The Influence of Thermoelastic Effect on Cracks of Automatic Hydraulic Fracturing in Injection Wells

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Abstract. Water injection with reservoir pressure maintenance changes the state of reservoir system and requires special attention. Formation of man-made cracks and cracks caused by automatic hydraulic fracturing is one of the risk factors in rapid flooding of production wells. The temperatures changes in the area of injection well affect local stresses in the reservoir and are manifested in the form of thermoelastic effect. This effect reduces the distribution pressure of existing hydraulic fracturing cracks. The article considers the probability of thermoelastic effect in injection wells in which hydraulic fracturing processes have been carried out. Examples and calculations are given for determining the probable occurrence of cracks caused by automatic hydraulic fracturing. It was found that for more than half of the cases cracks occur by automatic hydraulic fracturing due to the influence of thermoelastic effect.

Keywords: hydraulic fracturing, thermoelastic effect, automatic hydraulic fracturing, man-made cracks, injection well
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It is known that water injection by reservoir pressure maintenance (RPM) is the main tool to maintain reservoir pressure and enhance oil recovery at the fields of PJSC Tatneft. However, the process of water injection into the reservoir requires strict control of wellhead and downhole pressures, as high pressure of injection may exceed the strength of rocks and initiate the development of cracks in the well bottom zone, or lead to an increase of the existing natural fractures in the formation. This phenomenon of man-made cracks or disclosure of natural fractures is called automatic hydraulic fracturing and is accompanied by an increase in sweep by height and area. When increase of well injectivity is significantly higher than rate of pressure rise, it is characteristic of automatic hydraulic fracturing.

Uncontrolled crack growth can have a negative impact on the system development as a result of an early water approach to producing wells with their watering, unwanted breakthrough of water in the upper or lower horizons, etc. Therefore it is very important to control these processes, affecting the efficiency of the RPM system and the development of deposits in general. All these aspects must meet strict requirements to the quality of water used in the RPM by the content of mechanical impurities and biological contamination. However, apart from the danger of the reservoir pollution there is another criterion that affects the reservoir systems – the temperature of injected water. For deposits of Tatarstan throughout the year the temperature of the water injected into the reservoirs can vary from 18 to 10°C.

Water injection, which has a temperature below the reservoir temperature, creates two zones – waterflooded zone that represents rock volume occupied by injected water and cooled zone with a lower temperature.

A feature of the heat transfer mechanism in the oil reservoir is that the zone with a temperature different from the reservoir temperature moves slower than the water in the rock. In connection with this moving of cooled zone is behind the front of oil displacement by water (Zheltov, 1986).

The volume of the flooded zone, taking into account porosity, residual oil saturation and bound water, i.e. reservoir volume occupied by injected water (Perkins, Gonzales, 1985):

$$V_з = \frac{Q_ж}{m\cdot\left(1-S_{он}-S_{св}\right)}, \tag{1}$$

where $Q_ж$ – cumulative injection of water, m^3, $S_{он}$ – residual oil saturation, unit fraction, $S_{св}$ – bound water saturation, unit fraction, m – porosity, unit fraction.

The volume of the cooled zone, taking into account the porosity and residual oil saturation (Perkins, Gonzales, 1985):

$$V_x = \frac{\rho_в\cdot C_в\cdot Q_ж}{\rho_П\cdot C_П\cdot(1-m)+\rho_в\cdot m\cdot C_в\cdot(1-S_{ОН})+\rho_Н\cdot m\cdot C_Н\cdot S_{он}} \tag{2}$$

where $\rho_в$ – the density of water, kg/m^3, $\rho_н$ – oil density, kg/m^3, $\rho_п$ – the density of the rock, kg/m^3, $C_в$ – heat capacity of water, J/kg·K, $Q_ж$ – cumulative injection of water, m^3, $S_{он}$ – residual oil saturation, unit fraction, $S_{св}$ – bound water saturation, m – porosity, unit fraction.

