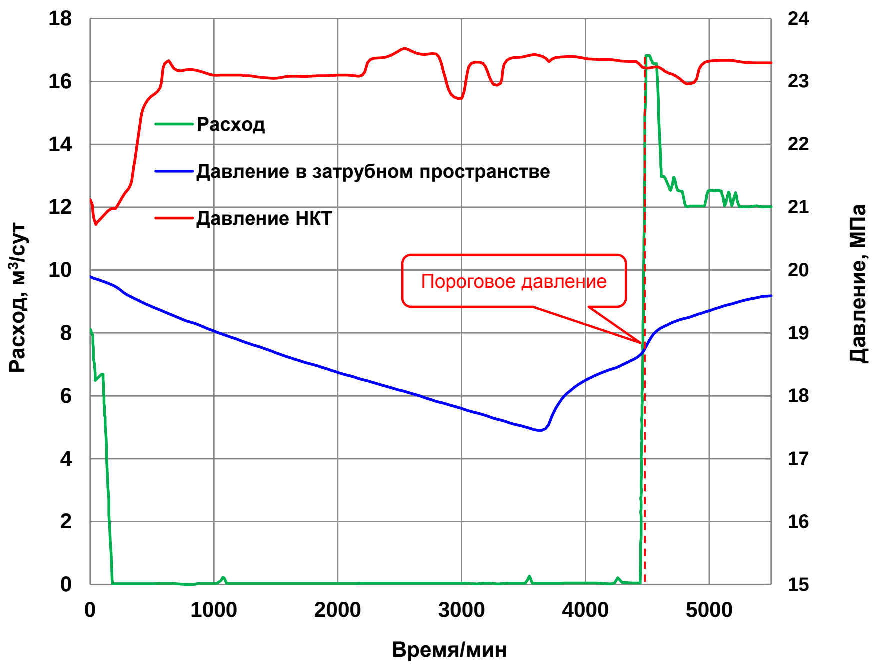
3. Water injection pressure threshold gradient determination

During the multilayer oil fields development process, the degree of complexity of the various production units feeding with the injected water differs due to the difference in the reservoir VFP and the contained fluids. If the water injection pressure reaches or exceeds one or another value, the fluids in a porous medium begin to move due to the narrow and small size of the porous space (pore radius ranges from several microns to hundreds of microns) in low-permeability reservoirs, the reserves of which are difficult to produce. The threshold pressure is the initial pressure at which a fluid in a porous medium begins to move [4].

The technology of monitoring the change in the water injection threshold pressure over time allows us to take effective and optimal measures for the injection wells intake rate profile alignment and optimize the distance between the wells in the multilayer oil fields development, and therefore is of practical importance. Today, most of the largest Chinese oil fields are at the late development stage and their reservoirs are characterized by serious heterogeneity and high water cut. In order to efficiently provide CSI for the reservoir it is necessary to use an intelligent borehole monitoring and real time CSI control system. Using an intelligent borehole monitoring and SCI control system, it seems possible to simultaneously measure the total volume of water injected, pressure and temperature in various production units, as well as to control the volume of water injected into each productive reservoir.

3.1. Threshold water injection pressure determination for each production unit

The intelligent borehole monitoring and CSI control system is a complex of integrated equipment used to optimize and control the processes of water injection into reservoirs in real time. Fig. 1 shows the pressure and flow rate measuring results for each production unit with time. The pressure at the wellhead in the annulus where water begins to flow into the well is considered as the water injection threshold pressure.



Source	Translation
Расход, М3/сут	Flow, m3/day
Давление, МПА	Pressure, MPa
Время, мин	Time, min.
Расход	Flow
Давление в затрубном пространстве	Annulus pressure
Давление НКТ	Tubing pressure
Пороговое давление	Threshold pressure

Figure 1. Water injection threshold pressure change results.

