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Analysis of Implementation Effectiveness of Two Working Fluids Characterized by Different Viscoelastic Characteristics at Hydrodynamic Impact on the Borehole Bottom Zone

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Abstract. Combination of hydrodynamic impact on the formation with acid treatment may be seen as a promising direction in the field of well development and repair in complex geological conditions. With multiple repetition of hydraulic shocks in conjunction with the injection of acid solution, the depth and opening of cracks gradually increases, which contributes to a deeper penetration of the acid solution into the reservoir. The article presents analytical studies, which are aimed at determining the effectiveness of applying the technology of hydrodynamic impact on the bottomhole zone of an oil reservoir when using two fluids with different viscoelastic characteristics as a working fluid. They are devoted to determining the pressure drop at the borehole bottom depending on the initial applied pressure at the wellhead, the velocity of the shock wave, the viscosity of the working and well fluid, and their quantity. These studies were based on the well-known models of Thomson – Tat and Maxwell, considering viscous liquid flow. The dependence obtained proves that with an increase in the pressure pulse generated at the wellhead, the development of pressure pulses at the borehole bottom is a power-law dependence, and with significant volumes of fluid in contact with the bottomhole formation zone, the pressure drop generated at the borehole bottom does not depend only on pressure pulses generated at the wellhead, but also on the dynamic viscosity of this fluid. Conducted studies have shown the effectiveness of hydrodynamic impact technology application when using two liquids with different viscoelastic characteristics and obtaining a synergistic effect during the development and repair of wells in low-permeable reservoirs. Analytical studies were based on data from previously conducted experimental industrial tests on the operating injection well.

Keywords: pressure pulse, intensification of well simulation, formation fracturing, fracture network, Thompson – Tat model, Maxwell model, dependence of pressure overbalance, visco-elastic characteristics of liquid

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Анализ эффективности применения двух рабочих жидкостей с различными вязкоупругими характеристиками при гидродинамическом воздействии на призабойную зону пласта

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Реферат. Перспективным направлением разработки технологии освоения и ремонта скважин в сложных геологических условиях является совмещение гидродинамического воздействия на пласт с кислотной обработкой. При многократном повторении гидроударов в совокупности с закачкой кислотного раствора постепенно увеличиваются глубина

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и раскрытость трещин, что способствует более глубокому проникновению кислотного раствора в пласт. В статье проводятся аналитические исследования, направленные на установление эффективности применения технологии гидродинамического воздействия на призабойную зону нефтяного пласта при использовании в качестве рабочей жидкости двух жидкостей с различными вязкоупругими характеристиками. Определен перепад давления на забое скважины, зависящий от начального прикладываемого давления на устье, скорости ударной волны, вязкости рабочей и скважинной жидкостей и их количества. Исследования базировались на известных моделях течения вязкой жидкости Томсона – Тэта и Максвелла. Полученная зависимость доказывает, что при увеличении импульса давления, сгенерированного на устье скважины, развитие импульсов давления на забое происходит по степенной зависимости при значительных объемах жидкости, контактирующей с призабойной зоной пласта; перепад давления, создаваемый на забое скважины, зависит не только от импульсов давления, генерируемых на устье скважины, но и от динамической вязкости этой жидкости. Проведенные исследования доказывают эффективность применения технологии гидродинамического воздействия при использовании двух жидкостей с различными вязкоупругими характеристиками и получение синергетического эффекта при освоении и ремонте скважин в низкопроницаемых коллекторах. Аналитические исследования базировались на данных ранее проведенного опытно-промышленного испытания на действующей нагнетательной скважине.

