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

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

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abrasive jet perforation, acid treatment, permeability, bottomhole pressure, reservoir pressure, filtration resistance, skin factor, productivity index.

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 consumptions 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.

Ключевые слова:
щелевая гидропескоструйная перфорация, кислотная обработка, проницаемость, забойное давление, пластовое давление, фильтрационные сопротивления, скин-фактор, коэффициент продуктивности.

Тщательно исследована история работы одной из скважин, эксплуатирующих карбонатные отложения в Пермском крае. В течение рассматриваемого периода на скважине проводилось два геолого-технических мероприятия: щелевая гидропескоструйная перфорация (ЩГПП) и кислотная обработка. Выполнен анализ результатов щелевой гидропескоструйной перфорации и кислотной обработки, проведена оценка изменения прироста коэффициента продуктивности после геолого-технических мероприятий от значений пластовых и забойных давлений. В результате промысловых исследований отмечено, что дополнительная добыча нефти в ходе применения геолого-технических мероприятий может существенно снижаться при уменьшении забойных и пластовых давлений. Установлено, что при проведении ЩГПП с кислотной обработкой прирост добычи нефти за счет ЩГПП составил около 65 %, за счет кислотной обработки – 35 %. Отмечено, что щелевая перфорация помогает щадящим способом увеличить дебит скважины и снизить затраты пластовой энергии на движение флюидов в призабойной зоне скважины. После проведенной на скважине спустя два года кислотной обработки увеличение добычи нефти за счет воздействия кислотой составило 15 %, за счет роста забойного давления и увеличения трещинной проницаемости – 85 %. Выявлено полное исключение затрат пластовой энергии на преодоление дополнительных фильтрационных сопротивлений сразу после проведения геолого-технических мероприятий. Поскольку залежь, эксплуатируемая рассматриваемой скважиной, имеет развитую трещиноватость, то и значения проницаемости призабойной зоны пласта, затрат пластовой энергии будут существенно зависеть от уровней пластовых и забойных давлений. Для повышения эффективности проведения геолого-технических работ на месторождениях с развитой естественной трещиноватостью рекомендуется поддерживать забойные давления выше бокового горного давления.

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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 paraffindeposition. To increase flow rates and reduce reservoir energy consumptiona 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 of N.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 rockto a certain depth. In the second stage there is an increase in the length of the PT, ashiftof 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 eachrun 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 1

Geological and physical characteristics of a reservoir of the Perm Region

Characteristics	Value
The average total thickness, m	28.2
Average oil saturated thickness, m	4.4
Porosity, %	15
Core permeability, μm^2	0.008
Initial reservoir temperature, °C	23
Initial reservoir pressure, MPa	15.5
Oil viscosity at reservoir conditions, mPa·s	2.41
Oil density at reservoir conditions, g/cm^3	0.804
Oil density in the surface conditions, g/cm^3	0.839
Paraffin content in oil, %	2.71
Saturation pressure, MPa	13.58
Gas content, m^3/t	53.8

Over the well lifetime, two well production enhancement operations were performed, the AJP with the acid treatment and two years lateronly 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 (ρ_{sl}) 1057.75 kg/m^3, 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 apear shapewhich size depends on the rock strength, the duration of exposure and the power of sand and liquid jet (Fig. 1).

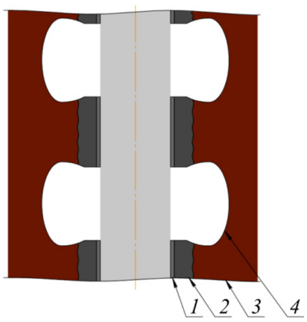

Fig. 1. A schematic of the bottomhole formation zone after AJP where *1* – casing string; *2* – cement stone; *3* – rocks; *4* – perforation channel

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 (ΔL_{PT_1}) will be:

$$\Delta L_{PT_1} = \frac{P_1 \cdot S_{p.\mathrm{PT}} \cdot L_{\mathrm{PT}}}{E \cdot S_{\mathrm{PT}} \cdot z} = \frac{20 \cdot 0.00302 \cdot 1836.2}{20 \cdot 10^4 \cdot 0.00116 \cdot 1{,}75} = 0{,}273\ m, \quad (1)$$

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 (ΔL_{PT_2}) was 0.410 m. Then the height of the slot (l_s) 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 1where 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 operationits 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]:

$$Q_{ex} = A + A_p\left(\frac{P_{res}}{P_{sat}}\right) + A_\mu \cdot \mu_{\text{н}} + A_h \cdot h + A_m \cdot K_p + A_k \cdot k + A_j\left(\frac{k}{\mu_{oil}}\right). \quad (2)$$

The coefficients of the multivariate model A, A_p, A_μ, A_h, A_m, A_k, A_j 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 $A = 2.2$; $A_p = 11.85$; $A_\mu = -2.534$; $A_h = 0.574$; $A_m = 0.831$, $A_k = 0$, $A_j = 0$.