The threshold pressure gradient for each productive reservoir is calculated using an intelligent well control and regulation system by the formulas (1)～(5) with the equation of oil inflow to the well under the radial flow regime and the measurement results:

$$q_{\mathrm{i}} = \frac{2\pi k_{\mathrm{i}} h_{\mathrm{i}} (p_{\mathrm{in,\,i}} - \overline{p}_{\mathrm{wf}} - \Delta p_{\mathrm{i}})}{\mu B \left(\ln \dfrac{r_{\mathrm{e}}}{r_{\mathrm{w}}} + s \right)} \tag{1}$$

$$\overline{p}_{\mathrm{wf}} = \sum_{j=1}^{n} p_{\mathrm{wf,\,j}} \Big/ n \tag{2}$$

$$r_{\mathrm{e}} = \sum_{j=1}^{n} r_{\mathrm{j}} \Big/ n \tag{3}$$

$$\Delta p_{\mathrm{i}} = p_{\mathrm{in,\,i}} - \frac{q_{\mathrm{i}} \mu B}{2\pi k_{\mathrm{i}} h_{\mathrm{i}}} \left(\ln \frac{r_{\mathrm{e}}}{r_{\mathrm{w}}} + s \right) - \overline{p}_{\mathrm{wf}} \tag{4}$$

$$G_{\mathrm{i}} = \frac{\Delta p_{\mathrm{i}}}{r_{\mathrm{e}}} = n \Delta p_{\mathrm{i}} \Big/ \sum_{j=1}^{n} r_{\mathrm{j}} \tag{5}$$

where q_{i} is the volume of water injection into the *i*-th productive reservoir, m^3/s; k_{i} is the permeability factor of the *i*-th productive reservoir, m^2; B is the water volumetric factor, m^3/m^3; h_{i} is the effective thickness of the *i*-th productive reservoir, m; μ is the water viscosity, Pa·s; $p_{\mathrm{in,\,i}}$ is the water injection pressure of the *i*-th productive reservoir, Pa; $\overline{p}_{\mathrm{wf}}$ is the mean bottom hole pressure, Pa; $p_{\mathrm{wf,\,j}}$ is the bottom hole pressure of the *j*-th development well, Pa; Δp_{i} is the additional pressure drop for the water injection start into the *i*-th production reservoir, Pa; r_{e} is the mean distance from the injection well and development wells, m; r_{j} is the distance from the injection well to the *j*-th development well, m; r_{w} is the injection well radius, m; n is the number of the development wells; G_{i} is the threshold pressure gradient, Pa/m; S is the skin factor.

3.2. CSI designing considering the threshold pressure gradient

Currently, there are two commonly used methods for calculating the injected water amount for each production unit in the injection system and development wells: a method for calculating the reservoir thickness and the reservoir conductivity factor [5]. However, these two methods do not take into account the influence of the water injection pressure threshold gradient on the calculation results. Therefore, in the development of multilayer oil fields, it is necessary to develop a methodology for determining the amount of water injected into the reservoir in each production unit studied, which would allow to increase the efficacy of injected water, realize the CSI operation, and also increase the oil flow rate of the well. In this work, we propose a CSI design method considering the threshold pressure gradient based on the analysis of field data, which helps to construct the specific CSI blanks under constant pressure in injection wells. The main design stages of the CSI are the following:

(1) Preparation of input data. Statistical field data for the studied injection wells are collected (the depth of the roof and the base of each production unit, the effective reservoir thickness, the water and oil viscosity, volumetric factor, etc.)

(2) Definition of new separate fluid movement elements in the injection and production wells system based on the constructed 3D-geological model.

(3) Calculation of each production unit threshold pressure gradient in injection wells. The calculation is based on the analysis of actual data obtained using an intelligent system of downhole control and regulation.

(4) Construction of specific CSI blanks under constant pressure based on the calculated threshold pressure gradient for injection wells.

4. Water injection pressure determination procedure for each operation unit

In order to increase the efficacy of the injected water and the balanced development of each production reservoir, it is necessary to create a suitable injection pressure across the reservoirs. For productive reservoirs that require water injection enhancement measures, it is necessary to increase the injection pressure, the value must be less than the upper limit (fracture pressure); for productive formations that require water injection maintain measures, it is necessary to maintain the injection pressure, the value must be within the threshold pressure and the upper limit (fracture pressure), and the actual water injection volume corresponds to the design value; for productive reservoirs that require measures to limit water injection, it is necessary to reduce the injection pressure, the value should be less than the threshold pressure, and the actual water injection volume is less than the design value; for productive reservoirs with high water cut (over 98%), the abandonment of the studied wells is required.

In most cases, when water is injected into productive reservoirs, the water injection pressure should be less than the reservoir fracture pressure [9]. This is due to the fact that if the water injection pressure is greater than the reservoir fracture pressure value, artificial fractures quickly supplying the injected water into the production well easily form in the reservoirs. This leads to a sharp increase in production wells water cut.

