Low frequency hydraulic hammer for wave action of injection wells

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Abstract. The deposition of salts, iron sulfide, precipitating from solutions as a result of disturbance of thermodynamic equilibrium, occurs during operation in the near-wellbore zone (NWBZ). Efficiency of field development, production rates of operating wells, injectivity of wells and the fraction of reservoir energy that can be used to lift fluid directly in the well significantly depends on the state of the bottom well formation zone (BWFZ). It is required to implement measures to influence NWBZ in order to reduce filtration resistance, to increase permeability, improve connectivity with the wellbore, and increase the system of fractures or channels to facilitate inflow and reduce energy losses in this limited formation area. The structural diagram and dynamics of the vibrator are revealed in the paper to accomplish the given tasks.

1. Introduction

Active wells, most of which have entered the late stage of development, remain the main source of hydrocarbon raw materials. However, the current level of oil recovery from the reservoir cannot meet the country's need for strategic raw materials [1–6]. Estimates made by scientists and field workers show that an increase in the oil recovery factor (ORF) by 1% enlarges the increase in its annual production by 20-30 million tons. In this issue, it is required to intensify scientific research and field work to enhance the completeness of oil extraction from reservoirs [7–10].

The bottomhole zone of a well is an area adjacent to the wellbore, within which a change in filtration characteristics is observed throughout the entire period of well operation, starting from its construction.

Here all the processes proceed with the greatest intensity: maximum oil velocity and pressure, maximum energy losses and filtration resistance. The state of this zone has a significant impact on the productivity of oil extraction.

The following factors are attributed to the main reasons for the decrease in the permeability of the bottomhole zone during the operation of production wells:

− penetration of killing fluid (fresh or salt water) during underground repairs or flushing fluid;
− water penetration into flooded wells during shutdown;
− swelling of clay cement particles of a terrigenous reservoir when it is saturated with fresh water;
− formation of oil-water emulsion;
precipitation and deposition of asphaltene-resin-paraffin components of oil or salts from produced water when temperature and pressure conditions change; 

penetration of mechanical impurities and metal corrosion products into NWBZ when killing or flushing a well.

For injection wells:

- swelling of clayey rocks in contact with fresh injected water, and with solutions of certain chemical reagents;
- colmatation of NWBZ with a solid phase of the drilling fluid when performing workover or other works in the well;
- increased residual oil saturation in the bottomhole zones of wells, which worked as producers before transferring to injection.

It is essential to ensure such conditions that a minimum amount of energy is spent on fighting filtration resistance when withdrawing or pumping fluid. Various measures are taken to reduce filtration resistance. They can be divided into three categories.

The classification of exposure methods

- Chemical - applicable when the permeability is deteriorated due to the deposition of soluble elements: salts, ferruginous deposits, etc.;
- Thermal - applicable when the oil has a high viscosity due to the presence of hydrocarbons such as paraffin, resinous substances, asphaltene;
- Mechanical - applicable in hard rock where it makes sense to create new fractures in the bottomhole zone to engage remote formation zones.

There are also methods that are combinations of the three above mentioned ones, for instance, thermal acid treatment. The method of action should be chosen considering the state of the bottomhole zone, existing thermodynamic factors, chemical composition, and physical properties of rocks and fluids.

A constant deterioration in the oil and gas permeability of the bottomhole zone is observed during the development of oil and gas fields. It is especially unfavorable in low-permeability and heterogeneous reservoirs.

The deterioration of natural permeability occurs even in drilling, when compressive stresses are formed in the annular zone around the well during rock removal. The rock surface is thermodynamically activated by mechanical interaction with the rock cutting tool and drilling fluid, which subsequently contributes to the formation of highly viscous surface bridging layers.

The drilling mud also forms a clay crust with a thickness of 2-3 mm on the well walls, and the filtrate penetrates into the formation. The drilling mud is also able to penetrate deeper into the formation through the fractures of the bottomhole zone arising from the appearance of hydrostatic pressures above the fracture pressure, for example, during operations to restore the circulation of drilling fluid or during tripping operations. According to laboratory studies, a decrease in the absolute permeability of rocks can be observed by 2-50 times, and in some cases - up to zero.

