NEW TECHNOLOGY FOR THE INTENSIFICATION OF OIL AND GAS RECOVERY FROM DEPLETED AND MARGINAL WELLS

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Abstract

The article studies the effect of cyclic loads on the strength characteristics and filtration in a porous medium, fatigue processes in the rock skeleton, and the prospects for developing technologies for active stimulation of formations in order to clean the bottom-hole zone and intensify oil and gas production. The issues of formation and growth of fatigue cracks in the rock under the influence of the pulse generator GKP-1 are also considered.

Analysis of recent researches and publications

The development of wells in low-permeability formations is associated with many difficulties in their construction and completion, as well as in the specifics of the selection of equipment and development of technologies. According to the world practice, in order to increase the initially low filtration and formation properties of the matrix of the formation rock, hydraulic fracturing is mainly used with various options for its implementation (interval, directional, acidic, local, multistage). However, when fracturing, highly permeable sections and systems of fractures are mainly included in the development, since the technology will most likely increase the length and openness of existing fractures rather than creating new ones. Therefore, technologies for active stimulation of the formation are being studied which allow creating, apart from main fractures, a network of fatigue cracks of different sizes and thereby increase the efficiency of field development.

Nowadays, a large number of experimental studies [2,12,17,18,21] confirms the hypothesis that under the influence of cyclic loads of a certain amplitude, the rock is actively destroyed at stresses, significantly less than the tensile strength of given rock. To the static loads acting constantly on the rock during cyclic action, a dynamic component is added, which is superimposed on them by the principle of superposition. As a result, microcracks can open, grow, or stop their growth depending on the anisotropic properties of the rock and the distribution of local stresses, the scale factor, and non-linear characteristics of the medium during the waves transmission [4,7,8,9]. That is, damage accumulation processes take place in a rock with a cyclic effect on it. Residual stresses are initiated before stress concentrators in the unloading cycle, and fatigue cracks develop in the direction perpendicular to the load axis [12]. Thus, the evolutionary process of existing microcracks growth and the formation of new ones takes place. This causes a change in the volume of fluid that is filtered through a unit of effective rock area per unit of time. Depending on the type of rock, fatigue during cyclic exposure occurs at loads of 60-80% of the maximum after 10-105 cycles [2,9,18,21]. Moreover, the presence of filtrate in the rock increases this effect [2,4]. According to the authors [5], in some cases, the activation energy of a fracture due to rock saturation with water can decrease by 4 times.

Numerous studies on the effect of alternating load on the rock by recording Kadomtsev A.G. acoustic emission [3,5], Morteza Ghamgosar computed tomography [17], Ko T.Y. video recording [12], Erarslan N. electron microscopy [13] show continuous accumulation of irreversible deformation, energy of dissipation under cyclic loading, growth and coalescence of microcracks into mesocracks and confirm the occurence of fatigue cracks. The studies of X. L. Zhao and J.-C. Roegiers [14], T.B. Celestino [15] and Y. Chen [20] showed that the number of cracks during cyclic loading had increased, along with their length, and the process had a three-stage nature: the first stage was for the growth of existing cracks; the second stage was for the formation of a fracture propagation zone; stage 3 - initiation of new crack growth (Fig. 1).

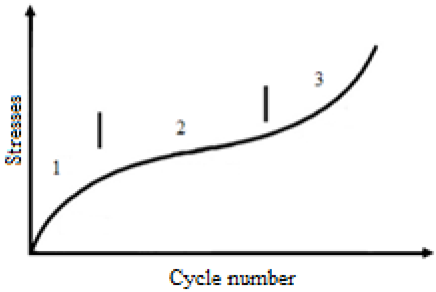


Fig 1. Stages of fatigue damage accumulation

The dislocation of microdestructions in rocks is transcrystalline (intragranular, intergranular) [1,3,11,17]. Such violations form the fracture propagation zone (FPZ) [13,16,17]. This zone consists of microcracks, each of which has its own submicrocrack zones, which turn into mesocracks. Such a hierarchy of structure for fatigue processes plays an important role since a large-scale effect is manifested. However, for shale rocks, as shown by studies with DIC surveys [10], the formation and growth of cracks is different, more complex and unexplored, due to the presence of a large number of layered structures. In [19], when conducting studies on the influence of the hydraulic pulses frequency on acoustic emission and formation characteristics, it was shown that a low frequency causes greater energy release and a greater intensity of crack opening inside test samples compared to a higher frequency. Therefore, studies were carried out within the frequency range of 50-100 Hz.

