Combined technological solutions to increase inflow in oil wells of offshore fields

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Abstract. Hydraulic fracturing (HF) technology is widely used all over the world. It enables to increase the efficiency of a well and put into operation wells with clogged bottomhole zone. Annually, service companies pay much attention to HF and promote new solutions to improve the efficiency of this technology, which contributes to its importance in stimulation of production. The main advantage of HF is the increase in the drainage area of a reservoir while multi-stage hydraulic fracturing. It is shown that HF and violation of the inflow stimulation technology can lead to proppant backflow not only at the stage of well development, but also during well operation. One of the solutions to prevent such complications is the use of technical means that provide proppant attachment in the fracture and reduction in the time of well development. The paper proposes technological and technical means to improve reservoir-to-well connectivity, to increase reservoir area covered by the fractured space, to reduce material and time costs during well development. It is shown that combined technological solutions for HF and well development lead to an increase in the flow rate of oil wells.

Keywords: hydraulic fracturing; fracture; complex technological solutions; near-wellbore zone; proppant; nitinol; self-expanding filter; hydraulic vibrator; jet pump

1. Introduction
In recent decades, the development of hydrocarbon deposits has shown the high efficiency of hydraulic fracturing (HF), which puts unprofitable reserves into operation and increases not only the rate of their production, but also the final oil recovery of low-permeable fracturing. Currently, HF is one of the most successful operations to increase the inflow of hydrocarbons. This technology provides high flow rates and increase in the productivity of wells. The actual problem is the "resuscitation" of the wells of the deposits that are at the final stages of development. It is possible to restore a profitable flow rate in such wells using combined technological solutions, including HF and well development.

HF is operated in vertical, directional and horizontal wells (VW, TW, HW) [1]. In vertical and directional wells, HF is commonly carried out under a traditional technology, in which a slab is processed according to the principle of "injection into one slab" despite its injectability along the length of the open trunk or in the thickness of cased and re-opened productive slab.

Wells with a horizontal termination have been widely used in recent years. Operating of such wells that tap insufficiently cemented slab affects a significant removal of mechanical impurities. In this regard, wells with horizontal ends require an equipment that prevents the flow of sand into a trunk.

2. The technology of multi-stage hydraulic fracturing
The technology of multi-stage hydraulic fracturing (MSHP) is widely used in wells with horizontal termination. MSHP provides the pumping of calculated volumes of fracturing fluid and proppant into a slab
intervally, covering the entire productive capacity (thickness) of a slab with significant increase in the production capabilities of a well [2]. For example, let us consider 8-interval HF using ZoneSelect system.

To carry out selective HF, a shank is dropped into an open horizontal shaft. A shank includes packers and circulation valves in an amount corresponding to the required number of intervals (the theoretical maximum of intervals is 25).

The system is activated hydraulically (Figure 1). During HF, a ball intended for the lower interval has a minimum size and is freely pumped through overlying landing saddles. Each subsequent ball has a larger size than the previous one and is oriented to the overlying interval [2].

![Figure 1. Opening of a circulation valve, sealing of an underlying interval](image1)

After HF it is necessary to flush a well, mill balls and landing saddles and perform development. Such operation requires a special equipment. This operation is carried out according to the work plan and the regulations for working with a coiled tubing.

3. The method for reducing the proppant removal from a crack into a well

Frequently, in HF there is the reverse removal of proppant from a frack into a well. In some cases, a horizontal wellbore is literally "filled with proppant". The proppant is removed from the fracture of HF not only at the stage of development, but also during well operation. If HF affects the flow of proppant from the crack into the wellbore, consequently, proppant packing has an unstable state that can lead to the closure of the fracture (Figure 2).

![Figure 2. The reduction of the conductive width of a fracture](image2)
Due to the removal of the wedging agent from the crack in perforation interval (PI), the effect of HF decreases, proppant accumulates in the PI, therefore, requires additional flushing of the bottom of the well. The proppant removed from the crack quickly disables the installations of electric submersible pumps (ESPs) of mechanized wells.

Such an urgent problem causes coupling of proppant granules to prevent the removal of small fractions into the wellbore. The existing technologies for proppant manufacturing used in HF have some disadvantages.