Ключевые слова: импульс давления, интенсификация притока, гидроразрыв пласта, сеть трещин, модель Томсона – Тэта, модель Максвелла, зависимость перепада давления, вязкоупругие характеристики жидкости

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Introduction

Nowadays, many of the world's oil and gas fields are in the process of falling production or are classified as deposits with hard-to-recover reserves or with complex structured reservoirs. With the commissioning of new fields, at present it is impossible to ensure a stable increase in recoverable reserves and to compensate for the current decline in hydrocarbon production at the exploited fields. The newly developed deposits are usually represented by low permeability, highly inhomogeneous and low-productive reservoirs, hydrocarbon reserves of which are classified as hard-to-recover [1]. Currently the main volume of production falls on the fields commissioned in the XX century, where an intensive extraction of fluid was observed, leading to a violation of optimal operating conditions, high water content of the production and significant contamination of the bottomhole zones of producing and injection wells. This forces specialists in the oil and gas industry to develop new energy efficient [2–4] and highly profitable technologies capable of ensuring stable maintenance and growth of hydrocarbon production in complex geo-logical conditions [5, 6].

Complications at the development of hydrocarbon fields are related to the operation of producing and injection wells:

– the difficulty or inability to develop wells after drilling or repair, due to the complex physico-geological characteristics of the deposits, such as low permeability and high heterogeneity of reservoirs, as well as their large depths;

– a significant drop, and sometimes a complete cessation of fluid extraction from production wells or water injection into injection wells, caused by accumulation of polluting particles in the process of operation at the main filtration fields, which impair the filtration characteristics of bottomhole well zones;

– high water content in the produced well fluid, often caused only by the break-through of water in a high permeable interval, which leads to unprofitable operation of the wells and, as a consequence, to the shutdown of the operating wells [5].

Because of the mentioned above reasons, in most all oil-producing regions, and especially in Russia, a large number of wells are in an inactive fund. The restoration cost of inactive and emergency wells is several times less than the capital expenditures for the drilling of new wells. Considering the equivalent production, putting idle non-profit wells into operation can have a significant impact on the efficiency of the oil industry performance.

Main part

The main object of influence for the most known methods of well treatment is the bottomhole zone [7–9], therefore, measures aimed at its purification and restoration of natural permeability, contribute not only to the growth of current production, but also increase oil recovery [10]. This technology is the most preferable, which can have a noticeable effect on the improvement of filtration and reservoir properties, without creating new heterogeneities, such as, for example, at hydraulic fracturing, which can lead both to the intensification of fluid inflow into the well and to the breakthrough of water [5].

Among the variety of currently used methods, which can improve the reservoir properties of the bottomhole zone, hydrodynamic methods are among most efficient [11, 12]. They are distinguished by the relative simplicity of technological operations, the availability and presence at the markets of the equipment used, low costs of material, labor and energy resources, and are able to act as operational methods for intensifying the work of producing and injection wells.

The most effective way is to create pressure drops that exceed the fracture pressure, although practice shows that it is not necessary to cause the hydraulic fracturing, because with a regular hydraulic impulse action, a system of existing cracks develops due to systematic deformation of the wellbore zone of the formation and new ones are formed. Pressure pulses at the bottom of the well must be sufficient to periodically expand the cracks.

With a qualitative creation of the impulse from the wellhead, its leading edge acts on the crack walls like a wedge moving with a high speed [13]. The energy of the impact pulse generated from the wellhead is expended on deformation of cracks and repackaging the grains of the rock of the formation rock. If the pressure generated at the bottom exceeds the formation pressure, then crack opening, deformation and development are carried out. If the pressure of the pumped liquid is reduced to the level of the formation pressure, the process of crack opening is stopped [14].