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 inwell productivity coefficients is due to rock deformation and oil dissolved gas in afree 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 Ozernoye 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_{lat}, so fracture permeability did not reduce to 0 (Table 2).

Table 2

Changes in the work indicators and BFZ permeability during well operation

Time after entering into operation, months	Q_{oil}, m^3/day	P_{res}, MPa	P_{bott}, MPa	P_{res}/P_{sat}	k_{total}, 10^{-3}·μm^2	k_{frac}, 10^{-3}·μm^2
Secondary completion with AJP and acid treatment						
1	36.48	12.23	6.03	0.49	30.60	117.06
5	30.93	12.23	3.89	0.32	25.95	84.18
8	10.84	12.23	3.83	0.31	9.09	10.33
14	9.64	12.23	3.12	0.26	8.09	8.18
16	7.78	12.23	2.78	0.23	6.53	5.32
22	3.95	14.51	3.11	0.21	3.32	1.38
Acid treatment						
23	36.23	14.50	5.30	0.37	30.39	115.46
24	34.23	14.50	9.7	0.7	28.72	103.11
30	26.26	14.11	7.69	0.55	22.03	60.68
36	24.96	14.11	6.47	0.46	20.94	54.80
40	22.31	14.27	3.71	0.26	18.72	43.79
43	14.92	14.58	2.43	0.17	12.52	19.58
44	13.81	14.58	2.65	0.18	11.59	16.78

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 Fig. 2).

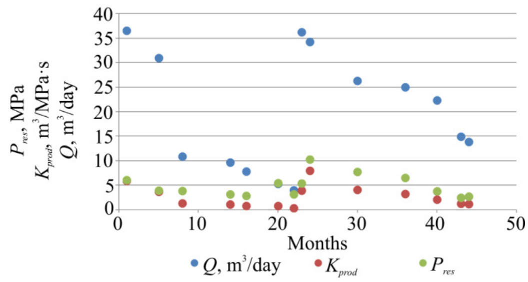

Fig. 2. Changing in well working parameters during the operation

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). Moreover, the well productivity coefficients do not fully recover after a significant reduction in pressure in the bottomhole formation zone. This phenomenon may be associated with plastic deformation of rocks. When we look at Fig. 3 it can be deduced that the well productivity decreases by half.

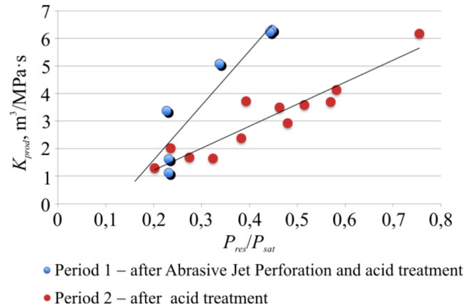

Fig. 3. Dependence of the well productivity index from relative bottomhole pressure

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

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

where k – reservoir permeability, m^2; P_{res} and P_{bott} – reservoir and bottomhole pressure, Pa; μ – 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

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

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

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

where k_{BFZ} – rocks permeability in BFZ.

From (4) it follows

$$S = \frac{2\pi k_{RFZ} h\left(P_{res} - P_{bott}\right)}{q_s \cdot \mu} - \ln \frac{r_b}{r_w}, \qquad (6)$$

where k_{RFZ} 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_{RFZ} = 0.0132 μm^2; k_{BFZ} = = 0.0076 μm^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

Initial data for the well

Parameter	Value
Net pay thickness h, m	4.4
Reservoir oil viscosity $\mu_{o\ res}$, Pa·s	$2.41 \cdot 10^{-3}$
Well radius r_w, m	0.1
External boundary radius r_b, m	250
Reservoir pressure P_{res}, MPa	12.23
Bottomhole pressure before stop P_{bott}, MPa	6.03
Well production before stop q_S, m^3/day	36.48

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

$$\Delta P_S = \frac{q_S \cdot \mu \cdot S}{2 \cdot \pi \cdot k_{RFZ} \cdot h}. \quad (7)$$

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

Pressure losses in BFZ

No.	Time after entering into operation, months	Flow rate Q_l, m^3/day	Depression on a layer, MPa	Skin factor	Additional pressure loss ΔP_s	ΔP_s share of total depression, %
Secondary completion with AJP and acid treatment						
1	1	36.48	6.02	–5.60	–	–
2	5	30.93	8.34	–0.89	–	–
3	8	10.84	8.40	–0.85	–	–
4	14	9.64	9.11	–0.25	–	–
5	16	7.78	9.45	0.03	0.01	0.04
6	22	3.95	11.4	1.67	0.17	1.52
Acid treatment						
7	23	36.23	9.2	–0.18	–	–
8	24	34.23	4.8	–3.83	–	–
9	30	26.26	6.42	–2.49	–	–
10	36	24.96	7.64	–1.47	–	–
11	40	22.31	10.56	0.95	0.10	0.94
12	43	14.92	12.15	2.28	0.24	1.95
13	44	13.81	11.93	2.09	0.22	1.82

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 in 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.

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