Efficient operation of oil producing wells in non-stationary fluid withdrawal mode

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Abstract. The article deals with the efficient non-stationary well operating mode during fluid withdrawal. In this well operating mode, the optimal pump switching periods are identified to increase the oil flow rate and reduce the water content of the fluid. The purpose of the study is to improve the efficiency of pilot production wells operation. A descriptive method was used during the study, which involved analysis of the reservoir-well-pump system transient phenomena on a simulation stand, interpretation of transient graphs, comparison and synthesis of the results. The paper presents the results of experimental studies of transient pressure changes on the simulation stand for different pump operating modes. The results of the research have shown that the pressure change depends on the pump operating mode, i.e. reservoir characteristics depend on the change in the hydraulic resistance of the reservoir-well-pump system.

1. Introduction

One of the most important challenges in oil industry is the enhancement of oil recovery from developed fields. Most of the oil fields of the Republic of Tatarstan are quite mature and oil remaining in place is classified as hard to recover, its share constantly growing.

Today, the focus is on the implementation of low-cost oil recovery enhancement methods. One of these methods is the non-stationary fluid withdrawal, which is used for efficient recovery of oil remaining in place [1-3].

The analysis of the cyclic impact (non-stationary mode) on oil recovery in a fractured-porous reservoir is provided in the works of the researchers Yu. M. Molokovich, A. I. Markov, E. I. Suleymanov, R. G. Farkhullin, N. N. Neprimerov, R. S. Khisamov [1-11]. The works [12, 13] show that the cyclic effect on a fractured-porous reservoir leads to its enhanced oil recovery in comparison with the stationary fluid withdrawal mode. The work of V. G. Belov, A. Yu. Gorshenin, V. A. Ivanov et al. covers a non-stationary oil recovery method [14], which involves exposure to periodic depression without stopping the submersible well pumping equipment. Based on this, a method aimed to put wells in an efficient operating mode [15] was developed, where a well is put in a stationary operating mode after non-stationary operation.

2. Problem statement

The main objective in respect of fractured-porous reservoirs is to enhance the oil flow rate and reduce the water content of the fluid in the non-stationary well operating mode. In a non-stationary mode, pressure filtration waves occur and propagate in the reservoir [16,17], which leads to creation of the
conditions for oil involvement in the filtration flows of the well’s bottom-hole zone and allows enhancing the oil recovery factor. The impulse effect of changing pump performance is transmitted from the pump along the wellbore to the bottom and then to the exploited reservoir.

Laboratory and field experiments are required to investigate into the effect of a production well non-stationary operation with the bottom-hole pressure fluctuating over time on the reservoir oil recovery and reduction of the water content of hydrocarbons produced.

3. Theory
Let us suppose a central production well with a radius $r_c$ is drilled in the reservoir. From the time $t = 0$, the bottom-hole pressure begins to fluctuate during well operation. A constant pressure is maintained at the outer reservoir boundary of the radius $R$. If we neglect capillary and gravitational forces at the scale approximation, then the non-stationary filtration across the averaged reservoir thickness $h$ is described by a system of equations [5]:

$$
\frac{1}{r} \frac{\partial}{\partial r} \left( \sigma_i r \frac{\partial p_i}{\partial r} \right) = \beta_i h \frac{\partial p_i}{\partial t} + A \sigma_i (p_i - p_{z-l}),
$$

$$
\frac{1}{r} \frac{\partial}{\partial r} \left( f_i \sigma_i r \frac{\partial p_i}{\partial r} \right) = \beta_{hi} h S_{i*} \frac{\partial p_i}{\partial t} + m_i h \frac{\partial S_i}{\partial t} + \bar{f}_i A \sigma_i (p_i - p_{z-l}),
$$