Research object

In the conducted experimental studies, the main attention was paid to the influence of cyclic loads in combination with surfactants on the strength properties of rock models, as well as on the change in the filtrate volume for artificial and natural core samples.

Research method

The experiment was carried out in two stages. At the first stage of research, we studied the strength characteristics of samples of cement stone with dimensions of 30×30×160 mm by non-destructive testing using an ultrasonic analyzer "Pulsar 1.1" and their change during combined exposure. Samples were formed over 90 days and were saturated with a surfactant solution (solpen) in accordance with the experimental design. Cyclic loading was carried out on a special installation with a retainer-holder, a loading system and a power control system. The study of the relative strength indices of cement stone samples was carried out in accordance with the Latin plan at five levels for three influential factors: surfactant content *c*, power *I* and time *t* of sample processing. Given the heterogeneity of the samples for strength testing, we studied the relative strength indicators averaged over four facet-ways before sample stimulation started.

To interpret the results of the studies, the relative strength index was used as the ratio of strengths after and before the experiment.

The experimental data were processed using regression analysis methods with the aim of constructing the most adequate model $\hat{\varepsilon}$ in the class *E* of second-order polynomials

$$\sigma_B = a^T b(c, I, t), \qquad (1.1)$$

where $b(c,I,t)=(1,c,I,t,cI,ct,cIt,c^2,I^2,t^2)^T$ - vector of basis functions; $a^T = (a_0, a_1,..., a_\varepsilon)$ - vector of model parameters.

Parameter estimations $\hat{a}$ and models $\hat{\varepsilon}$ ran in class $\varepsilon \in E$ of basic functions arbitrary combinations according to the conditions of the minimum adequacy variance

$$\min\left\{ S_s^2 = \frac{1}{n - r_s} \sum_{i=1}^{n} \left[a_s^T b(c_i, I, t_i) - \sigma_{Bi} \right]^2 \right\} \Rightarrow \{\hat{a}, \hat{\varepsilon}\}, \varepsilon \in E, \qquad (1.2)$$

where r_s - the number of estimated models' parameters.

The most adequate model $\hat{\varepsilon}$ dispersion efficacy $S_s^2 = 2{,}25 \cdot 10^{-4}$ and vector of basis function $b(c,I,t)=(1,c,I,t,cI,ct,cIt,c^2,I^2,t^2)^T$ with parameters' estimations

$$a^T = (1{,}015; 0{,}030; 8{,}898 \cdot 10^{-5}; -6{,}471 \cdot 10^{-4}; -2{,}26 \cdot 10^{-3}; 1{,}385 \cdot 10^{-6})$$

According to the results of the experiment, the presence of the influence trend of the cyclic load intensity (correlation coefficient *r*=-0.400) and the duration of the treatment (correlation coefficient *r*=-0.664 on the relative strength index and the absence of surfactant concentration influence (correlation coefficient *r*=0.004) is confirmed. A graphical interpretation of the processing parameters influence of the rock model on the relative strength indices is shown in the dependences $\sigma_B(c, I) = idem$, as well as $\sigma_B(I, t) = idem$ (Fig. 2).

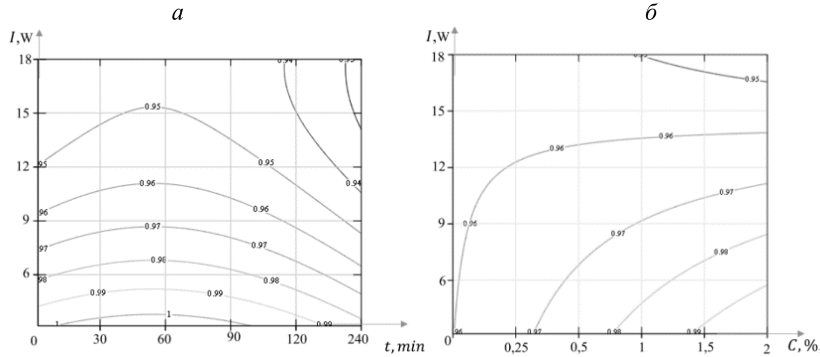


Fig. 2. Influence isolines of processing time (*a*) and surfactant concentration (*b*) change on samples strength

According to the results of the first stage, it was determined that for the experimental conditions there were areas of influential factors combinations that reduce the strength indices of rock models, as well as processing parameters and the necessary oscillation intensity for the technology to increase the FES [24] were selected.

