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Well Flow Rates at Secondary Well Stimulation

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Abstract

With the number of new deposits growing, the number of deposits with complex geological structures (reservoirs with low permeability, non-Newtonian fluids and highly dissected geological frameworks) containing hard-to-recover oil grows as well. This type of deposits requires science-based methods and reservoir impact facilities to design and use in order to boost hydrocarbon production, increase the oil recovery factor, and improve the system of hydrocarbon deposit development and exploitation.
Thus, the purpose of this article is to improve the methodological approach to determining the prime indicators of stimulated deposit development using mathematical process modeling, statistical methods, and field setting methods.

Keywords: *oil deposit, reservoir recovery rate, hard-to-recover reserves, flooding method, well flow rate.*

1. Introduction

The world knows many deposit development technologies, which were introduced both in the CIS and non-CIS countries. Discovery of new deposits and development operations performed at existing fields allowed identifying some extra geological, physical and technological factors. These are the formation frac gradient response to the borehole inclination angle; optimal and minimum injection pressure for formations with different filtration properties; regular changes in the wellhead pressure and the bottom-hole pressure in the exploitation/injection wells; and incomplete well surveys, which led to a decrease in the efficiency of producing hard-to-recover resources. Deformation processes that occur in active reservoirs at the time of mechanical improvement of formation permeability were investigated in [1-3]. They show that beneficial effect of intensifying operations is tied to the relation of mechanical stresses, changes in the reservoir volume and reservoir pressure. The maximum use of the oscillatory fluid filtration can be achieved by simulating the occurrence of processes numerically in a massive formation [4; 5]. The adopted development technology can be improved, and for that, the volume of the working agent injected into the porous fractured system must be changed [6; 7]. The formation is a medium with inner sediments of different shape and direction, which create local permeability anisotropy [8; 9]. Stimulation treatment can be improved by the introduction of flow-separating methods and by justifying the optimal bottom-hole pressure in the exploitation wells [10; 11; 12].
A detailed review of the literature on filtration processes shows that modern technologies and methods of well stimulation do not have proper grounds behind the theory and practice of fluid filtration for hard-to-recover cases in the changed low productive reservoir. The theory of non-stationary spatial filtration of fluids in deformable low productive porous fractured media needs further development as well to cover sharp fluctuations in permeability, flow capacity, and energy in multilayer strata, as they have the most significant effect on the production of hard-to-recover resources. The practice of multi-layer deposit exploitation shows that the practice of boosting oil production by improving the technology of exploiting low-productive reservoirs is the same as discovering new hydrocarbon deposits.
Each stimulation method ever applied is investigated and modified to improve the settings of fluid filtration.
Research results made it possible to tie certain factors to well productivity and well flow rates. This list of those factors includes the non-uniform distribution of permeability, thickness and

porosity within the reservoir; water-oil zone; capillary forces; well grid parameters; water flooding system, viscosity of oil, water and gas; pressure gradient [13].
Oil deposits with a complex geological structure, physical and chemical properties of reservoir fluids are currently developed by contour stimulation (block, spot, pattern, staged and otherwise water flooding. These methods allow an easy extraction of oil, but some areas will eventually house hard-to-recover reserves [14; 15].
Despite the advances made in the sphere of stimulation improvement, problems of assessing the improvement of hard-to-recover reserves production by water injection into the reservoir through new injection wells, drilled or shifted, are still open. In this production case, well productivity is being increased. At this point, the background behind the choice of the case-based stimulation method is of an academic and practical interest [16].

