EVALUATION OF RESERVOIR ENERGY CONSUMPTION DURING OIL WELL OPERATION ON THE NORTH PERM REGION

M. Wiercigroch¹, V.V. Poplygin, D.Iu. Rusinov

¹University of Aberdeen (39 Meston Building, Aberdeen, AB24 3UE, Scotland)
Perm National Research Polytechnic University (29 Komsomolskii av., Perm, 614990, Russian Federation)

ОЦЕНКА ИЗМЕНЕНИЯ ЗАТРАТ ПЛАСТОВОЙ ЭНЕРГИИ ПРИ ЭКСПЛУАТАЦИИ СКВАЖИНЫ НА СЕВЕРЕ ПЕРМСКОГО КРАЯ

М. Уирсигрох, В.В. Поплыгин, Д.Ю. Русинов

¹Абердинский университет (AB24 3UE, Шотландия, г. Абердин, Местон Билдинг, 39)
Пермский национальный исследовательский политехнический университет (614990, Россия, г. Пермь, Комсомольский пр., 29)

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In the article an account of extensive investigations of a well with carbonate deposits operating over a period of 44 months in Perm Region is given. Two well production enhancement techniques were used, namely abrasive jet perforation and acid treatment. A detailed analysis of abrasive jet perforation and acid treatment results was carried out, where changes of productivity index depending on reservoir and bottomhole pressures after operations were evaluated. It was shown, that an incremental oil production can significantly decrease with decreasing reservoir and bottomhole pressures. It was found that during the abrasive jet perforation with acid treatment, an incremental oil production has increased for abrasive jet perforation and acid treatment to about 65 % and 35 % respectively. It was also shown, that the abrasive jet perforation helps to slightly increase a well rate and decrease a reservoir energy consumption for fluid communications in bottomhole formation zone. After the acid treatment taking place two years later, oil production was increased and it is understood that 15 % of this increase is due to acid attack, and on 85 % due to growth in bottomhole pressure and fracture permeability. There was revealed a complete exclusion of reservoir energy consumption to overcome the additional filtration resistance immediately after conducting operations. The reservoir has an excellent intrinsic fracturing property, so bottomhole formation permeability and energy consumption significantly depend on the reservoir and bottomhole pressures. It is recommended to maintain reservoir and bottomhole pressures higher than lateral rock pressure to increase effectiveness of well operations in reservoirs with advanced natural fracturing.

Марьян Уирсигрох – PhD of Technical Sciences, Professor at the School of Engineering (тел.: +440 122 427 25 09, e-mail: m.wiercigrouch@abdn.ac.uk).
Владимир Витальевич Поплыгин – PhD of Technical Sciences, Associate Professor at the Department of Oil and Gas Technologies (тел.: +007 342 219 82 38, e-mail: poplygin@bk.ru).
Дмитрий Юрьевич Русинов – postgraduate student at the Department of Oil and Gas Technologies (тел.: +007 342 219 82 07, e-mail: rusinovdu@bk.ru). The contact person for correspondence.
Introduction

In oil well operations a decrease in flow rates and an increase in reservoir energy consumption are usually due to various factors including collector deformation, degassing, salt and paraffin deposition. To increase flow rates and reduce reservoir energy consumption a variety of production enhancement methods can be applied.

And after conducting production enhancement operations, the impact on the increase in oil production of various technological parameters should be assessed.