If we consider vertical injection well with already established hydraulic fracturing, the front of water movement from the hydraulic fracture can be taken in the form of an ellipse. The paper (Perkins, Gonzales, 1985) establishes the volume of injected water as ellipse volume of a confocal main axis of the hydraulic fracture. Major axis of ellipse (a) is located along the fracture, and the minor axis (b) is located along the fracture width and perpendicular to the major axis, and fracture half-length ($L_{тр}$) will be the focal distance.

To find large (by X axis) and low (by Y axis) semiaxes of the ellipse we used elliptical coordinates, in which the coordinate lines are confocal ellipses and hyperbola.

Two focuses F_1 and F_2 are usually taken as points C minus and C plus on the X-axis of the Cartesian coordinate system, in this case representing the fracture half-length $L_{тр}$.

$$x = C\cdot ch\xi\cdot cos\beta\ , \tag{3}$$

$$y = C \cdot sh\xi \cdot \sin\beta \,, \tag{4}$$

where $\xi \geq 0$, $\beta \in (0, 2\pi)$.

Линии уровня ξ являются эллипсами, линии уровня β – гиперболами. Гиперболический косинус (ch) и гиперболический синус (sh) находятся как:

Level ξ lines are ellipses; level β lines are hyperbola. Hyperbolic cosine (ch) and hyperbolic sine (sh) are both:

$$ch\xi = \frac{e^{\xi} + e^{-\xi}}{2} \tag{5}$$

$$sh\xi = \frac{e^{\xi} - e^{-\xi}}{2}. \tag{6}$$

For the major semiaxis $\beta = 0$, as it goes along the X axis and the cosine of 0 is unity. For minor semiaxis $\beta = \pi/2$ because it is perpendicular to the axis X and $\mathrm{Sin}\pi/2=1$ and $C = L_{\text{тр}}$. Therefore, we do not consider $\mathrm{Cos}\beta$ and $\mathrm{Sin}\beta$ in expressions (3, 4) and remove them as equal to unity, and obtain applicable for the considered fracture:

$$a = L_{mp} \cdot ch\xi = L_{mp} \cdot \frac{e^{\xi} + e^{-\xi}}{2} \,, \tag{7}$$

$$b = L_{mp} \cdot sh\xi = L_{mp} \cdot \frac{e^{\xi} - e^{-\xi}}{2} \,. \tag{8}$$

Having values of the major (a) and minor (b) semiaxes, we can calculate the volume of the confocal ellipse with a fracture:

$$V = \pi \cdot a \cdot b \cdot h = \pi \cdot h \cdot L_{mp}^{2} \cdot \frac{e^{\xi} + e^{-\xi}}{2} \cdot \frac{e^{\xi} - e^{-\xi}}{2} =$$

$$= \pi \cdot h \cdot L_{mp}^{2} \cdot \frac{\left(e^{2\xi} - e^{-2\xi}\right)}{4} \tag{9}$$

or

$$\frac{4 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}} = e^{2\xi} - \frac{1}{e^{2\xi}} \tag{10}$$

Having $e^{2\xi} = z$ for the equation (10), we obtain:

$$\frac{4 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}} = z - \frac{1}{z} \tag{11}$$

And further, by transforming (11), we obtain quadratic equation or algebraic equation of 2nd degree with one unknown:

$$Z^{2} - \frac{4 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}} \cdot Z - 1 = 0. \tag{12}$$

The provided resulting quadratic equation of the form $x^2+bx+c=0$ has the formula for the roots (Barsukov, 1966):

$$x_{1,2} = \frac{-b}{2} \pm \sqrt{\left(\frac{b}{2}\right)^{2} - c} \,. \tag{13}$$

Solution for Z will be:

$$Z = \frac{b}{2} + \sqrt{\left(\frac{b}{2}\right)^{2} + c} \,, \tag{14}$$

where $b = \dfrac{4 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}}$.