At the second stage, we studied the filtration processes in a porous medium during the action of cyclic loads with different frequencies and amplitudes. To obtain reliable results in the absence of oscillation interference (which are present when using installations for studying the permeability of core samples of the UIPK type), in IFNTUOG, together with the scientific and production company INTEX, a facility was developed for studying the permeability of a porous medium in the process of hydraulic impulse loads on the core UDC-2 (Fig. 3).

Using the installation, when filtering the working fluid through the core 2 in the liquid medium 3, periodic pressure hydraulic pulses were created and transmitted to the core and cause its cyclic loading. As the working fluid, it is possible to use distilled water, produced water, flushing and other process fluids or mixtures. The pressure draw-down across the core during filtration is supported by a pump 10, manufactured with incorporated structural elements of a deadweight pressure-gauge tester, which allows maintaining a predetermined pressure value with high accuracy. Using a piezosensor 8 and a personal computer 14, the stability of the pressure pulses amplitude in a liquid medium is controlled. For periodic measurements of cyclic stress parameters on the core, a 795 M107V vibrometer is used. Measurement of oscillation parameters is carried out by inserting the probe of the vibrometer into the fitting 12 before contact with the core.

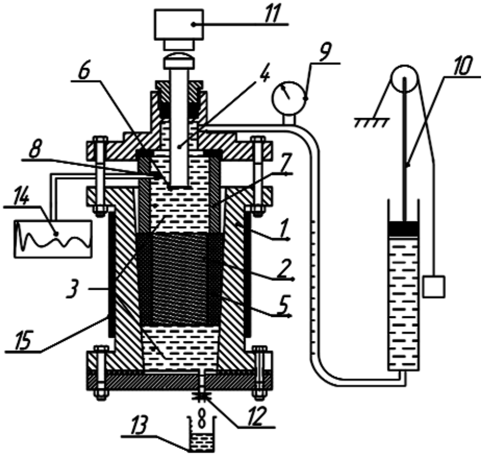


Fig. 3. Installation for studying the permeability of the pore medium in the process of pulsed core loads UDK-2: *1* – casing; *2* – core; *3* – working fluid; *4* - power plunger; *5*- rubber plug; *6* - ram tester; *7* - sealing plug; *8* - piezoelectric transducer; *9* - pressure gauge; *10* - pump; *11* - pressure pulse generator; *12* - fitting; *13* - measuring container; *14* - computer

Installation technical parameters

pressure draw-down on the core, MPa до 3;
lateral pressing, MPa до30;
pressure pulse repetition rate, HZ 50,100;
amplitude range, MPa 0.5-2;
duration of the pressure pulses leading edge, no more, ms 2;
operating temperature range, °C 20-70.

The volume of the filtrate, which is filtered through the core over time, directly indicates the state of spatial permeability, which varies depending on the conditions under which the filtration occurs. Since, during filtration and simultaneous cyclic influence, the fluid moves in the pores and microcracks of the core, changes in its rheological properties, the movement of uncemented particles (pollutant or parent rock) [6], electrokinetic processes, opening, closing, development of new microcracks, the amount of filtrate per unit time can vary within certain limits. In this case, it is necessary to investigate what kind of the filtrate volume will be before, during, and after the treatment with pressure hydroimpulses, and evaluate the changes in comparison with the initial results. It is also necessary to determine the characteristics of materials removed during core filtration by applying the methods of lithological-petrographic analysis.

In this regard, a set of experimental studies was determined on the effect of cyclic loads on core material in order to establish patterns of change in the volume of fluid that is filtered under given conditions depending on the amplitude and number of load cycles

For research purpose, we used an artificial core made on the basis of a sand-cement mixture according to the methodology [22], as well as a natural core made of sandstone for research according to the standard method of UkrNDPI PJSC Ukrnafta. The core was saturated with formation water during its evacuation. Mineralization of produced water was 50 g/l.