A new method for producing proppant granules has advantages over existing technological solutions [3]. Proppant granules are produced from a metal wire without temperature exposure. The alloy of the wire has a memory effect. A helical spiral spring is developed with diametrical dimensions based on the size of the hydraulic fracturing crack. The winding step of coils is taken from the condition of forming a filter layer to retain ceramic proppant particles. Additionally, metal proppant granules are formed by mechanical compression of the helical spring with the formation of a sphere. Figure 3 (a) shows the helical spiral spring, which plays the role of a proppant granule structure. Nitinol proppant acquires this form in the interval of the initiation of fracturing fracture after the exposure of elevated reservoir temperature. Figure 3 (b) demonstrates the proppant granule after rolling. In this form, the described propant is supplied into a blender, where the granules are mixed with a cross-linked gel.

The alloy of titanium and nickel in almost equal percentages 45% and 55% is called nitinol, which has the memory of an original shape and high elasticity. The memory effect of the original form of nitinol is expressed in the ability to restore the deformable profile to its original state under certain conditions when the temperature rises. The alloy exceeds steel by about 20 times in superelasticity. Additionally, it has high plasticity, corrosion resistance and strength. The permissible deformation is 8%, the permissible stretching is up to 12%. If the product is heated again, it takes its original shape, such as a spiral wound from a small diameter wire.

Proppant granules from nitinol during HF are applied by feeding them into a liquid and putting this suspension into a HF crack. When exposed to the reservoir temperature higher than \( T_{res} = 40^\circ C \), the proppant granules restore their spring shape, interact with each other and the rock, forming a permeable layer for the reservoir fluid. At the same time, the layer of springs filters retaining ceramic proppant granules and mechanical parts from the remote areas of the HF.

The proppant with the shape memory material is proposed to be injected at the final stage of crack fixing [4]. The peculiarity of the shape memory is that nitinol is an intermetallic metal. Such metals involve the order of atoms when quenching, which leads to the memorization of the shape. When the certain temperature is reached, the intermetallic compound returns to its original state.

The developed HF method is carried out by pumping ceramic proppant of the calculated fraction into remote areas of the fracturing crack with a certain rate of HF fluid supply [5]. Before the main HF, mini HF is carried out on a linear or cross-linked gel to assess the success of the main HF operation. Afterward, the calculated volume of the fluid is injected to create a crack in the productive formation. Further, a sand carrier liquid is pumped through the tubing column for fixing with the calculated concentration of proppant. Proppant fixes the
created crack and prevents it from closing. After the pumping down of the fraction sand carrier fluid, over flush is required to deliver the consistency to the crack.

The practice of HF shows that the flow rates of reservoir fluid in the fracture wings and its output differ several times. To ensure the supply of proppant of the calculated diameter into the fracture crack, the composition of the HF fluid and the rate of injection into the interval of the productive thickness are selected. The HF fluid (pillow), sand carrier fluid and over flush are pumped into the tubing volume with the possibility of ensuring complete displacement of proppant into the crack created by power pumps. After pumping the main portion of ceramic proppant, the calculated volume of nitinol proppant is placed in the hydraulic fracturing fluid. The injected nitinol spheres are placed in the near-well zone, open under the influence of the reservoir temperature and provide complete retention of ceramic proppant in the hydraulic fracturing crack (Fig. 4). For HF according to the proposed technology, it is necessary to use compressed nitinol springs with a radius depending on the expected size of the cracks. Studies carried out on a laboratory stand have shown that there is a removal of ceramic proppant at different heights of the bulk layer in the conduction cell. Injection of nitinol proppant at the beginning of crack initiation will allow compacting the proppant in the crack and preventing its return removal from the crack into the well perforation interval. Thus, the application of the developed method of HF in practice will allow forming a highly permeable layer of open nitinol springs located at the beginning of crack initiation in the presence of ceramic proppant optimally placed along the fracture fracture.

4. A well self-expanding filter
The operation of the old well stock is complicated by the removal of mechanical impurities into the perforation interval. The accumulation of clay-sand and proppant plugs affects decrease in the productivity of the wells. Additionally, negative consequences are manifested in the intensive wear of the elements in deep pumps and pump-compressor pipes, threaded connections, fountain fittings. Besides, the perforation intervals are blocked by sand plugs, that disrupts an operation mode and productivity of the well. Reducing the amount of solid phase entering the well is an urgent task. It requires to use the technical means of the downhole equipment.
The use of borehole filters does not always provide successful operation complex geological objects. To retain sand in loose and weakly cemented reservoirs, it is proposed to use a nitinol filter. This design is used in vertical, directional wells and has filter elements made of wire materials with shape memory (Figure 5).