Then

$$Z = \frac{2 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}} + \sqrt{\left(\frac{2 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}}\right)^{2} + 1} \,. \tag{15}$$

Since $e^{2\xi} = z$, then $\ln Z = 2\xi$ or

$$\xi = \frac{1}{2} lnZ = \frac{1}{2} \ln \cdot \left[\frac{2 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}} + \sqrt{\left(\frac{2 \cdot V}{\pi \cdot h \cdot L_{mp}^{2}}\right)^{2} + 1}\right] \tag{16}$$

Knowing the volume of the flooded the $V_{\text{з}}$ (1) area, we find that the major and minor semiaxes of the ellipse for the flooded area:

$$a_{\text{з}} = L_{mp} \cdot ch\left(\frac{1}{2} \ln \cdot \left[\frac{2 \cdot V_{\text{з}}}{\pi \cdot h \cdot L_{mp}^{2}} + \sqrt{\left(\frac{2 \cdot V_{\text{з}}}{\pi \cdot h \cdot L_{mp}^{2}}\right)^{2} + 1}\right]\right) \tag{17}$$

$$a_{\text{з}} = L_{mp} \cdot ch\left(\frac{1}{2} \ln \cdot \left[\frac{2 \cdot V_{\text{з}}}{\pi \cdot h \cdot L_{mp}^{2}} + \sqrt{\left(\frac{2 \cdot V_{\text{з}}}{\pi \cdot h \cdot L_{mp}^{2}}\right)^{2} + 1}\right]\right) \tag{18}$$

Also we calculated major and minor semiaxes for cool area, knowing the volume V_{x} of cooled area (2):

$$a_{x} = L_{mp} \cdot ch\left(\frac{1}{2} \ln \cdot \left[\frac{2 \cdot V_{x}}{\pi \cdot h \cdot L_{mp}^{2}} + \sqrt{\left(\frac{2 \cdot V_{x}}{\pi \cdot h \cdot L_{mp}^{2}}\right)^{2} + 1}\right]\right) \tag{19}$$

$$b_{\text{з}} = L_{mp} \cdot sh\left(\frac{1}{2} \ln \cdot \left[\frac{2 \cdot V_{\text{з}}}{\pi \cdot h \cdot L_{mp}^{2}} + \sqrt{\left(\frac{2 \cdot V_{\text{з}}}{\pi \cdot h \cdot L_{mp}^{2}}\right)^{2} + 1}\right]\right) \tag{20}$$

Cooling of the area around the hydraulic fracture leads to the thermal deformation, so it is necessary to take into account geomechanical features of the rocks behavior. Changing the temperature field leads to changes in local stress in the cooling zone and the emergence of thermoelastic ($\Delta\sigma^{T}$) effects. It determines the character of the local stress fracture directio, its growth in height, burst pressure, etc. The appearance of the thermoelastic effect changes the overall stress in the formation and may affect the initiation or spread of existing cracks.

Changing of thermoelastic stress ($\Delta\sigma^{T}$) reduces the local minimum horizontal stress (S_{h}) in the cooled zone. Due to the reduction of minimum horizontal stress critical pressure for the growth of cracks at the end of the crack can be less than the crack spread pressure.

If a crack exists, its propagation occurs when the stress intensity at the crack tip is higher than the critical fracture stress ($\sigma_{\text{кр}}$):

$$\sigma_{\text{кр}} = \frac{K_{Icr}}{\sqrt{\pi \cdot L_{mp}}} \,. \tag{21}$$

The condition for crack spread by the method of Irwin (Hagoort, 1981) is an increase in the minimum stress on the value of the critical fracture stress:

$$P_{mp} = S_{h} + \frac{K_{Icr}}{\sqrt{\pi \cdot L_{mp}}} \,. \tag{22}$$

For cracks greater than 3 m stress intensity factor K_{Icr} is very small and can be neglected (Hagoort, 1981). Taking into account the changes in thermal stress, expression (22) takes the form:

$$P_{\text{тр}}=S_h-\Delta\sigma^T_{L_{\text{тр}}}, \tag{23}$$

$$S_h=\frac{\nu}{1-\nu}\cdot\left(P_{\text{в}}-\alpha\cdot P_{\text{пл}}\right)+\alpha\cdot P_{\text{пл}}, \tag{24}$$

where ν – the Poisson's ratio, unit fraction; $P_{\text{в}}$ – the pressure exerted by the weight of the overlying rocks, MPa; α – coefficient Bio; $P_{\text{пл}}$ – eservoir pressure, MPa.