where the indices $i = 1, 2$ refer to the cracks and blocks in the reservoir, $S_i$ - water saturation, $\sigma_i = k_i \cdot k_{i*} \cdot h$, $k_{i*} = \frac{k_{bi}}{\mu_b} + \frac{k_{bi}}{\mu_i}$, $\bar{f} = \left\{ \begin{array}{ll} \bar{f}_1, & p_i \geq p_2, \\ \bar{f}_2, & p_i < p_2 \end{array} \right.$, $k_i$ - absolute permeability, $k_{bi}, k_{hi}$ - water-oil relative permeabilities, $\bar{f}_1$ - water cut in the flow; $\beta_i = \beta_{bi} S_i + \beta_{hi} (1 - S_i)$, $\beta_{bi} = \frac{m_i}{m} (\beta_i + \beta_{bi} m)$, $\beta_{hi} = (\beta_i + \beta_{hi} m)$ - porous medium, water and oil compression factors, $m = m_i + m_2$; and $A$ - fluid exchange ratio.

The solution of the system (1)-(2) is defined on an interval $r \in (r_c, R)$ subject to the following conditions:
1. initial
$$p_i(r,0) = p_0, \quad S_i(r,0) = S_{i,0} \geq S_{li*},
$$

2. borderline
$$p_i(r_c, t) = p_0 - p_{1c} \cos \left( \frac{2\pi}{T} t \right) < p_R,$$
$$p_i(R, t) = p_R \geq p_0,$$
$$S_i(R, t) = S_{i*};
$$

where $S_{li*}$ and $S_{i*}$ are the connate and cutoff water saturation values, and $T$ and $p_{1c}$ are the period and amplitude of the reservoir exposure.

Dependence of bottom-hole pressure on impulse impact when pump performance changes [18]:

$$P_{pl} = P_0 + P(1 - e^{-\frac{t}{\tau_{pl}}}),$$

2
where $P_{pl}$ is bottom-hole pressure, $atm$; $P_0$ is initial pressure, $atm$; $P$ is pulse pressure change, $atm$; $t$ is transient period, s; $\tau_{pl}$ is the time of reservoir response to the change in pump performance, calculated on the basis of transient time for each well.

In case of non-stationary fluid withdrawal, we shall consider a single interconnected reservoir-well-pump system for the purpose of effective oil recovery management.

The main purpose of the experimental studies is to identify conditions for supporting efficient well operation in a non-stationary fluid withdrawal mode.

A simulation stand was used to study the transient processes in the reservoir-well-pump system [19, 20] (Fig.1). Data was collected and transmitted from the simulation stand via the RS-485 interface to the controller and via the RS-232 interface to the engineer's automated workstation with the Master SCADA3 software installed.

The functional diagram of the stand (Fig. 1) consists of: $A1$ - hydraulic accumulator simulating reservoir capacity; $A2$ - hydraulic accumulator simulating well filling; $E1$ - fluid collection tank; $K1,2,3,4,5,6,7$ - ball valves; $F1,2$ - filters; $P$ - pressure reducer; $FE1,FE2$ - fluid meters; $PT$ - pressure gauge; $H1$ - centrifugal pump.

![Figure 1. The simulation stand functional diagram](image)

Experimental studies of the transient processes occurring in the reservoir-well-pump system were conducted on this simulation stand, and their results were used to analyze pressure transient processes, compare and summarize the results of experiments. The downhole pump operating modes were simulated by changing the position of the ball valves ($KSH$) on the simulation stand.

To perform laboratory tests, the following activities were carried out:

1. The experiment conditions were defined and the experiment matrix was developed: changing the degree, to which the $KSH_{1,2}$ ball valves open (()). Dependence of the number of experiments on the number of factor levels $N = p^k$, where $N$ — the number of experiments, $p$ — the number of factor levels, and $k$ — the number of factors. The initial state corresponds to the maximum fluid withdrawal, while all ball valves are fully open and the fluid is pumped from the tank to the hydraulic accumulators. Changing the degree of the ball valves ($KSH_{1,2}$) opening, we can simulate a change in the downhole pump operating mode. In this case, the level and factor variability interval is 10. With the number of factors being $k \geq 7$, we have to reduce, i.e., eliminate them, because otherwise a large number of experiments will be required.