After the maximum expansion of the cracks, the pressure of the liquid in the formation is reduced to the formation layer and gradual closure of the cracks due to extrusion of liquid from them. The grains of the formation's matrix, which under the action of the pressure pulse were displaced or deformed, completely overlap with the grains on the opposite side of the crack. In certain zones of cracks where, under the influence of the hydraulic pressure pulse, the grains of the formation's matrix are reoriented, the fracture walls do not close completely, leaving interconnected fine pores comparable in size with the cavities between the grains of the bedrock. The presence of such spacings increases the permeability of the reservoir rock [15]. The proposed method of influencing pressure impulses is similar in its effect to the implosion technology, with the difference that in this case the impacts can be alternated an unlimited number of times with a period of 3–10 s. The creation of repeated impulses increases the crack opening, their range and branching. Thus, the application of the hydrodynamic effect technology creates a developed network of cracks in the bottomhole zone of the productive reservoir, the presence of which increases the permeability [16–18]. This does not require the introduction of proppant, because due to reorientation of the grains of the formation rock, incomplete adjacency of the cracks occurs.

The pressure pulse generator placed at the wellhead must meet the technical requirements for the rate of buildup and the duration of pressure maintenance of the borehole fluid. Under these conditions, maximum deformation and development of the fractures occur.

To confirm the efficiency of the described technology, in June 2016 a test was conducted at the acting injection well No 1157 of the Tuymazinskoye field to increase the injectivity of the formation. To assess the parameters and condition of the bottomhole zone before and after the hydrodynamic effect, hydroimpulse studies of the well were carried out by Bashneft-Petrotest LLC.

In April 2016, based on the results of the studies following parameters were obtained: bottomhole pressure 17.2 MPa, formation pressure 15.5 MPa, specific-injectivity index 0.05 m^3/(day·MPa) (tab. 1). In July 2016 after the well was put into operation hydrodynamic studies were carried out, considering the results of the interpretation the following parameters were obtained: growth of injectivity up to 75 m^3/day (three times as compared to previous studies), an increase in the specific-injectivity index up to 0.27 m^3/(day·MPa) (five times over previous studies).

Thus, the results of pilot-industrial tests indicate the efficiency of the proposed technology of hydrodynamic impact on the bottomhole zone of the productive formation. The efficiency of the effect is confirmed by the conduct of hydrodynamic studies before and after the treatment [19].

Table 1

The summary of the hydrodynamic studies interpretation

Date of the study	Type of the study	Q_{inj}, m^3/day	P_{btm}, MPa	P_{frm}, MPa	K_{inj}, m^3/(day·MPa)	Skin
08.05.2013	PDC	69	17.7	17.0	0.18	–4.5
30.06.2014	PDC	33	17.2	14.9	0.14	–5.1
25.04.2016	PDC	24	17.2	15.5	0.05	+0.29
11.07.2016	PDC	75	17.7	15.0	0.27	–5.0

Carrying out described above technology implies the possibility of using two liquids with different viscoelastic characteristics. It can be an agent fluid (acid composition, surfactant or polymer solutions) in the lower part of the wellbore and working fluid (technical or formation water) in the upper part (fig. 1). In this case the working fluid perceives the generated pressure pulses at the wellhead, then passes them to the agent fluid, through which they are further transferred to the bottomhole. In this regard, the study of the relationship between the development of pressure pulses at the bottomhole from the ratio of the volumes of agent fluid and working fluid in the well and their dynamic viscosity are of considerable interest.

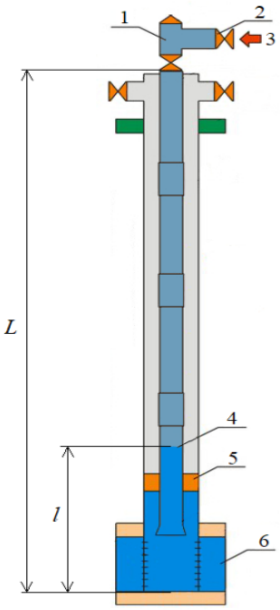

Fig. 1. Schematic diagram of the hydrodynamic impact technology with the use of two liquids with different viscoelastic characteristics: 1 – wellhead armature; 2 – buffer valve; 3 – generated pressure pulses; 4 – contact point of liquids with different viscoelastic characteristics; 5 – packer; 6 – productive reservoir; *L* – the initial depth of the well from the wellhead to the bottomhole; *l* – the height occupied by the agent fluid, calculated in meters from the bottomhole of the well to the point of contact with the working fluid

Accordingly, the amount of working fluid in the well is defined as *L*–l. These fluids have differrent viscoelastic characteristics (η_1 – dynamic viscosity of the agent fluid and η_2 – dynamic viscosity of the working fluid) and can be in the well in different proportions.