2. Methods

Research case was the Uzen Oil Field (Kazakhstan). The set goals were achieved comprehensively by applying modern concepts of the complex deposit structure and be performing a mathematical modeling of a deposit development process [17]. Research methods applied were the statistical methods, probability theory, and field setting.
The Uzen Oil Field is one of the largest deposits with complex thermo-hydrodynamic reservoirs. This is the deposit where oil production is stimulated by water flooding, and by using common and new well productivity boosters.
Stimulation method applied to the productive oil deposit in the Uzen Oil Field was a *staged water flooding* (SWF) method [18].
This method was applied is to improve the previously used block water flooding system. This required the creation of new rows of injection wells, which should be perpendicular to the already rows stimulated by block water flooding. This method is one of the best applied at the Uzen Oil Field to achieve the depletion of certain deposits and development targets. Many oil fields now enter the third and fourth stages of development, characterized by significant volumes of associated water and low depletion rates displayed by separate reserves.
These low productive areas will be probably stimulated, but first one has to calculate and determine the effectiveness of the stimulation method selected for the purpose. In other words, one has to estimate the key technological parameters (fluid flow rates) that were achieved with the given method.
Calculation results, obtained for a uniform formation, are indicated in [19]. Productive hydrocarbon formation are known to be non-uniform in terms of physical properties and geological structure. This feature has a great effect on the process flow, manifested in the well flow rates and in the rates of reservoir flooding.
Practice shows that indicators calculated for the oil deposit development and the real data are not the same, due to physical properties and geological structure (permeability, porosity, oil and gas saturation, heterogeneity, formation discontinuity, and otherwise). Thus, calculations must take into account these factors so that calculated data could describe the real state of a deposit at regulation.
In block-type stimulation, well flow rates can be determined by formulas from [18], modified with coefficients that take into account the environmental factors given above, namely the volumetric sweep efficiency (K_{VSE}). Thus, formulas will generally be as those below:

$$q_i = \frac{P_{Ki} - P_w}{\left(\Omega_i + \Omega_{i+1} + \omega_i\right)} \cdot K_{VSE}. \qquad (1)$$

Where: K_{VSE} is the product of vertical sweep (K_v) and areal sweep (K_a) efficiencies, $K_{VSE}=K_v \cdot K_a$.
Thus, (1) will transform into:

$$q_i = \frac{P_{Ki} - P_w}{\left(\Omega_i + \Omega_{i+1} + \omega_i\right)} \cdot K_v \cdot K_a. \qquad (2)$$

At the Uzen's, vertical sweep and areal sweep efficiencies were 0.6 and 0.8, respectively. Hence, volumetric sweep efficiency was 0.48, naturally.
Thus, (2) will transform into:

$$q_i = \frac{P_{Ki} - P_w}{\left(\Omega_i + \Omega_{i+1} + \omega_i\right)} \cdot 0,48. \qquad (3)$$

The calculations revealed that the prior average flow rate of a single exploitation well was 20.7 ton/day, while the actual value was 22.7 ton/day. In other words, calculated value was lower by 8.8%. Considering this difference in data, formula (3) provides the most real data on the flow situation within the formation.
After the SWF treatment, the actual average flow rate of a single exploitation well was 34.1 ton/day, which is 1.5 times higher than the initial value (Table 1).

Table 1: Water-Flooded Deposit-Averaged Actual Oil/Fluid Rates (The Uzen Oil Field)

№	Averaged Well Flow Rates, ton/day		Note
	Oil	*Fluid*	
1	16.0	19.1	
2	19.1	24.5	
3	18.6	22.7	
4	14.9	21.1	
5	10.6	22.5	
6	9.5	24.9	
7	10.1	24.7	
8	9.1	22.1	
9	20.4	40.0	When SWF treatment began
10	22.0	45.9	
11	14.4	33.5	
12	12.9	32.2	
13	12.6	35.9	
14	11.2	35.0	
15	7.8	29.0	
16	6.0	25.1	

This increment means that applied SWF treatment allowed increasing the volumetric sweep efficiency by 1.53 times, due to the switch of filtration flows across the reservoir sections. Therefore, the average well flow rate at SWF stimulation can be determined by:

$$q_{comb} = \left(q_{fluid-s} + \frac{q_{fluid-b}}{2}\right) \cdot K_{VSE}, \qquad (4)$$

Where: q_{comb} – fluid rate at combined block staged water flooding, ton/day; $q_{fluid-s}$ – fluid rate at SWF stimulation, ton/day; $q_{fluid-b}$ – fluid rate at block flooding, ton/day.

From (4), it can be seen that fluid rate is a multiple, due to block flooding, as there is a belief that the total well flow rate will increase at block flooding, due to the involvement of additional layers with a flow rate being equal to half-daily productivity of a non-simulated well.