2. The real-time transient pressure change graphs are built in the MasterSCADA3 software and data arrays are uploaded to MicrosoftExcel.

3. Qualitative characteristics are identified based on the transient pressure change graphs, such as reservoir response time, transient period, and maximum pressure deviation during the transient period.
4. Experimental results
In each experiment, pressure change graphs were obtained in a real-time mode with visualization in the *MasterSCADA 3* software and data arrays were uploaded to *Excel* (Figure 2-15).

**Figure 2.** Transient pressure change graph for experiment No.1 in *MasterSCADA 3*

**Figure 3.** Piece of transient pressure change graph for experiment No.1, exported to Excel

**Figure 4.** Transient pressure change graph for experiment No.2 in *MasterSCADA 3*

**Figure 5.** Transient pressure change graph for experiment No.2, exported to Excel

**Figure 6.** Piece of transient pressure change graph for experiment No.2, exported to Excel
Figure 7. Transient pressure change graph for experiment No.3 in MasterSCADA 3

Figure 8. Transient pressure change graph for experiment No.3, exported to Excel

Figure 9. Piece of transient pressure change graph for experiment No.3, exported to Excel

Figure 10. Transient pressure change graph for experiment No.4 in MasterSCADA 3

Figure 11. Transient pressure change graph for experiment No.4, exported to Excel

Figure 12. Piece of transient pressure change graph for experiment No.4, exported to Excel
The following qualitative indicators were calculated based on the transient pressure change graphs obtained: reservoir response time, transient period, and maximum pressure deviation during the transient period. For experiments, the following is defined in Table 1: reservoir response time $\tau_{ipl}$, transient period per one pressure change pulse jump $t$, and the maximum pressure deviation during the transient period $p$.

**Table 1.** Transient process qualitative indicators for the conducted experiments

| No. | $\tau_{ipl}$, (i=1...5) | $t$, sec | $p$, atm |
|-----|--------------------------|----------|----------|
| 1   | 50 25 19 4               | 3 136    | 0.52     |
| 2   | 16 79 12 8               | 5 192    | 0.6      |
| 3   | 24 39 25 7               | 6 136    | 0.53     |
| 4   | 29 9 33 26               | 11 133   | 0.61     |
| 5   | 50 25 4                 | 3 136    | 0.52     |

Using the calculated values, field studies were performed with the focus on the operating mode control in respect of the eight pilot production wells that were operated in a non-stationary fluid withdrawal mode.

The non-stationary operating mode assumes that the well requires some additional equipment (controller, control stations with a frequency-controlled electric converter, and deephole telemetry),
which allows achieving all well operating modes (stationary, periodic and non-stationary) in the borehole.

Putting eight production wells in the non-stationary fluid withdrawal mode, the duration of the non-stationary fluid withdrawal mode should be 20 days. The non-stationary mode parameter is the impact amplitude (change in pump performance) from the max swing/min to min swing/min.

It is recommended to perform non-stationary fluid withdrawal in accordance to the calculated well operating mode switch periods. The water content, flow rate, and dynamic level of the fluid must be registered in the non-stationary fluid withdrawal mode.

Table II presents on-line data from the pilot wells at the deposit studied (\(n_{\text{max}}\) is the number of maximum rod swings, swing/min; \(n_{\text{min}}\) is the minimum rod swings, swing/min; \(L\) is the rod stroke length, m; \(H_s\), \(H_d\) are static and dynamic levels, m; \(P_{\text{pl}}\) is the downhole pressure, \(\text{atm}\); \(Q_z\) is the fluid rate, \(\text{m}^3/\text{day}\); \(Q_v\) is the water cut, %).