The viscous fluid model can be represented in the form of the Thomson–Tat model or the Maxwell model [20, 21].

1. Thomson – Tat model

$$\tau = \tau_s + \tau_f = G\alpha + \eta \frac{d\alpha}{dt}, \qquad (1)$$

where τ – deformation; G – Poisson ratio; η – coefficient of dynamic viscosity; α – shear stress.

2. In the Maxwell model, the deformation of elasticity is considered as the sum of the shear stresses

$$\dot{a} = \frac{d\alpha}{dt} = \left(\frac{d\alpha}{dt}\right)_s + \left(\frac{d\alpha}{dt}\right)_f = \frac{1}{G}\cdot\frac{d\tau}{dt} + \frac{\tau}{\eta}. \qquad (2)$$

In considered case, it is important to determine the conditions for the development of the pressure pulse at the bottom of the well, taking into account the velocity of the shock wave from the mouth and its connection with the viscoelastic properties of the medium.

Let us consider the possibility of breaking the continuity of a viscous fluid

$$\frac{d}{dx}\left(\eta \frac{du}{dx}\right) = 0, \qquad (3)$$

where x – coordinate along the length of the well.

The fluid viscosity along the depth of the well may differ:

$$x < l;\ \eta = \eta_1;\ \eta_1 >> \eta_2;$$

$$x > l;\ \eta = \eta_2.$$

Let us determine the relationship between the velocity of the fluid and its viscosity:

$$\frac{du}{dx} = \frac{C_1}{\eta};\ x = 0;\ u = u_0,$$

where C_1 – coefficient of pressure change along the depth of the well, Pa.

The velocity of the fluid is determined by the initial velocity set at the wellhead and is the function of viscosity, taking into account the depth of the well

$$u = u_0 + C_1 \int_0^x \frac{dx}{\eta(x)}. \qquad (4)$$

The motion of the borehole fluid relative to the instantaneous position of the shock wave is determined as follows:

$$u = u_0 + \frac{C_1 x}{\eta_1}, \;\; x < l;$$

$$u = u_0 + \frac{C_1 l}{\eta_1} + \frac{C_1 (x-l)}{\eta_2}, \;\; x > l. \qquad (5)$$

When the bottomhole is reached:

$$x = L; \;\; u = 0;$$

$$u_0 + \frac{C_1 l}{\eta_1} + \frac{C_1 (L-l)}{\eta_2} = 0.$$

From here

$$C_1 = -\frac{u_0}{\dfrac{l}{\eta_1} + \dfrac{L-l}{\eta_2}}. \qquad (6)$$

Substituting equation (6) into (5), the velocity of fluid in the well is found as

$$u = u_0 - \frac{u_0 l}{\eta_1 \left(\dfrac{l}{\eta_1} + \dfrac{L-l}{\eta_2} \right)} - \frac{(x-l) u_0}{\left(\dfrac{l}{\eta_1} + \dfrac{L-l}{\eta_2} \right) \eta_2}. \qquad (7)$$

The pressure pulse created at the bottom of the well, according to Zhukovsky's formula, is determined by the change in the velocity of the fluid

$$\Delta p = \rho c \Delta u, \qquad (8)$$

where ρ – density of the liquid; c – velocity of the shock wave.

The change in the velocity of the fluid when the shock wave reaches the bottom of the well

$$\Delta u = \frac{(L-l) u_0}{\eta_2 \left(\dfrac{l}{\eta_1} + \dfrac{L-l}{\eta_2} \right)}, \qquad (9)$$

where $u_0 = \sqrt{\dfrac{2P}{\rho}}$.