This assumption is supported by numerous actual data on productive deposit exploitation in the Uzen Oil Field [17]. Based on formulas (1), (2) and (3), equation (4) can be represented in the following form:

$$q_{comb} = \frac{2\sigma\left[\left(P_{in.well-s} - P_{\exp.well-s}\right) + \frac{\Omega_{is} + \omega_{is} + \Omega_{(i+1)s}}{2\left(\Omega_{ib} + \omega_{ib} + \Omega_{(i+1)b}\right)}\cdot\left(P_{in.well-b} - P_{\exp.well-b}\right)\right]\cdot K_{VSE}}{S\cdot\left(\Omega_{is} + \omega_{is} + \Omega_{(i+1)s}\right)}, \quad (5)$$

Where: $P_{in.well\text{-}s}$, $P_{in.well\text{-}b}$ – bottom-hole pressures in the injection wells stimulated by SWF and block water flooding, respectively, MPa; $P_{exp.well\text{-}s}$, $P_{exp.well\text{-}b}$ – bottom-hole pressures in the exploitation wells stimulated by SWF and block water flooding, respectively, MPa; $\Omega_{is}, \Omega_{(i+1)s}, \Omega_{ib}$, $\Omega_{(i+1)b}$ – filtration resistances *i* and *i+1* for the rows of wells stimulated by SWF and block water flooding, respectively, $\frac{MPa\cdot s}{m^2\cdot m}$; w_{is} and w_{ib} – filtration resistances for wells in an *i* row, stimulated by SWF and block water flooding, respectively; 2σ – well spacing in a row; *S* – row length.

To validate the accuracy of (5), average fluid rate was calculated for one stimulated well. The initial data remained the same as indicated above.

The staged water flooding process was calculated according to M.M. Sattarov [19]. The procedure takes into account the recovery potential of reserves with regard to reservoir heterogeneity (discontinuity, compartments and dead-end zones). Because of this, exploitation analysis displayed a 30% decrease in the size of the reserves in the Uzen Oil Field [20].

3. Results and Discussion

Table 2 provides the calculated and actual figures associated with deposits from the Uzen Oil Field, which production was stimulated by block and staged water flooding.

Data in the Table 2 show a necessary in reducing the heterogeneity factor for better stimulation efficiency.

Table 2. Calculated and Actual Data on Stimulated Deposits in the Uzen Oil Field

Oil in Produced Fluid, unit fraction	Non-Dimensional Time (τ), unit fraction				
	0.21	0.23	0.24	0.25	0.28
By measurement	0.41	0.42	0.40	0.35	0.20
By calculation	0.40	0.41	0.39	0.33	0.22
Deviation, ±%	2.40	-2.38	-2.50	-5.70	+10.0

Heterogeneity factor can be reduced by drilling injection and exploitation wells in the productive strata with equal filtration characteristics, while isolating the 'old' perforated compartments. Secondly, fluid (water) injection pressure at the wellhead must be increased to reach separate reservoir intervals or interlayers and thereby stimulate the production. With higher $P_{specific}$, filtration rate increases. This leads to an increase in sweep efficiency, so the production of reserves is naturally higher.

Thirdly, the value of bottom-hole pressure in the exploitation wells must be optimized to create a pressure drop for the maximizing of deposit's potential. Fourthly, a well down spacing practice is required to increase liquid (oil) recovery. The bottom line here is that perforation should apply only to those layers which meet the previously developed systems by geological structure and filtration parameters.

The SWF stimulation method can be further boosted after a certain period of time by changing the production mechanism in both types of wells until a unsteady-state filtration of fluid through strata. This will enable the intensive production from unworked low productive areas. In the event of hot water injection, method effectiveness will be even higher.

Formulas for well flow rates were constructed for secondary well stimulation cases with regard to the given field settings.

In block-type treatment, formulas for determining the flow rates of wells in a row take into account the homogeneous layers and ignore the environmental factors [18]. Constructed formulas took into account the vertical sweep and areal sweep efficiencies, which values were true for the Uzen Oil Field.

Calculation results showed a 32.6 ton/day flow rate, but the actual value was 31.7 tons per day. Considering the 2.8% error, mathematical model of recovery (5) is accurate enough.

4. Conclusions

Research results were validated with oil recovery data and hydrodynamic calculations to compare calculations with actual results obtained on the back of SWF stimulation.

Comparative analysis applied to calculations and measurement revealed that the calculated average of fractional oil content was 10.6% lower than the actual figure, so the mathematical model can be considered highly accurate (Table 2).

Formulas introduced in this article can be used in calculations to assess the effectiveness of stimulation methods and to process data from the Uzen Oil Field, Zhetybai Oil Field, Kalamkas Oil Field (Western Kazakhstan). Obtained results can be applied by the relevant departments of the industry-specific R&D and design institutes as guidelines for the oil field development analysis and planning.

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