The amplitude of the hydraulic pulses was chosen at the level of 2 MPa based on the capabilities of the hydraulic pulse generator GKP-1 of the INTEX company. The indicated amplitude did not exceed the fatigue strength limit for sandstone [11]. The value of the pressure amplitude was determined by measuring the vibration acceleration on the core surface using a 795 M107V vibrometer. The number of load cycles was taken equal to 105, taking into account the repetition rate of hydro pressure pulses of 50 Hz and the processing time of 30 minutes

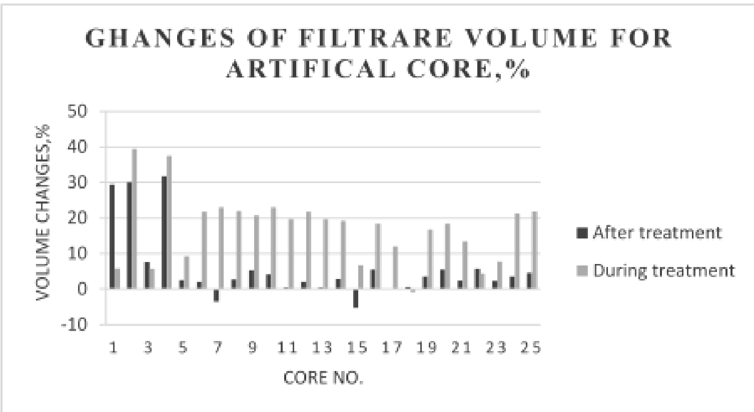
Lateral pressure on the core was maintained equal to 20 MPa. The pressure draw-down across the core was maintained at 1.3 MPa. The operating temperature of the installation was within 20±1 °C. Measurements of the filtrate volume were carried out after 30 min in a measuring container 13 during filtration without core cyclic loads, during loads, and also after loads. The effect of processing was determined by the ratio of volumes during and after processing to the volume of the filtrate without treatment. To assess changes in the inner surface of the pore space due to fatigue fracture of the rock, a fluid analysis was carried out, for which, fluid samples with removed particles of rock were taken into special ceramic cups before and after loads. Samples with object glasses inserted into the cups were dried, after which they were subjected to lithological and petrographic analysis under a microscope with a magnification of 1000^x. For each core, the initial parameters were determined by pumping 8 pore volumes, the first 5 of which were not taken into account, and the average value was taken from the last three. Such a sequence of actions makes it possible to minimize the influence of electrokinetic processes and processes occurring on interfaces at the beginning of filtration in a pore medium and to obtain statistically reliable information. After determining the initial values for the cores, a series of 10 experiments were carried out during the treatment with hydraulic pulses and 10 experiments after treatment. To build the dependencies, the average value of each indicator was taken.

Research results

As it is seen from Figure 4, the processing of natural and artificial core mainly caused an increase in the filtrate volume during filtration for the same period of time. The highest growth was observed for artificial cores 2,4 during processing and is equal to 36-38%. After processing, this figure drops to 30-32%. However, for artificial cores 7,11,15, despite the increase in the filtrate volume during processing by 24%, 19.8% and 7%, respectively, when the effect is removed, it decreases to the initial and even lower. For other artificial cores the filtrate volume increases on average by 20% during processing, and after processing this figure decreases by about 4 times. For sample 1, there was a slight increase in the filtrate volume by 6% during processing, and a further increase of the rate to 29.5% under filtration conditions after treatment. Only for sample 18, treatment with pressure hydroimpulses did not give statistically significant results, since the change in volume was only 1-2%. Dispersion for the obtained results is in the range of 8-15%, depending on the specific core. The situation is similar for natural cores. The maximum increase in filtrate volume was observed for cores 2,12,16 by 30-32% during processing and 17-42% after processing respectively. For natural cores 5,10,14 negative results were obtained - the filtrate volume decreased by 8-26%.

The analysis of fluid samples showed that, when filtering without core cyclic loads, the samples mainly show the presence of lumpy oxidized clay mass, as well as dusty clay particles and very small grains of quartz are present in an insignificant amount. Hydro-pressure pulses during filtration caused a significant increase in the samples of brownish clay mass and quartz grains coated with a clay film, and with further filtration without the action of hydraulic pulses, a gradual increase in rock cement particles is observed compared to the number of particles removed from the core before processing (by an average of 50%). The change in the filtrate volume for an artificial core is in the range of 5-30%, and natural 10-42%. The indicated indicates the appearance of additional fracturing of the rock. As for a natural core, processing is effective due to the presence of microfailures and microcracks in the samples that are not present in the artificial core, which is confirmed by the results of lithological and petrographic analysis. During filtration under the conditions of hydroimpulse exposure, core clay material, quartz particles are removed, and, consequently, the internal specific surface of the porous medium changes.