According to the proposal of the Guide to the Production of Oil and Gas in Offshore Fields [9], the bottom hole pressure of an injection well, with the value in the range of 80%～90% of the fracture pressure, is considered the maximum permissible water injection pressure. Therefore, we consider a coefficient of 0.9 as the upper limit of the water injection pressure. The threshold pressure measured with the intelligent borehole control and regulation system is selected as the lower pressure limit. The water injection pressure across the reservoirs is determined by the formulas (6)～(8).

With water pressure increase:

$$p_{\text{in}} = 0,9\,p_{\text{f}} \tag{6}$$

With water pressure maintain:

$$p_{\text{th}} < p_{\text{in}} < 0,9\,p_{\text{f}} \text{ и } q_{\text{in}} = q_{\text{st}} \tag{7}$$

With water pressure limit:

$$p_{\text{in}} < p_{\text{th}} \text{ и } q_{\text{in}} < q_{\text{st}} \tag{8}$$

where p_{in} is the water injection pressure for each operation unit, MPa; p_{th} threshold pressure for each operation unit, MPa; q_{in} is the actual volume of injected water for each operation unit, m^3/day; q_{st} is the design volume of injected water for each operation unit, m^3/day.

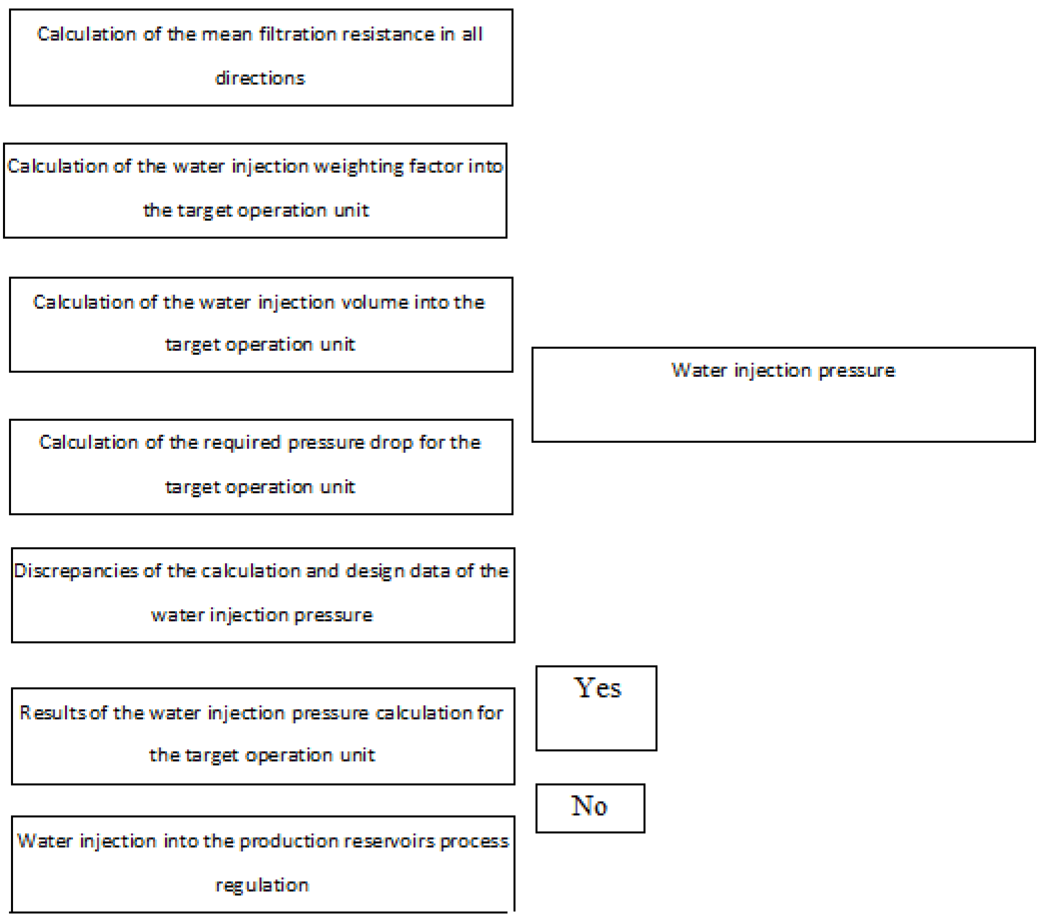


Figure 2. Water injection pressure determination procedure for each operation unit.