Coefficient Bio has a value in the range of 0.7 to 1 and is usually taken to be unity.

$\Delta\sigma^T_{L_{\text{тр}}}$ describes, by how much fracture propagation pressure is reduced and taken with a negative sign, as the reservoir temperature is reduced.

$$\Delta\sigma^T_{L_{\text{тр}}}=\frac{\alpha_T\cdot E\cdot\Delta T}{(1-\nu)}\cdot f_{(a,b,h)}, \tag{25}$$

Where $\alpha_{\text{т}}$ – thermal expansion coefficient, m/m°C; E – Young modulus, MPa; ν – Poisson's ratio, unit fraction; ΔT – the difference in temperature of the formation and injection water, °C; $f_{(a,b,h)}$ – Perkins factor used to account the pressure around the crack (Perkins, Gonzales, 1985).

Stress change occurs both along the fracture axis and perpendicular to it. Perkins ratio $f_{(a_x,b_x,h)}$ takes into account changes in the stress perpendicular to the fracture, affecting the forces that prevent the disclosure of cracks.

$$f_{(a_x,b_x,h)}=\frac{{}^{b_x}\!/_{a_x}}{1+{}^{b_x}\!/_{a_x}}+\left(\frac{1}{1+{}^{b_x}\!/_{a_x}}\right)\cdot\left(1\Big/\left\{1+\frac{1}{2}\left[1{,}45\cdot\left(\frac{h}{2\cdot b_x}\right)^{0{,}9}+\right.\right.\right.$$
$$\left.\left.\left.+\ 0{,}35\cdot\left(\frac{h}{2\cdot b_x}\right)^{2}\right]\cdot\left[1+\left(\frac{b_x}{a_x}\right)^{0{,}774}\right]\right\}\right) \tag{26}$$

Knowing wellhead injection pressure we can determine the bottomhole pressure

$$P_{\text{заб}}=P_{\text{уст}}+\rho_{\text{ж}}\cdot g\cdot H_{\text{скв}}\cdot 10^{-6}-\Delta P_{\text{т}}-\Delta P_{\text{перф}}, \tag{27}$$

Where $P_{\text{уст}}$ – pressure on the wellhead of the injection well, MPa; $\rho_{\text{ж}}$ – density of the injected water, kg/m3; H – depth of the injection interval, m; $\Delta P_{\text{т}}$ – pressure losses due to friction (Hydraulics, 1984), MPa; $\Delta P_{\text{перф}}$ – pressure loss due to perforation (Suleymanov et al., 1984), MPa;

$$\Delta P_{\text{т}}=\lambda\cdot\frac{L}{d}\cdot\frac{V^2}{2g}\cdot 10^{-2} \tag{28}$$

where λ – friction coefficient of the fluid flow in pipes;

$$\lambda=\frac{64}{\sqrt{\Re}},$$

at the Re > 2300 $\lambda=\dfrac{0{,}316}{\sqrt[4]{\Re}}$. (29)

The Reynolds number

$$\Re=\frac{V\cdot d\cdot\rho_{\text{ж}}}{\mu}, \tag{30}$$

where V – fluid velocity, m/s; d – inner diameter of the tubing, m; $\rho_{\text{ж}}$ – fluid density, kg/m³; μ – dynamic viscosity of the fluid, Pa·s; L – length of tubing, m (31).

$$\Delta P_{\text{перф}}=\frac{8\cdot Q^2\cdot 10^{-2}}{\pi^2\cdot n^2_{\text{перф}}\cdot d^4_{\text{п}}\cdot\varphi^2\cdot g}, \tag{31}$$

where Q – injectivity of wells, m³/s; $n_{\text{перф}}$ – number of perforations, pcs; $d_{\text{п}}$ – diameter of perforations, m; φ – flow coefficient depending on the nature of the fluid outflow.

