Optimization of accumulation and pumping periods during well cyclic operation

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Abstract. In this work, the authors have expanded the boundaries of the scientific and methodological foundations of the effective operation of wells in the short-term periodic mode of their operation. Based on the symbiosis of numerical, physico-mathematical and hydrodynamic modeling methods, the mechanism of fluid inflow to the well is investigated, in particular, the need for a differentiated approach to determining the optimal periods of accumulation and drainage of deposits is substantiated in detail. Based on the proposed mathematical formulas, an integral assessment of the variation in the values of the periods of accumulation and selection of liquid was made, which, in conditions of a significant deterioration in the energy state of deposits, will allow the subsurface user to obtain additional oil production from a fund that is low-profitable for habitual operation. The models developed by the authors, describing the dependence of pressure changes on time when working in a short-term periodic mode, have a wide range of use due to their adaptation to various mining and geological conditions of field development.

1 Introduction

The optimal well operation mode is when the duration of the accumulation and pumping periods is determined on the basis of the maximum profit from the produced fluid.

The paper summarizes the dependence of the fluid pressure in a well on the time of the entire cycle. It provides formulas that determine the optimal values of the accumulation and pumping period, provided that such parameters as the productivity ratio of the neighboring formations, formation pressure and pump capacity are constant [1-5].

Over time these parameters undergo certain changes, therefore, the study proposes the method for their recalculation for subsequent adjustment of accumulation and pumping periods. The recalculation is carried out based on the measurement data of a number of pressure values at pump suction using the bottomhole-wellhead communication channel. This method reduces well service time and operating costs.

The purpose of the study is to find a time dependence of pressure in a well throughout the cycle, to determine the optimal values of the accumulation period T and pumping period t₁, which ensure the greatest profit from the produced fluid [6].

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2 Methods and materials

The extraction of formation fluid requires material and financial investments. This factor impacts the method of production management.

Let us introduce the designations: \( \alpha \) – value of the unit of time spent on well servicing and associated expenses (in the sense of the amount of associated expenses: depreciation, current repair and maintenance, oil treatment and transportation, etc.; a priori we can accept \( \alpha = 200 \text{ rub/h} = 0.0556 \text{ rub/s} \)); \( \beta \) – value of the unit of pump operating time (it can be assumed that \( \beta \) is the uninterrupted electric power consumption of the pump drive expressed in monetary units; in the first approximation let us accept \( \beta = N \cdot C_{\text{el}} = 20 \text{ kW} \cdot 5 \text{ rub/(kW} \cdot \text{h}) = 100 \text{ rub/h} = 2400 \text{ rub/day} = 0.0278 \text{ rub/s} \) (\( N, C_{\text{el}} \) – drive power and cost of electricity)); \( \gamma \) – value of the unit volume of produced fluid (cost per unit volume of fluid (oil) at delivery at the oil receiving unit; in the first approximation let us take \( \gamma = 18000 \text{ rub/m}^3 \)).

The value of the fluid produced per unit time is \( \gamma q \), where \( q \) – average production per unit time, or the average pump capacity. The extraction of fluid makes sense when its value exceeds the cost of its extraction:

\[
\gamma q > \alpha + \beta .
\]  \( \text{(1)} \)

Let \( Q \) be the well flow rate. Continuous pumping is possible only when the pumped volume is constantly replenished with the arriving fluid: \( q \leq Q \). For a stripped well, the low pump capacity \( q \) may not be enough to satisfy the inequality (1). It is required to use a pump with a higher capacity than the well flow rate [7-9]:

\[
q > Q .
\]  \( \text{(2)} \)

Condition (2) means that continuous pumping is not possible. The well is put into a cyclic mode of operation, where the periods of fluid accumulation \( T \) alternate with pumping periods \( t_1 \).