Then equation (8) takes the form [12]

$$\Delta P = \rho c \frac{(L-l) \cdot \sqrt{\dfrac{2P}{\rho}}}{\eta_2 \left(\dfrac{l}{\eta_1} + \dfrac{L-l}{\eta_2} \right)}. \qquad (10)$$

For the technical calculation according to the formula (10) we accept the following assumptions, which are at most correspond to the test conditions: L – depth of the well, 1600 m; l – height of the agent fluid column from the wellhead, from 1 to 800 m; η_1 – dynamic viscosity of the agent fluid from 1.5 to 10.0 MPa·s; η_2 – dynamic viscosity of the working fluid 1.0 MPa·s; P – generated pulse pressure at the wellhead, from 1 to 20 MPa; ρ – density of the borehole fluid, assumed equal to 1050 kg/m^3 (since there are two liquids in the well with densities that differ little from the density of the technical (formation) water); c – for referent conditions equal to the velocity of sound in water 1000 m/s (for pipeline systems). Results are shown in fig. 2.

As seen in the fig. 2, with the increase in the pressure pulse P generated at the wellhead, the development of the pressure pulses at the bottomhole ΔP occurs in a power-law manner. For a more detailed analysis, we will expand it into components depending on the ratio of the filling of the well with the agent fluid (fig. 3):

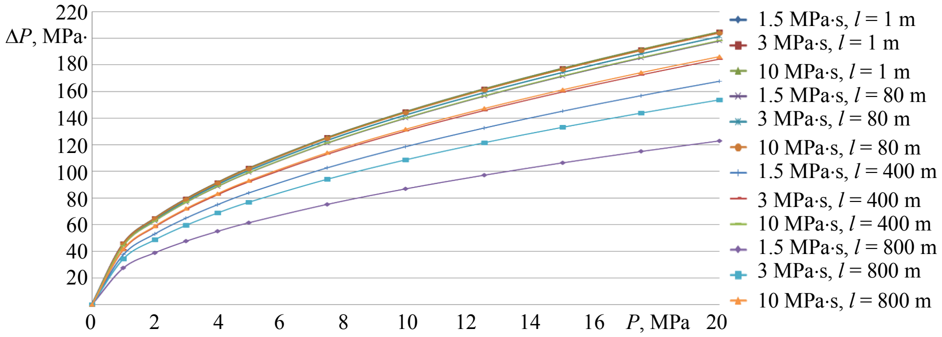

Fig. 2. The analytical dependence of the pressure pulses development at the bottom from the generated pulse at the wellhead, the height of the column and the viscosity of the agent fluid