Based on the results of experimental studies, technologies and equipment have been developed for active impact on the productive horizon in conditions of repression or depression on the formation [23].



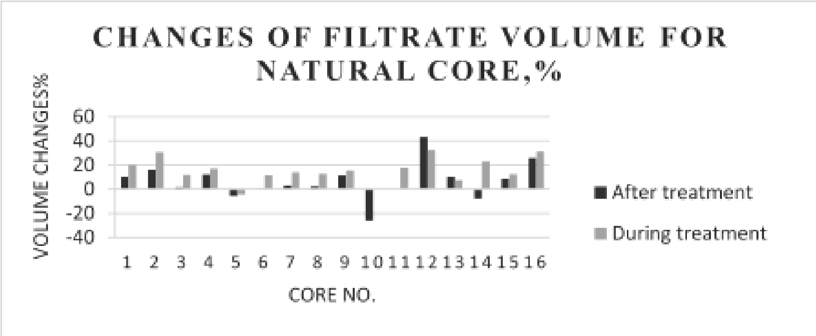


Fig. 4. Changes of filtrate volume during processing of natural and artificial core

The technology of hydroimpulse effects on the reservoir during depression.

The following equipment is used to implement the technology:

1. Multifunctional jet pump UEOS-4 with incorporated hydropulse generator GKP-1.
2. Coiled tubing installation;
3. Mechanical packer PMKV;
4. Depth pressure gauge;
5. Three-section calibrated container of 12-15 m^3.

The technology allows the following operations in wells:

1. Decreasing the bottomhole pressure only in the sub-packer space of the well and causing inflow from the reservoir. This eliminates the possibility of oil emissions and collapse of the casing string.
2. Hydropulse effect on the formation using a hydro-pulse generator and a jet pump with the subsequent generation of controlled depression in order to clean completely the bottom-hole formation zone (PZP) from the mud.
3. Injection of acid or other chemical reagents during repression and simultaneous hydro-pulse treatment of the formation.
4. Selecting of reaction products from the formation at the time required by the technology with controlled depression and simultaneous hydroimpulse effects on the formation.
5. Hydrodynamic investigation of wells in order to assess the initial and final state of the near-bottomhole zone of the formation by recording and decoding the pressure recovery curve of the HPC. The

recording and comparison of hydrodynamic parameters can be carried out with various depressions on the reservoir.

When performing technological operations, the working fluid is supplied to the nozzle of the jet pump through tubing pipes, and to the hydraulic pulse generator through a flexible pipe.

The fluid pumped out from the reservoir moves to the surface along the annular space.

The operations (Fig. 5) are performed as follows:1) the body of the jet pump (2) and the mechanical packer (3) are lowered into the well to the calculated depth at the tubing (1);

the packer is installed, as well as the pressure testing of the tubing and the packer is performed by using special inserts;

after the packing operation, a hydro-pulse generator (5) is descended into the sub-packer zone on the flexible pipe (4).

The generator is lowered with a sealing unit (6), which is fixed in the landing seat of the jet pump housing.

Later, a set of technological operations is carried out to affect the BFZ in accordance with the work plan.

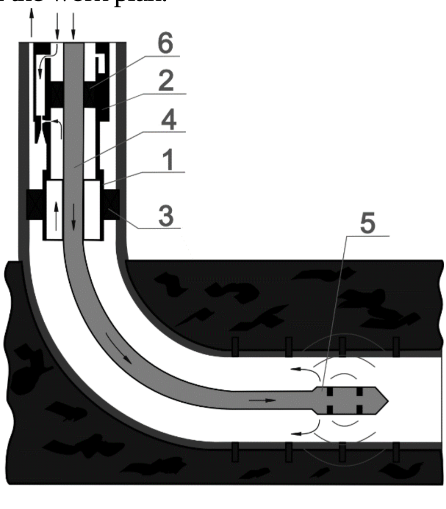


Fig 5. Schematic illustration of equipment for formation stimulation
1-tubing pipe; *2*-jet pump UEOS-4 (UEOS-4B); *3*-packer PMKV; *4*-flexible pipe; *5*-pulse generator GKP-1; *6*-sealing unit

The technology of impact on the colmatage reservoir with hydraulic pressure pulses of adjustable amplitude.