3 Results and Discussion

The fluid production cycle is divided into two temporary parts. During the first period of the \( 0 \leq t \leq T \) cycle (accumulation period) the pump does not work. At the beginning, the fluid column above the level \( E \) of the pump suction provides pressure \( p_0 \) large enough to exclude the release of gas at the suction and ensure the normal operation of the pump (Fig. 1). Then fluid arrives from neighboring formations into the annulus, and its variable level \( C \) rises from the initial \( D \) at \( t = 0 \) to the level \( B \) at \( t = T \). At the moment \( t = T \) the pump is turned on and the second \( T \leq t \leq T_1 \) period begins – the pumping period. According to (2), pumping occurs faster than fluid inflow, so level \( C \) drops to the original \( D \). Thus it is required:

- To find the dependence of pressure in the annulus on time during the whole cycle.
- To find accumulation periods \( T \) and pumping periods \( t_1 = T_1 - T \) ensuring the greatest profit from the produced fluid [10].
- To specify the algorithm for determining new values of formation pressure \( p_{\text{fcr}} \), well productivity index \( k \), pump capacity \( q \) so that values \( T, t_1 \) can be recalculated and pump operation corrected.

The latter requirement is explained by the fact that the parameters of the neighboring formations and equipment change over time.

The following assumptions were made:

- Pumping is performed with fixed capacity \( q \).
Fluid density $\rho$ in a well is the same, i.e., gas release in the upper layers is not taken into account.

Well productivity index $k$ and formation pressure $p_{\text{for}}$ are constant throughout the cycle.

The part of the well below the pump does not have to be vertical. Therefore, in the general case, $F$ – level of fluid inflow into the well, $p_3(t)$ – fluid pressure at this level.

Fig. 1. Design diagram: pump is off, fluid from the neighboring formations flows into the well: A – level from which the formation pressure is calculated; B – maximum level of fluid lift in the annulus; C – variable fluid level; D – fluid level ensuring the absence of gas release at the pump suction; E – level of pump suction; F – bottomhole level; $p(t)$ – pressure of the fluid column at level D; $p_0$ – pressure sufficient to prevent gas release at the pump suction; $p_3(t)$ – fluid pressure at the bottomhole; $p_{\text{for}}$ – formation pressure.

$$p_3(t) = p(t) + \rho gh,$$  \hspace{1cm} (3)

Where $\rho$ – fluid density, $g$ – acceleration of gravity, $h=DF$ – constant height of the fluid column in a well above the bottomhole.

Well flow rate at any given time $t$ (volume of fluid delivered per unit time):

$$Q = k[p_{\text{for}} - p_3(t)],$$

Where $k$ – well productivity ratio, $p_{\text{for}}$ – formation pressure. The values $k$ and $p_{\text{for}}$ are considered constant in time. By substituting (3), we get:

$$Q = k[A - p(t)],$$  \hspace{1cm} (4)

Where $A$ – constant, $A = p_{\text{for}} - \rho gh$.

In an instant period $dt$ we get the following volume:

$$dV = Qdt = k[A - p(t)]dt.$$  \hspace{1cm} (5)

Let $V(t)$ be the volume of fluid filling the annulus with the height $CD$ at the moment $t$. It creates pressure at level $D$:

$$p(t) = \frac{\rho g V(t)}{S}$$  \hspace{1cm} (6)

Where $S$ – cross-sectional area of the annulus. Let us determine $p(t)$ for each period of well operation.

During $0 \leq t \leq T$ period with the pump turned off, the pressure $p(t)$ of the flowing fluid
increases from \( p(0)=0 \) to \( p(T)=p_t \). The fluid column \( DF \) is constant, so the incoming fluid will fill the space above level \( D \). In accordance with (5), the following volume will enter the well over time \( t \):

\[
V(t) = k \int_0^t [A - p(t)]dt. \tag{7}
\]

By substituting (7) in (6) we get the equality:

\[
p(t) = a \int_0^t [A - p(t)]dr,
\]

Where:

\[
a = \frac{\rho g k}{S}. \tag{8}
\]

The differentiation of both parts of equality gives:

\[
p'(t) = a[A - p(t)].
\]

Given the condition \( p(0)=0 \), we get a solution to this differential equation:

\[
p(t) = A(1 - e^{-at}). \tag{9}
\]

By substituting (9) in (3) will get:

\[
p_1(t) = A(1 - e^{-at}) + \rho gh. \tag{10}
\]

The diagram of functions (9) and (10) is shown in Figure 2.