One of the effective methods to increase well productivity and reduce reservoir energy consumption for fluid movement in the bottomhole formation zone is the abrasive jet perforation technology.Perm scientists under the leadership ofN.I. Krysin [1] have developed a method of creating deep filtration channels using the features of the dynamic behavior of abrasive jet perforation in a combination with Production Tubing (PT) lift and an appropriate implementation of the relevant regimes of Abrasive Jet Perforation (AJP). Unlike the known and established technologies, it is recommended to make AJP without the use of perforator's movers and centering devices. Long, wide slots are formed due to the PT column extraction in the transition from one to another operating mode, the longitudinal and transverse vibrations of perforator are generated. AJP is performed in two stages at the working pressures of twenty and thirty MPa (for wells up to 2500 meters). During the performance in the first stage, there is a creation of slot channels in the production casing, cement, and reservoir rock to a certain depth. In the second stage there is an increase in the length of the PT, ashift of AJP and formation of slot filter channels below the place where cracks were formed during the first stage and deepening of the slots already created. At the same in the second stage, a speed of creating perforation channels increases significantly because of a more high-speed sand carrier liquid discharge from nozzles reducing a backflow resistance. The created slot filtration channels increase in transverse dimensions due to the longitudinal and transverse vibrations of abrasive jet perforator. As a result of these actions at each run using the perforator with four nozzles, it is possible to cut four channels disposed at an angle of 90°. This allows to obtain a significant increase in filtration area and reduction of filtration resistance.

Operating practice of abrasive jet perforation

The paper deals with indicators of well operating in fractured carbonate reservoir on one of the fields of the Perm Region (Table 1).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The average total thickness, m</td>
<td>28.2</td>
</tr>
<tr>
<td>Average oil saturated thickness, m</td>
<td>4.4</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>15</td>
</tr>
<tr>
<td>Core permeability, µm²</td>
<td>0.008</td>
</tr>
<tr>
<td>Initial reservoir temperature, °C</td>
<td>23</td>
</tr>
<tr>
<td>Initial reservoir pressure, MPa</td>
<td>15.5</td>
</tr>
<tr>
<td>Oil viscosity at reservoir conditions, mPa·s</td>
<td>2.41</td>
</tr>
<tr>
<td>Oil density at reservoir conditions, g/cm³</td>
<td>0.804</td>
</tr>
<tr>
<td>Oil density in the surface conditions, g/cm³</td>
<td>0.839</td>
</tr>
<tr>
<td>Paraffin content in oil, %</td>
<td>2.71</td>
</tr>
<tr>
<td>Saturation pressure, MPa</td>
<td>13.58</td>
</tr>
<tr>
<td>Gas content, m³/t</td>
<td>53.8</td>
</tr>
</tbody>
</table>

Over the well lifetime, two well production enhancement operations were performed, the AJP with the acid treatment and two years later only acid treatment.

For the AJP a perforator of construction [2] was used. The AJP parameters in the well were as follows: perforator nozzle's diameter \(d_{noz}\) 6 mm, sand carrier liquid density \(\rho_{sl}\) 1057.75 kg/m³, PT of K brand with diameter \(d_{PT}\) 73 mm, number of perforator's nozzles \(n\) 2 units. A quartz sand of the GS-PK brand (fractions of 1.0...0.63) was used. The AJP was conducted in two stages wherein the first the injection pressure of the sand carrier liquid was 20 MPa and in the second – 30 MPa. By increasing the injection pressure of the sand fluid carrier, an extension of the PT column and vertical cuts and channels were achieved. The rock cavern is washed out into a pear shape which size depends on the rock strength, the duration of exposure and the power of sand and liquid jet (Fig. 1).

![Fig. 1. A schematic of the bottomhole formation zone after AJP where 1 – casing string; 2 – cement stone; 3 – rocks; 4 – perforation channel](image-url)
Six cuts in the production casing were made at depths from 1836.2 to 1830.8 m by pumping of either 1960 or 700 kg of sand on each level. The injection time on each mode was between 15 and 20 min. After the AJP process, a hydrochloric acid treatment was conducted with the DN-9010 to increase the volume of filtration channels.

The height of slots formed at the working pressure \(P_1\) of 20 MPa will be called the first mode and at the working pressure \(P_2\) of 30 MPa the second mode.