| No. | \(n_{\text{max}}\), swing/min | \(n_{\text{min}}\), swing/min | \(L\), m | \(H_s\), m | \(H_d\), m | \(P_{\text{pl}}\), atm | \(Q_z\), m\(^3/\text{day}\) | \(Q_v\), % |
|-----|-------------------------------|-------------------------------|---------|----------|----------|-----------------|----------------|---------|
| 1   | 3.3                           | 1.0                           | 2.40    | 141      | 411      | 39              | 26.0           | 85      |
| 2   | 2.9                           | 1.0                           | 2.50    | 59       | 275      | 52              | 7.0            | 81      |
| 3   | 5.0                           | 1.0                           | 2.10    | 45       | 274      | 51              | 7.5            | 82      |
| 4   | 3.7                           | 1.0                           | 2.10    | 57       | 174      | 62              | 6.4            | 89      |
| 5   | 3.5*                          | 1.0*                          | 3.50    | 70       | 177      | 60              | 7.5            | 56      |
| 6   | 3.5*                          | 1.0*                          | 3.50    | 80       | 121      | 64              | 7.1            | 75      |
| 7   | 3.0*                          | 1.0*                          | 3.00    | 72       | 254      | 54              | 6.6            | 60      |
| 8   | 2.4                           | 1.0*                          | 3.00    | 75       | 494      | 39              | 6.8            | 84      |

In case of the deposit studied, the non-stationary operation was possible only on four wells: 1, 2, 3, and 4 due to some technical limitations. At the wells 5 and 6, the beam-pumping unit was underutilized because of jamming; 7 – formation of emulsion, and 8 – low dynamic level.

The dynamic level was calculated for well No.1 using the pressure values obtained by means of a downhole measuring system.

When measurements are performed using a sounder, the well annulus must be pre-discharged, i.e., there is a need to bleed off the excess pressure. These measures often lead to foaming of the fluid level in the annular space and the formation of a “foam cap”, which makes a clear signal reflection impossible and does not allow shooting the fluid level.

Therefore, the use of sounder data is limited to approximate estimates. Only in case of favorable conditions the results of such measurements can be used to identify almost the full range of reservoir parameters. In addition, echo sounding is not allowed in oil wells with a high gas factor and in case of the product water cut exceeding 80%. The registration period must be at least 1 \(\div\) 2 days. Short-term dynamic level measurements are uninformative.

Since the "foam cap" formed as a result of the fluid level foaming in the annulus can reach at least 30 m, the convergence criteria (6) in operation may be a fluid level less by \((30 \div 60)\)m, than the level measured by sounder.
$H_{d,\text{r}} = H_{d,\text{i}} - (30 + 60), \quad (6)$

where $H_{d,\text{r}}$ is a calculated dynamic level, m and $H_{d,\text{i}}$ is a measured dynamic level, m.

In well No.1, fluid pressure and dynamic level are measured. However, the dynamic level measurement may not be always precise. This is due to the influence of gas in the well. The dynamic level value can be obtained by calculating the pressure at the bottomhole.

The bottomhole pressure formula is [21]

$$P_{pl} = \rho \cdot g \cdot H_d,$$ \( (7) \)

where $P_{pl}$ is the bottomhole pressure, atm; $\rho$ is the oil density, kg/m$^3$; $H_d$ is the dynamic level, m; $g$ is the free fall acceleration, m/s$^2$.

From formula (7) we can express the fluid dynamic level in the well:

$$H_d = \frac{P_{pl}}{g \cdot \rho}, \quad (8)$$

Figure 17 shows a graph of calculated and measured dynamic level values for well No.1 (the bottom hole pressure, measured level and the one calculated using the formula (8)).

![Figure 16. Calculated and measured level graph](image)

As it can be seen from the graph (Figure 16), the difference between the measured and calculated fluid level values is $67 \div 82$m. The average calculated dynamic level value is 193. According to the convergence criterion (6): $193=(193 \div 184)$, which attests to the reliability of data obtained by calculation and confirms their applicability in solving problems related to optimal control of well operating modes.

For wells suitable for the non-stationary fluid withdrawal study, the time period for monitoring the water cut in well products was calculated at minimum and maximum number of swings.