The water injection pressure determining procedure of each operation unit is as follows:

1) Calculation of the average filtration resistance of the target operation unit in all directions in the injection well;

2) Calculation of the weighting coefficient of water injection into each target operation unit in the injection well;

3) Calculation of the of injected water volume into the target operation unit with a known total injected water volume;

4) Calculation of the required pressure drop for the target production facility between injection and production wells;

5) Calculation of the design water injection pressure of the target operation unit based on the bottom hole pressure of the production well and the threshold pressure obtained using the intelligent system of downhole control and regulation.

6) In the event of a discrepancy between the calculated and design data on the water injection pressure, it is necessary to regulate the water injection process based on the identification of process indicators of inefficient water injection, and repeat the calculation with formulas (6)～(8) and new parameters until a proper correlation between the calculated and design data is achieved.

5. Example

The application of the proposed methodology for optimizing the constant pressure CSI designing is illustrated by field data obtained in a studied system of an injection well and production wells using the Daqin oil field in People’s Republic of China as the example.

5.1. Identification of the inefficient water injection process indicators

The current state of operation of the studied SII10 operation unit in the system of injection and production wells of the Daqing oil field in People’s Republic of China test site is analyzed. Table 1 shows the statistical results of the operation of the studied SII10 operation unit.

Table 1. Statistical results of the operation of the studied SII10 operation unit.

Injection well No.	Reservoir	Production well No.	Specific injectivity (%)	Daily water injection volume (m^3/day)	Production well water cut (%)
X1	SII10	Prod. No.1	0.68	0.1	99.1
		Prod. No.2	0.01	0	99.2
		Prod. No.3	0.09	0.01	86.5
		Prod. No.4	49.16	7.21	98.5
		Prod. No.5	0.42	0.06	97.8

Based on the Statistical Determination of the Cumulative Probability method, the current operation state of the studied operation unit from the moment the injection and production wells were put into development was analyzed and 4 process indicators of inefficient water injection were selected (daily water injection volume, specific injectivity, production well water cut and permeability factor) to determine the dominant channels feeding the well with water. Statistical results are shown in Fig. 3.