Drilling mud filtrates can penetrate into productive formations to an even deeper depth. The penetration depth of the latter reaches 0.2-3.0 m. Besides, a strong deterioration in the natural reservoir properties of BWFZ occurs due to:

- swelling of the reservoir clay particles, if the filtrate water differs in its salt composition from the formation water;
- decrease in the phase permeability to oil through the appearance of an aqueous phase and the formation of near-wall layers of water on the surface of pores, which have increased viscosity and elastic shear resistance;
- occurrence of capillary phenomena at the boundaries of water contact with reservoir oil;
- the formation of stable water-oil emulsions of the “water-in-oil” type, which are poorly filtered not only due to their high viscosity, but also owing to their pronounced thixotropic properties;
- clogging of pores with sediments insoluble in water and oil, which are formed as a result of the chemical interaction of filtrates and flushing fluids with formation fluids.

It is known that changing the productivity of production and injection wells by adjusting the parameters of the well bottomhole zone is possible. Therefore, the methods of artificial influence on the NWBZ are a powerful way of increasing the efficiency of hydrocarbon reserves recovery. It emphasizes that not all methods have the same efficiency, but each of them can give the maximum positive effect only if the selection of a particular well is reasonable. Therefore, the issue of well selection is fundamental when using one or another method of artificial stimulation on NWBZ.

The conclusion about the need for an individual approach to each treatment was made at the Institute of Field Chemistry at Russian State University of Oil and Gas named after I.M. Gubkin, according to the results of numerous studies on acid treatments.

Vibration is most expedient in wells: 1) with BWFZ permeability below the average formation permeability or more distant from the well formation zones; 2) with deteriorated reservoir properties of NWBZ as a result of the penetration of drilling and cement mud, weighting agents, water, etc. into the formation during development or repair work; 3) producing reservoirs composed of low-permeability rocks, which contain clay materials; 4) with low permeability of rocks, but high reservoir pressure. Positive outcomes of vibration treatment have been obtained in wells, the flow rate of which is subject to a sharp decrease, not associated with a decrease in reservoir pressure and their flooding with extraneous water. In such cases, the initial flow rate can be restored as a result of vibration treatment.

The purpose of the vibration wave action is to transform it into a one-way-directional monotonous movement, carried out by an indispensable technological process. The structural diagram and dynamics of the vibrator are brought into operation to accomplish the given tasks. The cleaning speed increases in the well, the intensification of crossflows between heterogeneous parts of the reservoir occurs in the formation, which leads to the dispersal of the clogging effect into the void space of the material in the formation volume, and to unblocking of zones, pillars saturated with oil and formation water.

Asphaltene deposits pulsator for downhole and surface equipment of ESP.

The following requirements for the designs of dynamic generators have been revealed on the basis of analytical studies and the experience of applying wave fields to increase oil recovery from a low-permeability environment:

1. Elimination or minimum losses for the transport of wave field energy to the bottom of well.
2. Providing the ability to position waves of higher frequency on the crest or the vibrator back.
3. Minimum energy losses of the radiated waves when passing through perforations or directly through the walls of the casing, when passing from the near-wellbore zone to the formation pore channels for dissipation by the viscosity and thermal conductivity of the medium, as well as by the forces of fluid relaxation against the channel walls and internal friction into the rock skeletons.
4. Inappropriateness of forced vibration of the rock skeleton at frequencies higher than infrasonic.
5. Providing the ability to control the waveform for enhancing its propagation depth and use efficiency.
6. Providing the ability to control and periodical adjustment of frequency and wave amplitude considering the parameters (productivity, pressure, etc.) of a particular well.