The water cut of the extracted fluid is monitored with a glance to this time period, when the reservoir fluid reaches the wellhead flow moisture meter. It is the time interval, which allows a reliable determination of the fluid water content [21, 22].

To ensure the optimal well operating mode in case of a non-stationary fluid withdrawal mode, a consistent pattern is observed manifesting itself as lowering water content of the fluid depending on the depression cycles.

Figure 17 shows graphs of changing average product water content during 2 hours and the 2-hour oil mass at the oil metering unit for the entire period of field research.
5. Discussion
The laboratory studies of transient processes revealed that the pressure change occurs exponentially over time $5\tau_{n3}$, during which the pressure changes by 99.3% of the created pulse pressure, while the reservoir response continues. To effectively control the filtration pressure wave, it is advisable to use the pump operating mode change period equal to the reservoir response time $3\tau_{n1}$, since during this time the pressure changes by 95% of the created pulse pressure. It was found that after a period of time exceeding $3\tau_{n3}$ the pressure changes slower, while $3\tau_{n2}$ is different for each experiment, since the reservoir-well-pump simulation system is influenced by the change in the system's hydraulic resistance.

Based on the results of field studies conducted with the use of the appropriate producing well operating mode control tools, there are options for periodic generation of impulses to the reservoir with subsequent pump stop, where it is seen that the change of the pump engine speed from the maximum value to the specified minimum value leads to a change in the pressure on the reservoir, when porous reservoir blocks accumulate pressure energy almost equal to the reservoir pressure during the build-up period, and then, during pumping, oil is squeezed out of the pore space into cracks under the influence of the difference $P(p_l - P_1)$. This oil moves towards the bottomhole through the cracks. Therefore, we can state that when stopping the well, the fluid water content decreased somewhat before the start of non-stationary treatment. However, the reliability of this fact requires multiple verifications. For this purpose, the procedure for evaluating the water content reduction effect has been changed. Figure 18 shows graphs of changing average product water content during 2 hours and the 2-hour oil mass at the oil metering unit for the entire period of field research. After obtaining the time constants $\tau$ for the build-up and pumping sub-steps and 95% durations of the amplitude of each of them, equal to $3\tau$, the time of fluid portion movement from the pump intake to the moisture meter and the time (1 hour) required to count reliable moisture meter values was added thereto, since the fluid flow through the pump is stationary only at this time interval, i.e. the pump flow rate is equal to the inflow from the reservoir. The time from the start of pumping to the first vertical dotted line is 95% of the disturbance amplitude. The adjustable parameters are the amplitude and time of impact on the reservoir. The amplitude can be adjusted by the difference between the maximum and minimum quantities, i.e. the flow rate of the fluid pumped. The exposure time is tuned by the software using a controller that controls the frequency control electrical converters. This is done to be able to watch the process of water content reduction in the fluid and identify the time to stop the non-stationary withdrawal based on a certain criterion (minimum water content of the fluid).
6. Summary and conclusions

It is confirmed that the pressure change occurs exponentially over time $5\tau_{ns}$, during which the pressure changes by 99.3% of the created pulse pressure;

It is revealed that, to effectively control the filtration pressure wave, it is advisable to use the pump operating mode change period equal to $3\tau_{ns}$, since during this time the pressure changes by 95% of the created pulse pressure;

It was found that the reservoir response time $3\tau_{ns}$ for each transient process is different, since the reservoir-well-pump simulation system is influenced by the change in the system's hydraulic resistance;

To identify the optimal period of non-stationary impact on the reservoir from the producing well, it is recommended to obtain the reservoir response time $\tau_{ns}$ at the maximum and minimum fluid withdrawal.

In case of non-stationary well operation, the well flow rate increases and its water cut decreases in comparison with stationary and periodic operating modes. During the stationary mode, the average oil flow rate at the metering unit was 10.245 m$^3$/day with an 80.1% water content. In case of the non-stationary mode, the average oil flow rate at the metering unit was 15.2 m$^3$/day with a 76.28% water content.

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