The effect of pressure pulses with a leading edge duration of up to 5 ms and an amplitude of up to 6 MPa on the BFZ makes it possible to create alternating pressure gradients up to 1.5 MPa/m in the formation, resulting in fatigue cracks in the rock as well as a decrease in the viscosity of the colloidal-dispersed structure in the BFZ. After such BFZ processing, the final stage of well development is carried out using a jet pump.

Calculation of parameters for elastic oscillations and generator acoustic power, necessary for the arising of fatigue cracks in the sandstone formation.

To simplify the calculations, the generator operation in the horizontal part of the wellbore is considered and a number of assumptions is adopted:

- a cylindrical wave is propagated in the formation;
- the direction of wave propagation in the horizontal part of the wellbore is perpendicular to the rock layers;
- the thickness of the layers is constant;
- to assess the fatigue strength of the rock, the cyclic loads of the formation with alternating pressure were taken into account;
- strength (strength limit σ_p) and acoustic (density ρ, longitudinal wave propagation velocity in the reservoir c_n, absorption coefficient k of elastic oscillations in a given frequency range f) rock characteristics were constant and consisted of:

rock tensile stress limits σ_p=1÷3 MPa (it was assumed in calculations: σ_p=2,4 MPa);

rock density ρ= 2200÷2600 kg/m^3;

longitudinal wave propagation velocity in the rock c_n=3000 m/s;

absorption coefficient of elastic oscillations in the frequency range 1-100 Гц –k=10^{-4} м$^{-1}$.

Elastic oscillations in the rock arise due to the action of hydraulic pressure pulses in the borehole space. The oscillation generator in this case is an acoustic system consisting of one or more generators of pressure pulses, the fluid of the well and part of the perforated casing. Such a system emits cylindrical elastic waves (Fig. 6).

Hydraulic pressure pulses create elastic oscillation packets in the reservoir medium. The duration period of the elastic oscillations at the point $x_1$is the shortest and, and in the first approximation it is determined according to the expression: $T_{x_1} = 4\tau_{\Phi}$, where τ_{Φ} is the leading edge duration of the hydraulic pressure pulse in the well media. The first quarter of fluctuations period in the package is the forced oscillation of the borehole medium, which is arisen in the reservoir during the action of the hydraulic pressure pulse. Depending on the acoustic characteristics of the formation, the frequency of elastic oscillations, when propagating in the formation, will decrease due to the absorption of high-frequency components of the oscillations package (Fig. 7). The high-frequency components of the oscillation packets during propagation in rocks damp at small distances from the generator. At distances of about 20-100 m, oscillations in the frequency range 30-80 Hz are dominant for low-permeable rocks.

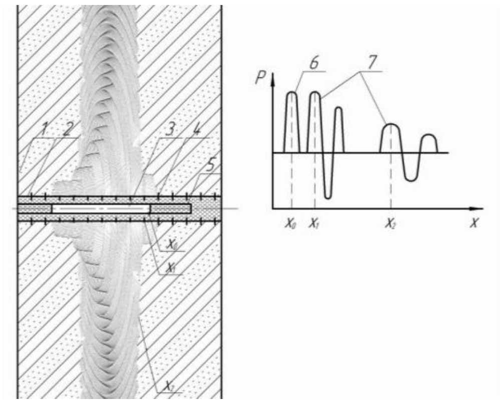


Fig 6. Schematic representation of a borehole emitter of a cylindrical wave and packets of elastic oscillations in the formation: *1* - formation; *2* - perforated casing; *3* - pressure pulse generator; *4* - working fluid; *5* - column tubing; *6* - hydraulic pressure pulse; *7* - packages of elastic vibrations in the formation