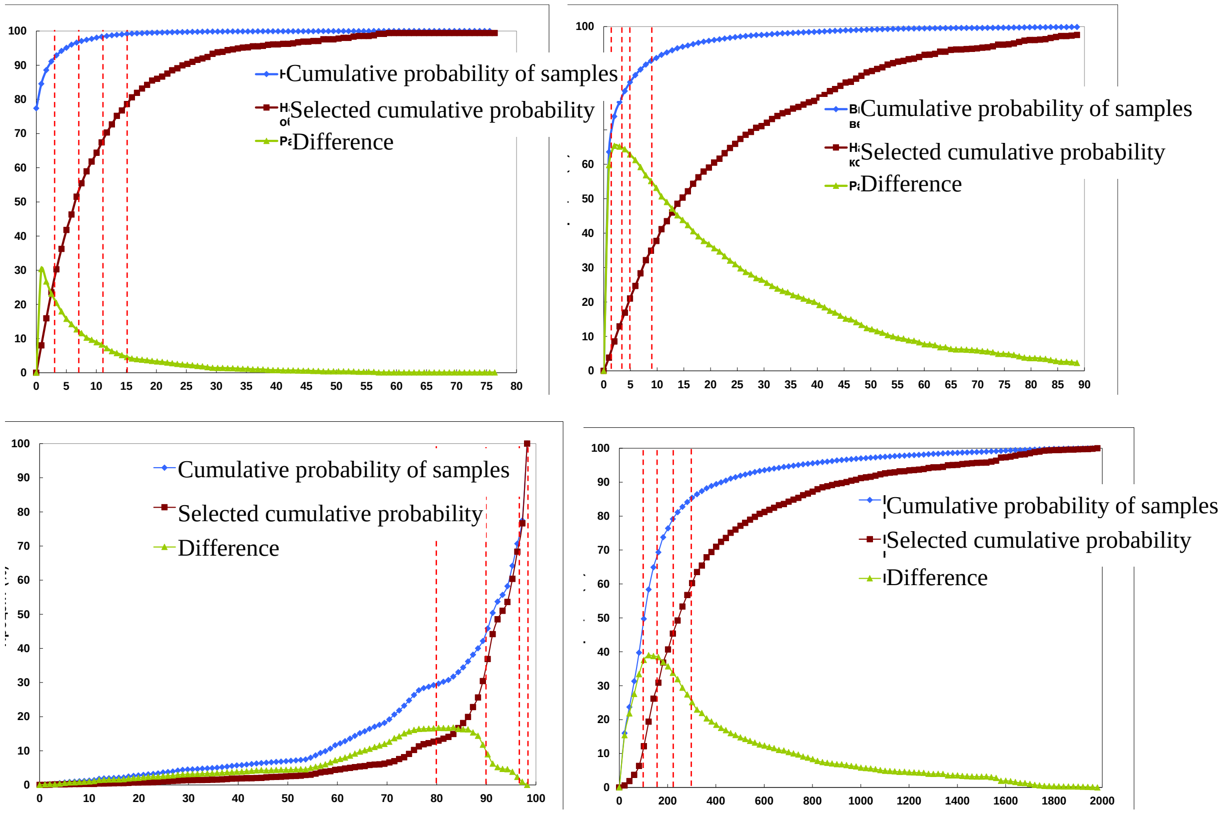


Figure 3. Statistical results of the inefficient water injection process indicators limit values (daily water injection volume, specific injectivity, production well water cut and permeability factor).

Fig. 3 demonstrates that the inefficient water injection process indicators limit values in the studied area are: the daily water injection volume above 15m^3/day, the specific injectivity above 9m^3/m/day, the production well water cut above 98% and the permeability coefficient above 300 mD.

5.2. Determination of the water injection pressure threshold gradient

Using the intelligent borehole control and regulation system, each reservoir flow rate and pressure were measured and the threshold pressure gradient was calculated with formulas (1)～(5). Table 2 shows the threshold pressure gradient calculations results for each reservoir.

Table 2. Threshold pressure gradient calculations results across reservoirs.

Injection well No.	Reservoir	Roof depth (m)	Base depth (m)	Actual threshold pressure (MPa)	Threshold pressure gradient (MPa/m)
X1	S5.1- S10.2	916.7	934.3	15.42	0.0349
	S14- S2.3	949.9	968.5	18.76	0.0498
	S3.1- S4	969.9	973.7	17.73	0.0438
	S5.1- S6	975.8	982.3	20.47	0.0567

S9+10.1-P1.1	993.6	1008.6	16.48	0.0385
P42.2- P5.1	1047.4	1058.3	23.66	0.0716
P7.1- P9	1065.4	1102.4	22.03	0.0749

Based on the threshold pressure gradient calculation results, special blanks were constructed for use in the optimal constant pressure CSI design in injection wells, using production field data.

Table 3. Constant pressure SCI design results (s = 0, r_e = 100m).

k*h/ μ_w (D*m/ mPa.s)	Threshold pressure gradient (MPa/m)	Pressure drop (MPa)						k*h/ μ_w (D*m/ mPa.s)	Threshold pressure gradient (MPa/m)	Pressure drop (MPa)					
		10	12	14	16	18	20			10	12	14	16	18	20
		Water injection volume (m^3/day)								Water injection volume (m^3/day)					
0.05	0.03	24.98	32.12	39.26	46.40	53.54	60.68	0.25	0.03	124.92	160.62	196.31	232.00	267.69	303.39
	0.04	21.42	28.55	35.69	42.83	49.97	57.11		0.04	107.08	142.77	178.46	214.16	249.85	285.54
	0.05	17.85	24.98	32.12	39.26	46.40	53.54		0.05	89.23	124.92	160.62	196.31	232.00	267.69
	0.06	14.28	21.42	28.55	35,69	42.83	49.97		0.06	71.39	107.08	142.77	178.46	214.16	249.85
	0.07	10.71	17.85	24.98	32.12	39.26	46.40		0.07	53.54	89.23	124.92	160.62	196.31	232.00
0.10	0.03	49.97	64.25	78.52	92.80	107.08	121.35	0.30	0.03	149.91	192.74	235.57	278.40	321.23	364.06
	0.04	42.83	57.11	71.39	85.66	99.94	114.22		0.04	128.49	171.32	214.16	256.99	299.82	342.65
	0.05	35.69	49.97	64.25	78.52	92.80	107.08		0.05	107.08	149.91	192.74	235.57	278.40	321.23
	0.06	28.55	42.83	57.11	71.39	85.66	99.94		0.06	85.66	128.49	171.32	214.16	256.99	299.82
	0.07	21.42	35.69	49.97	64.25	78.52	92.80		0.07	64.25	107.08	149.91	192.74	235.57	278.40
0.15	0.03	74.95	96.37	117.79	139.20	160.62	182.03	0.35	0.03	174.89	224.86	274.83	324.80	374.77	424.74
	0.04	64.25	85.66	107.08	128.49	149.91	171.32		0.04	149.91	199.88	249.85	299.82	349.79	399.76
	0.05	53.	74.	96.	117	139	160		0.05	124	174	224	274	324	374