**Results in estimation of AJP**

With a cross-section area of the PT \((S_{p,PT})\) of 0.00302 m\(^2\) and a cross-section area of the PT metal \((S_{m,PT})\) – of 0.00116 m\(^2\), the PT column extension in the first mode \(\Delta L_{PT1}\) will be:

\[
\Delta L_{PT1} = \frac{P_1 \cdot S_{p,PT} \cdot L_{PT}}{E \cdot S_{PT} \cdot z} = \frac{20 \cdot 0.00302 \cdot 1836.2}{20 \cdot 10^4 \cdot 0.00116 \cdot 1.75} = 0.273 \text{ m},
\]

where \(E\) is Young's modulus in Pa; \(z\) is coefficient taking into account the friction between the pipe and casing wall.

The PT column extension during the second mode \(\Delta L_{PT2}\) was 0.410 m. Then the height of the slot \((l_p)\) was 0.137 m.

According to [3–7], for specified conditions of the AJP, the slot depth is 22 cm. We believe that the layer in the well area was homogeneous prior to the AJP, and its average permeability, according to the HDI, was 0.032 m\(^2\). After the AJP we assume that the fluid flow to the well is described by the model of zonal inhomogeneous reservoir. It is divided into 2 zones, zone 1 where there is a slot and zone 2 where there is no slot. Then, based on the formula of zonal inhomogeneous flow we can determine the permeability in region 1, which amounted to 0.033 µm\(^2\).

Immediately after the placing in operation its production rate became equal to 36.5 m\(^3\)/day, while the relative bottomhole and reservoir pressure were 0.45 and 0.99, respectively, and the productivity ratio was 6.2 m\(^3\)/(day·MPa).

According to [8–12] the production rate after acid treatment during AJP should increase by 4.2 m\(^3\)/day. Expected initial well production \(Q_{ex}\) can be identified by the multivariate statistical dependence [8]:

\[
Q_{ex} = A + A_p \left( \frac{P_{res}}{P_{sat}} \right) + A_n \cdot \mu_n + A_h \cdot h + A_m \cdot K_p + A_k \cdot k + A_f \left( \frac{k}{l_{oil}} \right).
\]

The coefficients of the multivariate model \(A, A_p, A_n, A_h, A_m, A_k, A_f\) are determined for specific geological and technical conditions of the development. In terms of operational objects of the Upper Kama region for the Bashkirian deposits the following values were established \(A = 2.2; A_p = 11.85; A_n = -2.534; A_h = 0.574; A_m = 0.831, A_k = 0, A_f = 0\).

On the basis of equation (2) for the well the initial flow rate without enhanced operation's conducting had to be 12.4 m\(^3\)/day. It turns out that due to AJP conducting the well production increased to 19.9 m\(^3\)/day. That is, each run with AJP provided an increase in production of about 3 m\(^3\)/day.

**Dynamics of well performance**

When changing the relative bottomhole pressure from 0.45 to 0.25, the value of the well productivity index has declined from 6.2 to 1 m\(^3\)/(day·MPa). Also the well oil flow rate decreased from 36.48 to 3.95 m\(^3\)/day.

In [13–16] it is indicated that a decline in well productivity coefficients is due to rock deformation and oil dissolved gas in a free phase. Let us consider what is a change in well productivity when changing of bottomhole pressure. According to the research undertaken in [17–19], the carbonate reservoirs of the Ozernoe field and the neighboring fields have substantial fracturing. Closures of vertical fractures occur during pressure decreasing below the lateral rock pressure, which for the Ozernoe field’s conditions was determined by the method described in [17]. With an average density of rocks 2650 kg/m\(^3\) and a total porosity of about 15 % for the Ozernoe field’s conditions, the lateral rock pressure is around 5.90 MPa.