The conducted analysis allowed revealing the following disadvantages of known wave generators:

- Known hydrodynamic generators, operating at the expense of the fluid flow energy, do not have nodes for increasing the power and impulse (energy accumulators) due to the periodic accumulation of the flow energy.
- Main designs of hydrodynamic generators do not provide for the possibility of controlling the waveform: electro-hydraulic, electromagnetic, powered and ultrasonic hydrodynamic generators.
- Additional nodes for supplying power, lifting and other equipment are available in separate designs of relatively high cost.
The lack of nodes provides frequency and amplitude adjustment depending on the reservoir properties of the formation and the technological parameters of the well, which sharply limits the generator versatility. A sharp decrease in the radiation intensity can be observed in some cases when changing the mode of pumping liquid for generators operating in modes of natural vibration frequencies (including self-oscillating ones).

Excessive high frequency of radiation from generators used without a combination with a low frequency generator is exclusively applied for enhancing oil recovery.

2. Materials and methods
The hydraulic hammer design has been developed for a variety of well applications [11–13].

Figure 1 presents a shortened model of the hydraulic hammer by eliminating the stem for downhole operations. The hammer consists of body 1, an upper sub 4, a lower sub 2 equipped with an anvil 3, intended for connection with oil well tubing. Valve box 7, rigidly connected to striker 6, and spring 5 are located inside the body. Connecting rod 9, which is bounded by pin 10 with the rocker valve 11, is fixed inside the valve box on axis 8.

The operating principle of the hydraulic hammer is as follows. Rocker valve 11 in the initial position closes the channel of the rectangular section of valve box 7. Connecting rod 9 and rocker valve 11 occupy a vertical position in accordance with the law of hydrostatics when flushing fluid is supplied through the channel of the valve box under the pressure drop influence.

Subsequently, connecting rod 9 moves to the extreme right position by inertia, dragging rocker valve 11. As a result, the channel of the valve box is closed; a pressure drop is created at the upper end of valve box 7, and the impact mass 6 moves downward under the influence of a pressure drop, while impact occurs on anvil 3. Spring 5 is compressed and receives potential energy. Rocker valve 11 takes a vertical position in consequence of impact and pressure from the flushing fluid. The pressure drop on the upper end of the valve box is significantly reduced due to the free movement of fluid in the channel of the valve box and striker 6 moves upward under the action of spring 5 and takes its original position. Subsequently, rocker valve 11 by inertia moves to the extreme left position and the cycle repeats.

Low-frequency hydraulic hammer dynamics.

Hydraulic hammer includes striker, rocker valve, resilient element, anvil and body.

![Fig. 1. Low frequency hydraulic hammer for wave action of injection wells](image-url)
3. Results and discussion

Consider the work of a hydraulic hammer in bench conditions, when its body is connected to a massive foundation. The pressure force depending on the liquid speed, striker speed, and the valve position, acts when the liquid flows through the hydraulic hammer to the diverter valve:

\[ F_h = \rho g k(a) \frac{(U_{liq} - U_{im})^2}{2}, \]  

where \( \rho \) – fluid density; \( g \) – gravity acceleration; \( k(a) \) – coefficient of hydraulic resistance (determined in bench conditions); \( U_{liq} \) – fluid speed; \( U_{im} \) – striker speed.

Fluid speed depends on \( Q \) fluid flow rate and the cross-section area of \( S \) striker:

\[ U_{liq} = \frac{Q}{S}. \]  

The spring resilience force depends on its stiffness \( C \) and on the deformation \( x \):

\[ F_{res} = Cx, \]  

where \( x \) – striker displacement from the equilibrium position. The striker movement is described by Newton’s second law:

\[ mx'' = F_{hydr} - Cx, \]  

where \( m \) – striker mass (includes valve mass).