![Diagram of filter design](image)

1 - hollow body; 2 - petals; 3 - perforation holes; 4 - filter shell; 5 - axial channel; 6 - coils of a spiral spring; 7 - drainage holes

Figure 5. The design view of well self-expanding filter

The developed self-expanding filter (SEF) consists of the hollow body with perforations and longitudinal grooves in which spiral springs are placed [6]. The filter shell of the SEF is designed in the form of the winding coils of a nitinol spiral spring wound on stringers. To block the direct flow of reservoir fluid to the perforations, reflective rings are installed on the filter shell of the SEF. The protective nitinol casing is prefabricated in the form of paired thin-walled cylinders. The retention of the proppant pack in a stable state after HF is achieved by centering the filter in the axial channel of the casing pipe and self-expanding the filter to the size of the bottom-hole zone when installed at the planned interval.

Filter throughput for the nominal filtration fineness is 200 microns on water at $p=1000 \text{ kg/m}^3$. A filter is lowered to the tubing at the planned installation interval. Low hydraulic resistance of the liquid makes it possible to reduce the overall length of the filter by 1.5...2 times compared to systems on slotted grids. The design of the nitinol stringers and the filter housing permits to repeatedly discard mechanical impurities from the filter elements when the layout is cooled. The filter has high corrosion and erosion resistance of nitinol filter elements. The filter surface of the device provides high-quality filtration regardless of the geometry of the particles. The device casing protects the filter surface from mechanical damage, including descent and lifting operations. To prevent a decrease in the flow rate of the well due to clogging of the filter elements, it is possible to use a bypass system.

5. The application of a jet pump and a hydraulic vibrator

After HF in various wells it is necessary to wash the perforation interval and perform development. As terms of the development of integrated technological solutions for the intensification of inflow in the oil wells, a jet pump (JP) and a hydraulic vibrator (HV) is proposed, which can be used both in an open well and in cased wells. The studies are carried out at any angle of borehole inclination, including at horizontal endings of the boreholes. The work can be carried out at a reservoir temperature of up to 150 °C and a reservoir pressure of up to 100 MPa. The technology of using a vibrator and a jet pump is designed to seal the proppant, call the inflow and bring the well to an effective operating mode. This technology significantly reduces the time spent on mastering and research using traditional methods. The technology is designed for the development of low-
permeable reservoir formations and has a wide range of possibilities for influencing the formation (depression, repression, pulse-shock method).

To create a pulse-shock effect, a hydraulic spool vibrator (HSV) is used [7]. The well hydraulic vibrator contains a housing and a barrel mounted coaxially in the housing on bearings with slots made at an angle to an generatrix and an axial channel. Additionally, the vibrator contains a spool with slots made at an angle to the generatrix and in the opposite direction to the slots of the trunk. The housing from below is muffled and with radial holes with a reflector in opposite (Figure 6). The outer surface of the specified spool has a screw shape.

![Figure 6. Borehole vibrator](image)

A rotating blade with a passage channel and profiled blades is installed in the axial channel of the barrel. Below the rotating nozzle in the housing, radial channels are made for suction of reservoir fluid. Hydraulic monitoring nozzles are installed in the radial holes intended for the mixed liquid output.

The HSV descends into the well after HF and well flushing and enables compacting the proppant pack in the fracture. The HSV is lowered into the well on the pump and compressor pipes and installed in such a way that it is directly at the point of the perforation interval of the formation. The place of installation of the downhole hydraulic vibrator for processing the propane packing is selected beforehand, according to field geophysical surveys. Hydrofoil treatment of the formation is carried out by feeding the working fluid $Q_w$ through the central axial channel of the HSV at operating pressures created by ground pumping units CA-320 or three-plunger pumps with a working pressure $P_w=4-7$ MPa. The optimal mode of HSV operation is achieved when the flow rate of the washing agent is from 7 to 9 l/s. The working fluid $Q_w$ at a high speed creates a discharge that is transmitted through the slots to the annulus space. Thus, at the depth of the downhole hydraulic vibrator installation, the high and low pressure zones are formed alternately relative to the perforation holes of the formation. Under these conditions, the filtration flow of the reservoir fluid and the well wall are treated with hydrodynamic pressure pulses. The energy of elastic hydraulic vibrations is transferred to the bottom-hole formation zone, which contributes to high-quality and effective compaction of the propellant in the fracture. The reservoir fluid $Q_{rez}$ is mixed by the blades of the vibrator with the working fluid $Q_w$, and due to the hydraulic monitoring nozzles, creates a hydraulic monitoring effect on the formation, which makes it possible to attract additional reservoir fluid to the working fluid during well flushing. Due to the use of the
hydraulic vibrator, the downhole zone of the productive reservoir acquires a "new state". The influence of the skin factor in bottom-hole formation zone after treatment has a minimal value.