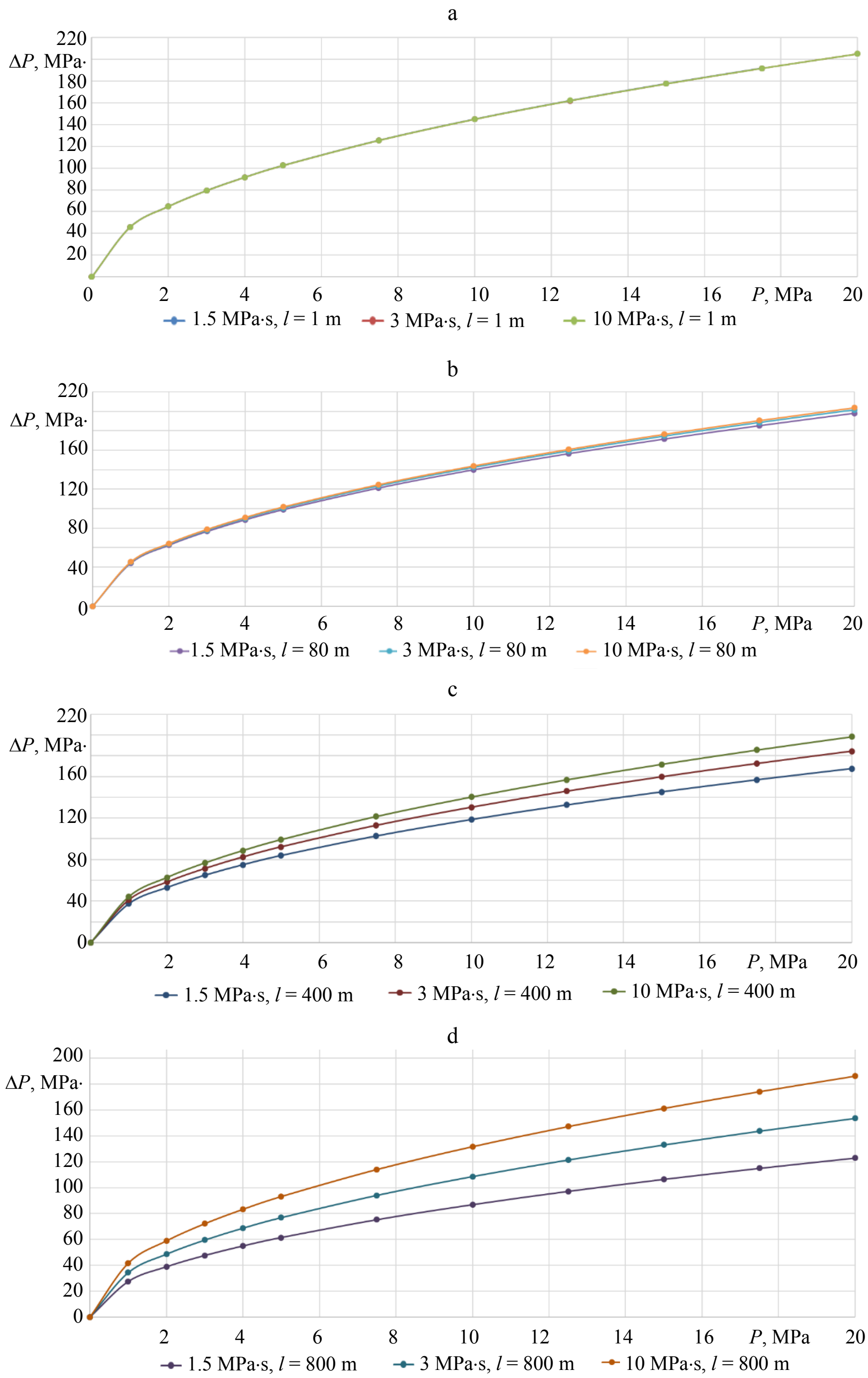

Fig. 3. Dependences of the change in the effecting impulse on the ratio of the fluids' volumes in the well:
a – calculations at a fluid height of 1 m; b – calculations with a height of 80 m; c – calculations at a fluid height of 400 m;
d – calculations with a height of 800 m

Analyzing the graphs in the fig. 3, it can be concluded that at low altitudes agent fluid pressure drop created at the borehole bottom is virtually independent of changes in the dynamic viscosity of the agent fluid, and depends only on pressure pulses P, generated at the wellhead. With further increase in height of agent fluid column and decrease of working fluid column height, differences of their dynamic viscosities have an increasing negative effect on pressure's pulse amplitude generated on the bottom ΔP at the same pressure pulses P generated at the wellhead. At a ratio of the heights of the agent fluid and the working fluid of 1:1 and the relatively small difference in their dynamic viscosities, the efficiency of forming the pressure pulses at the bottom of the well is almost halved. To maintain the maximum pressure pulse produced at the bottom ΔP, when using a large amount of agent fluid, it is necessary to increase its dynamic viscosity relative to the working fluid by several times.

CONCLUSION

The conducted analytical studies prove the efficiency of applying the hydrodynamic technology with the use of various liquids with different viscoelastic characteristics and obtaining a synergetic effect in the development, repair and operation of wells in complex geological conditions.

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