Let us estimate the general and fracture permeability of rocks in the area of the well within two years following the AJP (see Table 1). According to the data both the general and fracture permeability of rocks significantly declined, resulting in a significant decrease in well production. It is worth noting, that the bottomhole pressure at the borehole walls was below the lateral rock pressure. The average pressure in the bottomhole zone remained above \(P_{hbb}\) so fracture permeability did not reduce to 0 (Table 2).
Table 2

<table>
<thead>
<tr>
<th>Time after entering into operation, months</th>
<th>$Q_{oil}$, m$^3$/day</th>
<th>$P_{res}$, MPa</th>
<th>$P_{bott}$, MPa</th>
<th>$k_{frac}$, $10^{-3} \mu m^2$</th>
<th>$k_{total}$, $10^{-3} \mu m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary completion with AJP and acid treatment</td>
<td>1</td>
<td>36.48</td>
<td>12.23</td>
<td>6.03</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>30.93</td>
<td>12.23</td>
<td>3.89</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>10.84</td>
<td>12.23</td>
<td>3.83</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>9.64</td>
<td>12.23</td>
<td>3.12</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>7.78</td>
<td>12.23</td>
<td>2.78</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>3.95</td>
<td>14.51</td>
<td>3.11</td>
<td>0.21</td>
</tr>
<tr>
<td>Acid treatment</td>
<td>23</td>
<td>36.23</td>
<td>14.50</td>
<td>5.30</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>34.23</td>
<td>14.50</td>
<td>9.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>26.26</td>
<td>14.11</td>
<td>7.69</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>24.96</td>
<td>14.11</td>
<td>6.47</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>22.31</td>
<td>14.27</td>
<td>3.71</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>14.92</td>
<td>14.58</td>
<td>2.43</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>13.81</td>
<td>14.58</td>
<td>2.65</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Fig. 2. Changing in well working parameters during the operation

The values of total and fracture permeability, productivity index reduced similar to the period following the AJP.

It is worth noting that with a decrease in the productivity ratios and the flow rates of the well after repeated acid treatment, they remained below the values at the same bottomhole pressure before the acid treatment (see Fig. 3).

Two years later after the AJP an acid treatment was carried out on the well with DN-9010 composition ($V_{acid} = 30$ m$^3$) with a simultaneous increase in bottomhole pressure in 1.8 times. Thereafter, the productivity index reached its initial value. The value of production rate increase after acid treatment exceeded the values obtained for the dependences of the [8–10, 20]. According to [8–10] the production rate had to increase by 4.88 m$^3$/day. It turns out that the rest of the production rate increase was due to changes in the bottomhole pressure. Within two years after the acid treatment the bottomhole pressure decreased, and at the same time production rate reduced (see Table 2).

Fig. 3. Dependence of the well productivity index from relative bottomhole pressure

**Estimation of reservoir energy loss**

According to the Dupuis formula for fluid inflow into the well, its production rate (for a radial linearly flow in a homogeneous reservoir) can be calculated as

$$ q = \frac{2\pi kh(P_{res} - P_{bott})}{\mu \ln \left( \frac{r_b}{r_w} \right)} \text{, m}^3/\text{s}, \tag{3} $$

where $k$ – reservoir permeability, m$^2$; $P_{res}$ and $P_{bott}$ – reservoir and bottomhole pressure, Pa; $\mu$ – dynamic viscosity of the fluid, Pa·s; $r_w$ and $r_b$ – well radius and external boundary radius (reservoir drainage area radius of the well).

In case of reducing the permeability of in a circular reservoir area around the well with a radius of $r_{BFZ}$, a fluid inflow decreases as follows

$$ q_s = \frac{2\pi k_{BFZ} h(P_{res} - P_{bott})}{\mu (\ln \left( \frac{r_b}{r_w} \right) + S)} \text{,} \tag{4} $$

where $k_{BFZ}$ – remote formation zone permeability; $S$ – skin factor – the value which depends on the permeability of BFZ and its size is:

$$ S = \left( \frac{k_{BFZ}}{k_{BFZ}} - 1 \right) \ln \left( \frac{r_{BFZ}}{r_w} \right), \tag{5} $$

where $k_{BFZ}$ – rocks permeability in BFZ.