Fig. 2. Pressure buildup curves (PBC): a – at level \( D \); b – down the hole; \( p_0=20 \text{ atm} \), \( p_{for}=120 \text{ atm} \), \( S=0.0028 \text{ m}^2 \), \( \rho=900 \text{ kg/m}^3 \), \( g=g=9.81 \text{ m/s}^2 \), \( h=826.5 \text{ m} \), \( k=0.085 \text{ m}^3/(\text{day} \cdot \text{atm}) \).

At the end moment \( t=T \) of the first part of the cycle at level \( D \), the pressure equals:
\[ p(T) = A(1 - e^{-at}), \]  
(11)

And down the hole \( F \):

\[ p_3(T) = (p_m - \rho gh)(1 - e^{-at}) + \rho gh. \]

By substituting (9) in (7), we will find the volume of accumulated fluid above level \( D \) at this moment:

\[ V(T) = \int_0^T kAe^{-at} \, dt = \frac{kA}{a}(1 - e^{-at}). \]

(12)

In the second part of the cycle, during period \( T < t \leq T_1 \) the pump lifts the fluid at a constant average productivity \( q \). During \( dt \), it pumps out the volume \( qdt \). During the same time, the volume \( Qdt \) will get into the well, so the actual loss of fluid in the annulus is equal \( (q - Q)dt \), or, according to (4), \( \{q - k[A - p(t)]\}\,dt \). Over the period of time \( [T, t] \) the losses will make:

\[ \Delta V(t) = \int_T^t \{q - k[A - p(t)]\}\,dt. \]

The initial volume \( V(T) \) will decrease by \( \Delta V \), so the volume of fluid in the annulus at any moment \( t \in [T, T_1] \) will be equal to:

\[ V(t) = V(T) - \Delta V(t) = V(T) - \int_T^t \{q - k[A - p(t)]\}\,dt. \]

(13)

Let us substitute (13) in (6):

\[ p(t) = \frac{\rho g}{S} \left[ V(T) - \int_T^t \{q - k[A - p(t)]\}\,dt \right]. \]

The differentiation of both parts by \( t \) leads to the equation:

\[ p'(t) = a[A - p(t)] - b, \]

Where \( b = \frac{\rho gq}{S} \).

Taking into account the condition \( p_3 = p(T) \), we get a specific solution:

\[ p(t) = \left( p_T - A + \frac{b}{a} \right)e^{-at} + A - \frac{b}{a}. \]

Let us substitute \( p_1 \) from (11):
Pressure at level $D$ during pumping is determined by this formula. Note that:

$$\frac{b}{a} = \frac{q}{k}. \quad (14)$$

Let us combine both cases and write the dependence of pressure at level $D$ on time for the entire cycle:

$$p(t) = \begin{cases} 
A(1 - e^{-at}) & \text{при } t \in [0, T]; \\
\left(\frac{b}{a} - Ae^{-at}\right)e^{-a(t-T)} + A - \frac{b}{a} & \text{при } t \in [T, T_1],
\end{cases} \quad (15)$$

By substituting (15) in (3), we will find a dependence of the bottomhole pressure on time.