To prevent the development of cracks it is necessary to observe the condition of not exceeding the bottomhole pressure over crack propagation pressure:

$P_{\text{заб}}<P_{\text{тр}}$. (32)

On the example of well 891 of oil-and-gas production department Bavlyneft, PJSC Tatneft we consider the effect of cold-water injection of and occurrence of temperature effects

Parameter	Value	Parameter	Value
The volume of cumulative injection, $Q_{\text{ж}}$	601074 m³	Thermal expansion coefficient, $\alpha_{\text{т}}$	$5\cdot 10^{-6}$ m/m°C
The hickness of layer, h	5,6 m	Young modulus, E	8000 MPa
Porosity, m	0,22 unit fraction	The Poisson's ratio, ν	0,25 unit fraction
Oil saturation, $S_{\text{он}}$	0,39 unit fraction	Temperature of the formation, $T_{\text{пл}}$	23 °C
Bound water saturation, $S_{\text{св}}$	0,162 unit fraction	Temperature of injection fluid, $T_{\text{ж}}$	10 °C
The density of water, $\rho_{\text{ж}}$	1090 kg/m³	Reservoir pressure, $P_{\text{пл}}$	14,8 MPa
The density of the rock, $\rho_{\text{п}}$	2600 kg/m³	Surface injection pressure, $P_{\text{уст}}$	7,0 MPa
Oil density, $\rho_{\text{н}}$	856 kg/m³	Depth of the injection interval, H	1207 m
Dynamic viscosity of the fluid, μ	1,53 MPa·s	Number of perforations, $n_{\text{перф}}$	100 pcs.
Heat capacity of water, $C_{\text{в}}$	4200 J/kg·°C	Inner diameter of the tubing, $D_{\text{нкт}}$	0,062 m
Heat capacity of the rock, $C_{\text{п}}$	750 J/kg·°C	Diameter of perforations, $d_{\text{п}}$	0,01 m
Heat capacity of oil, $C_{\text{н}}$	2100 J/kg·°C	Length of tubing, L	1207 m
Length of fracture wing, $L_{\text{тр}}$	74 m	Average daily injection, Q	111,3 m³/day
Flow coefficient, φ	0,62		

Table 1. Initial data.

Parameter	Value	Parameter	Value
Flooded area volume, $V_з$	6098,5 thous. m^3	Perkins coefficient $f_{(ax,bx,h)}$	0,99
Main semiaxes of flooded area, $a_з$	591,2 m	Friction losses	0,05 MPa
Minor semiaxes of flooded area, $b_з$	586,6 m	Perforating losses	$3,6 \cdot 10^{-5}$ MPa
Cold area volume, V_x	120,18 thous. m^3	Bottomhole preassure	19,8 MPa
Elliptic coordinate, ξ_x	1,96	Thermoelastic effect $\Delta\sigma^T_{L_{mp}}$, at 10 °C	0,7 MPa
Main semiaxes of cold area, a_x	266,7 m	Minimum horizontal stress, S_h	20,1 MPa
Minor semiaxes of cold area, b_x	256,3 m	Fracture propagation pressure, $P_{тр}$	19,4 MPa

Table 2. Results of calculation.

Well No.	Calculated bottomhole pressure $P_{заб}$, MPa	Fracture propagation pressure $P_{тр}$, МПа	Probability automatic hydraulic fracturing
3911	24,5	26,3	no
7207	35,8	31,1	yes
22662	29,6	27,5	yes
22678	29,3	26,5	yes
1220	27	28,5	no
891	19,8	19,4	yes

Table 3 Results of calculation for the injection wells with hydraulic fracturing.

on the change in fracture propagation pressure by automatic hydraulic fracturing.