For further calculations, the frequency of elastic oscillations in the reservoir was taken up as $f_{x_2} = 50$ Hz. The limit of the rock fatigue strength σ_B was taken up at the level of 0.5 from the limit of its tensile strength. Then σ_B=1.2 MPa. Based on the conditions of fatigue cracks formation in the reservoir, when the amplitude of the alternating pressure P_{x_2}) exceeds the fatigue strength limit, it was taken up that $P_{x_2} = 1{,}2$ MPa. It should be noted that the expansion of the rock during the wave propagation would be carried out in the phase of pressure decreasing, which with the appropriate number of oscillation cycles would cause the occurence of fatigue cracks in the rock. In the pressure increasing phase, the rock will undergo compression, in which the rock strength is much higher and, accordingly, there is no fatigue cracking. The intensity of the fluctuations necessary to create the amplitude of alternating pressure P_{x_2} in the reservoir, is determines by the expression

$$P_{x_2} = \sqrt{2\rho c_n I_{x_2}} \ ,$$

where I_{x_2} - distance of oscillations intensity x_2 meters from well generator, when $I_{x_2} = I_{x_2}^2 / 2\rho c_n$. After calculations, it is received: I_{x_2} =10,435 W/cm². To evaluate the intensity fluctuations I_{x_0} on the emitter surface, necessary to get the intensity I_{x_2} in the formation, so the expression to determine the change in the intensity of the cylindrical wave depending on the distance to the generator can be applied

$$I_{x_2} = \frac{I_{x_0}}{x_2} e^{-2kx_2} \ ,$$

where x_2 - distance from the generator to the point of the reservoir, taken up equal to 2 m

After calculations it is receives: I_{x_0} =21 W/cm². For an intensity of 21 W/cm², with an average radiation area of the pressure pulse generator 300 cm², the acoustic power of the generator should be at least 6.3 kW. The hydraulic power of such a generator based on its acoustic power of 6.3 kW is to be determined. As a fact, the power created by hydraulic downhole devices can be determined by the values of the pressure draw-down across the device and the amount of working fluid passing through the device per unit of time according to the expression

$$N = \frac{Q \cdot \Delta P}{600} \cdot \eta ,$$

where N - hydrogenerator power, kW ΔP- pressure draw-down across the generator, bar; Q - fluid flow through a hydrogenerator, l/min; η - device efficiency.

The maximum pressure draw-down across the hydrogenerator type Intex GKP-1 is 7 MPa at a flow rate of 900 l/min. Thus, the hydraulic power generated by the generator is 94.5 kW. Taking up the coefficient of hydraulic energy conversion into acoustic energy equal to 0.3, the acoustic power of the generator is obtained equal to 28.35 kW. On the radiation area, in the zone of maximum oscillation intensity equal to 300 cm^2, the intensity of the oscillations in the well is 94.5 W / cm^2. Given the loss of acoustic energy during the transition from the liquid medium of the well into the formation, the transmission coefficient of acoustic energy is taken up as 0.8. Then the intensity of oscillations at the entrance to the formation (on the surface of the cylindrical emitter) will be 75.6 W/cm^2.

These calculations confirm the possibility of alternating pressure occurrence with an amplitude of more than 1.2 MPa in the reservoir at a distance of 2 m from the downhole hydrogenerator. The time required for processing the reservoir is to be deternimed. The recycling frequency of the hydraulic pressure pulses of the GKP-56M generator is in the range of 20-70 Hz. For the value of the recycling rate of 50 Hz and the number of rock loading cycles N=106, the obtained treatment time of the formation is equal to 2 hours 47 minutes. The effect of surface-active substances (SAS) on the processes of crack formation in rocks under cyclic loads, in particular the Rebinder effect, is not taken into account in the above written issues.

Conclusions

Industrial testing of technologies that took place in the oil wells of Ukraine and Dagestan [24], showed their effectiveness and promising for exposing the depleted and marginal wells on the bottom-hole zone. So in most cases, cleaning of the bottom hole from the mud was performed and restoration of well productivity lasted for a period of 6-18 months. Well productivity was restored in some cases by 200-300% of the initial values.

This result makes it relevant to develop new technologies for exposing the formation used in the development of oil and gas wells, intensifying the production of shale gas and oil, coal beds degassing and before hydraulic fracture operations.

Further development and improvement of technologies for wells stimulation with low permeable or colmatage formations will occur in the direction of combining cyclic hydro-pulse wave action and hydraulic fracturing, as phased components of a basic technology for intensifying oil and gas recovery.

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