Pumping ends at $t = T_1$ when level $C$ drops to level $D$. At this point, $p(T_1) = 0$. In this equality we substitute (15, b) at $t = T_1$:

$$\left(\frac{b}{a} - Ae^{-at}\right)e^{-a(T-T_1)} + A - \frac{b}{a} = 0.$$  

Here $t_1 = T_1 - T$ – duration of the second part of the cycle. From this equation we will find:

$$t_1(T) = \frac{1}{a} \ln \frac{\frac{b}{a} - A}{\frac{b}{a} - Ae^{-at}}. \quad (16)$$

The pumping time depends on the accumulation time. The duration of the entire cycle equals:

$$T_1 = T + t_1 = T + \frac{1}{a} \ln \frac{\frac{b}{a} - A}{\frac{b}{a} - Ae^{-at}}.$$  

During the cycle, the pump pumps out the volume:

$$V(T) = qt_1(T) = \frac{q}{a} \ln \frac{\frac{b}{a} - A}{\frac{b}{a} - Ae^{-at}}.$$
By defining $T$ and $t_1$, we can build the dependence diagram (15).

![Diagram showing pressure change at level $D$ in two cycles during periodic pumping $q=12$ m$^3$/day (reservoir properties and fluid characteristics are the same as in Figure 2).](image)

**Fig. 3.** Pressure change at level $D$ in two cycles during periodic pumping $q=12$ m$^3$/day (reservoir properties and fluid characteristics are the same as in Figure 2).

The flow rate change $Q(t)$ in cyclic pumping is shown in Fig. 4.

![Diagram showing flow rate of the well in two cycles (reservoir, fluid and pump characteristics are the same as in the previous figures).](image)

**Fig. 4.** Flow rate of the well in two cycles (reservoir, fluid and pump characteristics are the same as in the previous figures).

In cycle $T+t_1$, the costs equal $\alpha(T+t_1)$, $\beta t_1$, and the revenue is $\gamma q t_1$. Therefore, the profit per cycle is:

$$\Pi = \gamma q t_1 - \alpha(T + t_1) - \beta t_1.$$  

Let us modify the right side:

$$\Pi = (\gamma q - \alpha - \beta)t_1 - \alpha T,$$

And substitute $t_1$ from (16):
\[ \Pi(T) = \frac{\gamma q - \alpha - \beta}{a} \ln \frac{b}{a - A} - \alpha T. \]  
\[ (17) \]

Maximum \( P(T) \) is reached at:

\[ T_{\text{opt}} = \frac{1}{a} \ln \frac{Aa(\gamma q - \beta)}{\alpha b}, \]
\[ (18) \]

or, taking into account the ratio (14):

\[ T_{\text{opt}} = \frac{1}{a} \ln \left( \frac{\gamma q - \beta}{\alpha q} \right). \]

The formula defines the cost-effective duration of the first period in a cycle. By substituting (18) in (16), we can find the duration \( t_1 \) of the second period.

Let us denote:

\[ \delta = \gamma q - \beta. \]

Condition \( T_{\text{opt}}>0 \) implies a limitation \( \alpha < Aa\delta/b. \)

By substituting (18) in (17) we get the formula for calculating the maximum profit per cycle:

\[ \Pi_{\text{max}} = \frac{\delta - \alpha}{a} \ln \frac{b}{a - A} \left( 1 - \frac{\alpha}{\delta} \right) + \frac{\alpha}{a} \ln \frac{\alpha b}{Aa\delta}. \]

The procedure for calculating \( T_{\text{opt}}, t_{1\text{opt}} \) and \( V \) for the cycle is shown in the tables below.