For injection well 891 hydraulic fracturing was carried out in Bobrikovian interval. According to the factual data the injection volume in 2015 before fracturing in the well 891 ranged from 39.2 to 86.1 m^3/day at wellhead pressure $P_{уст}$ = 7.6 MPa. After conducting fracturing, the well injectivity is increased to an average of 111.3 m^3/day with a reduction of wellhead pressure to $P_{уст}$ = 7.0 MPa. For calculations we applied water temperature of 10 °C as the least favorable condition.

Initial data and results of calculations are presented in Tables 1 and 2 (data for accumulated injection, well construction, reservoir parameters are taken from the corporate information of PJSC Tatneft ARMITS system, characteristics of hydraulic fractures are according to the report of fracture design LLC Tatneft-LeninogorskRemServis; Young modulus and Poisson's ratio for the horizons operated on fields of PJSC Tatneft, prepared by the institute TatNIPIneft as a result of research conducted).

Thermoelastic effect arising due to temperature changes in the cooled zone decreases in this case local stress to 0.7 MPa in the cold season. As can be seen by the results of the calculation, the bottomhole pressure in the well 891 exceeds the value of the minimum horizontal stress (S_h), reduced by thermoelastic effect $\Delta\sigma^T_{L_{mp}}$. Condition $P_{заб} < P_{тр}$ is not respected and there is a possibility for the development of automatic hydraulic fracturing in the pumping of water to the well. It is necessary to monitor the change in injectivity index, the dynamics of injection pressure and behavior of surrounding reacting wells. Therefore, more research, control of the surrounding wells and simulations are needed.

A similar calculation was made for the injection wells of oil-and-gas production department Bavlyneft where hydraulic fracturing has been produced (Table 3).

Calculations show that in 67% of the wells there is a possibility of automatic hydraulic fracturing due to the high injection pressure, i.e., in more than half cases it is necessary to pay attention to technological modes of wells.

As is known, according to the results of mini-fracturing we can determine closure pressure (or pressure of cracks development), equal and counteracting the minimum major stress in the rock. In case of excess injection pressure over closing pressure man-made cracks are formed or natural fractures are disclosed with an increased likelihood of their further development.

To prevent the occurrence of automatic hydraulic fracturing in injection wells we need to collate and analyze the data obtained in the course of mini-fracturing in these or neighboring wells with field data for injection and, if necessary, to make quick changes to the operation of injection wells.

The low-permeability reservoirs with very small volumes of processing specific to mini-fracturing have values of instantaneous shut-in pressure (ISIP) approaching the closing pressure (Gidley et al., 1989).

Conclusions

1. Reservoir temperature of Bavly fields vary within an average of 25-40°C, so there is no pronounced occurrences of the thermoelastic stress changes, but nevertheless they need to be taken into account, as they are an integral part of the flooding process.

2. The growth of cracks as a result of automatic hydraulic fracturing increases their length and height, and this creates risk of an early water approach to the production wells or breakthrough in the top or bottom intervals. Therefore, the choice of development systems should be implemented within the parameters of the planned hydraulic fracturing, the probability of automatic hydraulic fracturing, determination of the major stress directions, and orientation of fracture propagation.

3. Control of cracking process, continuous monitoring of cracks, relevant research and modeling are necessary for the effective functioning of the reservoir pressure maintenance and successful development using hydraulic fracturing.

This is especially important in respect of low-permeability reservoirs, where it is necessary to maintain a high injection pressure, so the influence of the thermoelastic effect may be more pronounced. Calculation of low temperature zone dimensions allows us to estimate the size of cracks in the event of their development.

4. The results can be taken into account in the hydrodynamic models to improve the technological parameters both in the whole model and individual wells. Data of such calculations

must be taken into account when planning exploration for wells in order to increase their efficiency.

5. Conducted calculations show that in 67% of the wells of oil-and-gas production department Bavlyneft there is a possibility of automatic hydraulic fracturing due to the high injection pressure, i.e. in more than half cases we need to pay attention to technological modes of wells.

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