The development of the wells after HF in vertical and directional wells requires a jet pump with the diameter of 38 mm, which is lowered to the coiled tubing [8]. The method of development, intensification of oil and gas tributaries and water isolation works in wells includes the descent of the device housing with a packer into the well on the external pump and compressor pipes until the formation perforation interval [9]. Then the packer is installed and checked for tightness by crimping. Furthermore, the installation and crimping of the central row of pump and compressor pipes is carried out. The supply of working fluid, pumping of reservoir fluid and the supply of mixed fluid from the well to the surface is carried out through the annular space. The ring space is equipped with an external and central row of tubing. The device contains a housing with a pressure valve located between the outer radial channel and the channel connecting the coaxial channels of the jet pump nozzles and check valves. The housing has a flow-through axial, longitudinal and radial external and internal channels for receiving and discharging liquids, jet pumps with diffusers. Each jet pump is additionally equipped with an upper check valve located in the longitudinal channel above the diffuser (Figure 7). To start the jet pumps, the working fluid is fed through the pressure valve through the annular space formed between the operating column and the outer row of tubing. The device and method of the proposed technology can be implemented by creating various variable depressions on the formation by reducing bottom-hole pressures by pumping liquid from the central row of tubing connected to the formation and having a limited internal volume by jet pumps. The use of the developed device complies with environmental norms and standards [10].
Figure 7. Device for well development

However, this technology does not allow achieving the desired effect after HF in wells with horizontal ends, with shank diameters of 102 mm. For the successful development and research of these wells after HF, the authors developed a small-sized jet pump with a cuff packer. Under the jet pump there is a container with a small-sized autonomous installed deep-depth electronic device, which monitors the development and exploration of the well.

The use of jet pumps and hydraulic slide vibrators in the processes of well development after HF enables the entire operation to be carried out in one cycle, which significantly improves the quality of the work carried out to intensify inflows and increase the productivity of the wells.

6. Conclusion

1. HF with injection of nitinol proppant provides forming a highly permeable layer of the opened nitinol springs located at the beginning of crack initiation in the presence of ceramic proppant optimally placed along the fracture. The formed layer can keep small fractions of ceramic proppant in the HF crack, by forming a metal filter in the form of a "package" of the helical coil springs at the wellbore exit, due to the influence of a high reservoir temperature.
2. The use of a downhole self-expanding nitinol filter makes it possible to center the filter in the axial channel of the casing pipe, by changing the diametrical dimensions of the protective casing. Installing the filter results in the direct flow of the filtration of the reservoir fluid to the perforations on the housing. It ensures filtration over the entire area of the filter shell formed by the coils of the winding made of a helical nitinol spiral spring.

3. The use of the downhole vibrator permits to pack proppant seal of the crack. After the processing of the bottom-hole formation zone by this device, the downhole zone acquires a "new state".

4. The development of wells using jet pumps allows not only to significantly reduce the duration of the cycle of putting new wells into operation, but also to decrease the risks of accidents at wells by reducing the number of descent and lifting operations. The maintenance-free period of well operation the during oil production by the jet pump is at least 8 months.

5. Various wells may be processed by the method of HF with the injection of nitinol granules at the final stage of crack fixing and the use of jet pumps and hydraulic slide vibrators in the processes of well development after HF.

Borehole self-expanding nitinol filters are recommended for installation after HF in the vertical and directional wells.

6. A significant increase in the inter-repair period of operation and the flow rate of the well has been established with the combined use of technological solutions for retaining propane in the perforation zone and, accordingly, "sparing" development of the wells by the jet devices.

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