### Table 1. Input data for \( T_{\text{opt}} \) calculation.

<table>
<thead>
<tr>
<th>( p_{\text{tor}} ), atm</th>
<th>( p_{0} ), atm</th>
<th>( \rho ), kg/m(^3)</th>
<th>( g_{r} ), m/s(^2)</th>
<th>( h ), m</th>
<th>( k ), m(^3)/day-atm</th>
<th>( q_{r} ), m(^3)/day</th>
<th>( S ), m(^2)</th>
<th>( a_{b} ), rub/s</th>
<th>( \beta ), rub/s</th>
<th>( \gamma ), rub/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>115.4</td>
<td>20</td>
<td>900</td>
<td>9.81</td>
<td>826.5</td>
<td>0.096</td>
<td>12</td>
<td>0.0028</td>
<td>0.0556</td>
<td>0.0288</td>
<td>18000</td>
</tr>
</tbody>
</table>

### Table 2. Calculation results.

<table>
<thead>
<tr>
<th>( a ), 1/s</th>
<th>( b ), kg/m(^3)/s</th>
<th>( A ), atm</th>
<th>( T_{\text{orr}} ), h</th>
<th>( t_{1\text{orr}} ), h</th>
<th>( V ), m(^3)/cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.52 \cdot 10^{-5}</td>
<td>4.38 \cdot 10^{-4}</td>
<td>42.41</td>
<td>18.26</td>
<td>3.02</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Parameters:

\[ A = p_{\text{tor}} - \rho gh \quad a = \rho gk/S, \]
\[ (19) \]

Determining the dependence of pressure on time in formula (15) also change over time due to changes in the characteristics of the formation, produced fluid, (variability in
formation pressure due to the operation of formation pressure maintenance, water cut, viscosity, gas content, colmatation of the pores of the bottom-hole area, wear of the pump, casing, etc. It becomes necessary to recalculate them in order to correct the time of accumulation $T$ and pumping $t_1$.

We can define these parameters using the least squares method. The expression (15, a) is represented as:

$$A(1-e^{-at}) - p = 0,$$

(20)

Where $p$ – pressure at level $D$ determined by the formula:

$$p = p_{by example} - p_0.$$

Let at the moments $t_1, t_2, \ldots, t_n$ after the pump was stopped, the pressure measurements are made and at level $D$ the values $p_1, p_2, \ldots, p_n$ are obtained. In general, not all corresponding pairs of $t_i, p_i$ $(i = 1, n)$ turn the left side in (20) to zero. Let us make the sum of squares of deviations from zero:

$$f(a, A) = \sum_{i=1}^{n} [A(1-e^{-at_i}) - p_i]^2,$$

(21)

By minimizing $f(a, A)$ we get the desired values $a, A$.

Let the pressure measurements during the accumulation period give the following results: $t_1= 1$ h, $p_1=5$ atm; $t_2= 2$ h, $p_2=10$ atm; $t_3= 3$ h, $p_3=13$ atm; $t_4= 4$ h, $p_4=17$ atm.

In this case, the minimum of the function $f(a, A)$ is achieved at $a=3.521 \cdot 10^{-5}$ s$^{-1}$, $A = 4.241 \cdot 10^6$ Pa.

Hence $p_{for} = A+ pgh = 115.4$ atm; $k=aS/\rho g = 1.117 \cdot 10^{-11}$ m$^3$/s Pa = 0.096 m$^3$/day$\cdot$atm.

Now let us calculate the optimal $T$ and $t_1(T)$. Having values $a=3.521 \cdot 10^{-5}$, $A=4.241 \cdot 10^6$, $q=1.221 \cdot 10^{-4}$, $\alpha=0.0556$, $\beta=0.0288$, $\gamma=18000$ by formulas (18) and (16) we get $T_{opt}=18.26$ h, $t_{1opt}=3.02$ h.

During the cycle the pump pumps out the volume $V=qt_{1opt}=1.51$ m$^3$.

4 Conclusion

Thus, the pressure build-up determined by bottomhole pressure measurements makes it possible to significantly simplify and optimize the process of selecting the period of fluid accumulation in stripped wells during periodic operation. Besides, if there is a bottomhole-wellhead communication channel, the startup and shutdown time of the suction pump can be automated according to the commands of the controller, which takes data from the pressure sensor to build the current pressure build-up and calculate $T_{opt}$.

References