		54	95	37	.79	.20	.62			.92	.89	.86	.83	.80	.77
	0.06	42.83	64.25	85.66	107.08	128.49	149.91		0.06	99.94	149.91	199.88	249.85	299.82	349.79
	0.07	32.12	53.54	74.95	96.37	117.79	139.20		0.07	74.95	124.92	174.89	224.86	274.83	324.80
0.20	0.03	99.94	128.49	157.05	185.60	214.16	242.71	0.40	0.03	199.88	256.99	314.09	371.20	428.31	485.42
	0.04	85.66	114.22	142.77	171.32	199.88	228.43		0.04	171.32	228.43	285.54	342.65	399.76	456.87
	0.05	71.39	99.94	128.49	157.05	185.60	214.16		0.05	142.77	199.88	256.99	314.09	371.20	428.31
	0.06	57.11	85.66	114.22	142.77	171.32	199.88		0.06	114.22	171.32	228.43	285.54	342.65	399.76
	0.07	42.83	71.39	99.94	128.49	157.05	185.60		0.07	85.66	142.77	199.88	256.99	314.09	371.20

5.3. Water injection pressure determination for each operation unit

The water injection pressures for each operation unit and further measures to regulate the water injection mode are determined based on the results of the inefficient water injection process indicators limiting values in the injection and production wells system. Table 4 shows the results of the measures taken to regulate the water injection mode.

Table 4. Measures taken to regulate the water injection mode across reservoirs in the injection well X1.

Rerservoir	Specific injectivity (%)	Daily water injection volume (m^3/day)	Development well water cut (%)	Surface efficiency (%)	Distance from the injection well to the development wels (m)	Type measures taken	Water ofinjection pressure (MPa)
S25-1	1.26	1.24	97.2	0.69	215.7	Limitation	15.39
S210	32.68	32.08	98.1	0.75	205.8	Limitation	15.39
S215	5.67	5.57	97.5	0.69	194.5	Limitation	18.64
S31	0.44	0.43	93.8	0.32	172.1	Increase	26.42
S32	1.05	1.03	98.3	0.73	188.1	Limitation	18.64
S32-1	2.26	2.22	96.7	0.57	202.3	Maintain	29.52
S32-2	0.39	0.38	98.9	0.25	195.7	Abandonment	/
S33-1	3.99	3.92	96.9	0.8	201.9	Maintain	32.67

S35	7.52	7.38	97.3	0.72	195.7	Limitation	17.92
S35-1	3.27	3.21	98.8	0.39	195.6	Maintain	24.66
S36	0.54	0.53	99.6	0.63	180.8	Abandonment	/
S39-1	12.29	12.06	97.4	0.76	195.7	Limitation	16.56
P142-2	1.41	1.38	67.1	0.58	343.4	Increase	30.63
P142-3	3.42	3.36	31	0.91	214.1	Increase	30.54
P15	5.51	5.41	97.5	0.66	246.9	Limitation	23.71
P15-1	12.26	12.03	92.5	0.56	331.7	Increase	29.77
P17	0.66	0.65	98.8	0.53	149.4	Abandonment	/
P23	1.51	1.38	97.2	0.5	158.5	Limitation	24.46
P27	0.75	0.74	96.8	0.59	173.7	Limitation	24.46

6. Conclusions

(1) As a result of the studies, a new methodology was proposed for the water injection threshold pressure determination in the reservoir using an underground intelligent device and special blanks were constructed that are used for the optimal design of concurrent and separate water injection in injection wells.

(2) Using an intelligent borehole control system, it seems possible to quickly determine the optimal volume of water to inject into each reservoir, both for the injection well and for the group of injection wells. The water injection threshold pressure change with time monitoring technology allows to take effective and optimal measures for the injection wells injectivity profile alignment in the development of multilayer oil fields.

(3) An optimal water injection pressure of each production facility determination procedure during the development of multilayer oil fields was developed. Field tests of enhanced oil recovery technology using the proposed methodology were successfully made at the experimental site of the Daqin field of the PRC. The calculation results show that the inefficient water injection process indicators limiting values are: the water injection daily volume is above 15m^3/day, the specific injection rate is above 9m^3/m/day, the water cut of the producing well is above 98% and the permeability coefficient is above 300 mD. The constant pressure injected water efficacy factor value significantly increased by 8.6% due to the reasonable separation of the water volume injected into the reservoir.

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