From (4) it follows

$$ S = \frac{2\pi k_{BFZ} h(P_{res} - P_{bott})}{q_s \cdot \mu} - \ln \left( \frac{r_b}{r_w} \right), \tag{6} $$
where $k_{BFZ}$ permeability can be determined by processing the pressure recovery curve, obtained by the study of unsteady well working modes.

Let us estimate the impact of changes in BFZ permeability on the reservoir energy consumptions in the well described in Table 3.

When the pressure recovery curve is processed it was obtained: $k_{BFZ} = 0.0132$ $\mu$m$^2$; $k_{BFZ} = 0.0076$ $\mu$m$^2$, in accordance with (6) $S = -5.6$. That is, in the initial period after the enhancing operation the skin factor is negative and the state of bottomhole zone does not cause a significant loss in formation energy for the fluid inflow into the well. After 22 months following the AJP and acid treatment the BFZ condition deteriorated and skin factor increased to the value of 1.67.

Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net pay thickness $h$, m</td>
<td>4.4</td>
</tr>
<tr>
<td>Reservoir oil viscosity $\mu_{o, res}$, Pa·s</td>
<td>2.41·10$^{-3}$</td>
</tr>
<tr>
<td>Well radius $r_w$, m</td>
<td>0.1</td>
</tr>
<tr>
<td>External boundary radius $r_e$, m</td>
<td>250</td>
</tr>
<tr>
<td>Reservoir pressure $p_{res}$, MPa</td>
<td>12.23</td>
</tr>
<tr>
<td>Bottomhole pressure before stop $p_{bott}$, MPa</td>
<td>6.03</td>
</tr>
<tr>
<td>Well production before stop $q_{w}$, m$^3$/day</td>
<td>36.48</td>
</tr>
</tbody>
</table>

According to the formula (7), the loss of reservoir pressure to overcome the additional resistance in BFZ amounts as 0.17 MPa,

$$\Delta P_s = \frac{q_s \cdot \mu \cdot S}{2 \cdot \pi \cdot k_{BFZ} \cdot h}. \quad (7)$$

Thus, 1.5% of the total depression on a layer (formation energy) $\Delta P_{res} = P_{res} - P_{bott} = 11.4$ MPa is spent on overcoming the action of the skin effect in BFZ.

Table 4 lists the results of processing the PRC and the calculations for the well. After the second operation (acid treatment) additional losses of energy in the BFZ are not observed.

Table 4

<table>
<thead>
<tr>
<th>No.</th>
<th>Time after entering into operation, months</th>
<th>Flow rate $Q$, m$^3$/day</th>
<th>Depression on a layer, MPa</th>
<th>Skin factor</th>
<th>Additional pressure loss $\Delta P$, MPa</th>
<th>$\Delta P_s$ share of total depression, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>36.48</td>
<td>6.02</td>
<td>-3.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>30.93</td>
<td>8.34</td>
<td>-0.89</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>10.84</td>
<td>8.40</td>
<td>-0.85</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>9.64</td>
<td>9.11</td>
<td>-0.28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>7.78</td>
<td>9.45</td>
<td>0.03</td>
<td>0.01</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>3.95</td>
<td>11.4</td>
<td>1.67</td>
<td>0.17</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Conclusions

The paper analyzes the results of an abrasive jet perforation with acid treatment and acid treatment alone on one of the wells in the field of the Perm Region. It was found that during the AJP with acid treatment a growth in oil production by the AJP and acid treatments amounted to about 65 and 35% respectively. The acid treatment carried out two years later acid, has resulted in an increase of oil production, which was 15% due to the acid treatment and 85% due to the growth of bottomhole pressure and fracture permeability’s increase. Abrasive Jet Perforation helps to increase slightly well production rate and to decrease a reservoir energy consumption for fluid communications in the bottomhole formation zone. It is recommended to maintain the reservoir and bottomhole pressures higher than the lateral rock pressure for increasing effectiveness of well operations in reservoirs with advanced natural fracturing.

Acknowledgments

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