The equation is as follows after substitution:

\[ mx'' = \rho g k(a) \left( \frac{Q}{S} - x' \right)^2 - Cx. \]  

There are two indeterminates in the equation: \( a \) and \( x \)

It is necessary that the oscillation period of the rocker valve coincides with the oscillation period of the striker for regular operation of the hydraulic hammer. This can be achieved when several conditions are met:

a) hydraulic force must be insufficient to open the valve when the striker moves down;

b) resilience force must be large enough to lift the striker when the valve is open;

c) valve opening should begin at the moment the striker hits the anvil.

Consider the striker movement in a steady flow. Suppose that at the initial moment the striker is located on top, the valve is closed, \( x = 0, t = 0 \).

The striker begins to lower, compressing the spring under the action of the pressure force in accordance with equation (4), and the force \( F_{hydr} \) is constant, since the valve is closed, \( a = a_{max} \). The impact occurs at time \( t_1 \) after the end of the striker's move, which can be found from the conditions:

\[ x = L, \quad t = t_1, \]  

where \( L \) – striker stroke length.

Hydraulic hammer bounces. The rebound rate depends on the elasticity of the collision and can be taken into account through the recovery coefficient \( k_r \):

\[ U_{reb} = k_r U, \quad x = L. \]  

The upward stroke begins with the initial conditions:

\[ x = L, \quad t = t_1, \quad x = -U_{reb} = k_r x, \quad t = t_1 + 0. \]  

The upward movement of the striker is described by the same equation (4), but in this case the hydraulic force is already variable, the valve is slightly open. Valve movement is determined by valve design and flow rate. The valve tilts over after opening. The tipping speed is increasing all the time. We determine the valve rotation time taking the rotation to be uniformly accelerated:

\[ 2a_{max} = e \Delta \tau^2 / 2. \]
On the other hand, it is known that the throw-over time of the diverter valve is determined by the following equation:

$$\Delta t = \frac{2SL_v}{Q},$$ (10)

where $L_v$ – diverter valve length.

We obtain the following equation from the last two ratios:

$$e = \frac{4a_{in}}{(2SL_v/Q)}.$$ (11)

The valve is closed after $\Delta t$ time. The pressure on the valve increases and the striker of the hydraulic hammer hits the anvil.

The computation of the hydraulic hammer movement is carried out by the numerical method. The time interval of interest $(0; T)$ is divided into $N$ equal sub-intervals with $dt = T/N$ duration.

The function $x(t)$ is replaced by the grid function $x_i$, where $x_i = x(t_i) \quad \text{and} \quad x(dt_i)$. (12)

The main differential equation (1), which determines the valve movement, is replaced by the differential one:

$$m \frac{x_{i+1} - 2x_i + x_{i-1}}{dt^2} = pgk(a) \left( \frac{(x_i - x_{i+1}) - \Delta U_{tg}}{2} \right)^2,$$ (13)

whence, knowing two consecutive positions of the striker, we can calculate the following:

$$x_{i+1} = 2x_i - x_{i-1} \frac{dt^2}{m} \left( pgk(a) \left( \frac{(x_i - x_{i+1}) - \Delta U_{tg}}{2} \right)^2 \right).$$ (14)

When solving (5), the striker flow area is designated by the following formula:

$$S = \frac{\pi d^2}{4},$$ (15)

where $d$ – through-passage channel diameter.

For satisfactory operation of the hydraulic hammer:

$$S \leq S_{vb},$$ (16)

where $S_{vb}$ – flow area of the valve box.

The work of the hydraulic hammer is simulated using a computer for the following constant data: $p = 1000$ kg/m; $k_r = 0.5$; $Q = 0.025$ m$^3$/s; $L = 0.1$m; $L_v = 0.18$ and various values of mass and spring parameters.

4. Conclusion

The research demonstrates that the hydraulic hammer frequency decreases and the impact force increases with the addition of the striker mass or calibrated valve sleeve.

Analytical studies of the rocker valve operation show that the design of the hydromechanical vibrator is efficient. The theory of the hydraulic hammer operation has been developed, the working element of which is a rocker valve mounted on a spring.

The hydraulic hammer is installed at the level of the well perforated zone when restoring the injectivity of wells.

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