Wave-pulse simulation in high-viscosity oil wells

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Abstract. The thixotropic properties of high-viscosity oils have been found to be highly dependent on temperature and pressure treatment. As the temperature increases, the efficiency of the wave-pulse method to reduce the thixotropic properties of high-viscosity oil increases. The effect of the wave interference on the productive formation decreases over time, and after 3-7 days of development, the well must be treated again to ensure its operation in an intensive mode. Wave-pulse treatment facilitates the separation of light fractions from high-viscosity oil and hydrophobization of the reservoir. Heat and wave-pulse treatments complement each other and contribute to a complex effect on high-viscosity oil, but they must be carried out simultaneously or alternated with minimal interruptions in order to avoid the space lattice restoration.

1. Introduction
Due to the increasing development of hard-to-recover deposits [1-6], the interest in the integrated use of thermal and wave effects on formations in the production of viscous oil has increased sharply in recent years. It was found that the heat transfer is significantly intensified if the heat treatment of the formation is combined with wave treatment, for example, ultrasonic [7].

The effect of pulsed pressure on enhanced oil recovery was studied in laboratory conditions at the University of Waterloo (Ontario, Canada). The results of experiments showed that with impulsive motion the speed of oil movement in the formation is 2.5-3 times higher than the standard speed. Oil recovery efficiency was more than 10% higher than with pulseless motion, which confirms the feasibility of applying variable pressure [8].

2. Materials and methods
During well trial runs, the oscillations of borehole fluid were carried out due to the piston action of the plunger of a pumping pump or a swab. It turned out to be quite difficult to find an optimal range of amplitude and frequency characteristics of pressure pulses. An unexpected effect during pulsations was the formation of an emulsion and the separation of light oil products from oil.

In addition, studies were conducted to compare pulsed and pulseless flooding. Preliminary experimental work showed a significant increase in the flow of pumped fluid during pulsations, but only for one phase, which does not take into account the complex interaction between immiscible phases.
Similar studies were also carried out by the technology center of the UK Department of Trade and Industry. In 82% of the experiments, the acceleration of oil movement in the reservoir was recorded due to pulsed injection of fluid. A laboratory test was also carried out with the duration of fluid injection with a pulseless flow for 45 minutes. The oil recovery in the total oil volume in a 200 ml sample was 35%. In a pulsed flow repeated test, the recovery was 90% over 38 minutes. It is evident that the pulsed pressure of the injected fluid significantly improves the oil recovery efficiency. Recent studies showed a significant increase in the passage of viscous fluid through capillaries at a pulsed rate of about 1 Hz. The experiment was conducted with a series of about 270 pulses for 15 minutes. The experiment revealed that the flow rate increased from 3.96 ml/h (at constant speed) to 81.4 ml/h [9].

According to Canadian experts, pressure pulses for viscous oil in wells are relevant in three cases:
- tillage of bitumen-containing sand during the application of CHOPS technology;
- increase of reservoir permeability for oil transfer;
- injection and uniform scattering of chemicals in a reservoir.

3. Results and Discussion

It was found that high pressure low-frequency pulses contribute to a more complete opening of the fracture space and increase the oil recovery factor. Besides, it was revealed that with high values of pressure pulses, well production increases over 5-30 hours for many months and even years. Based on data posted by Canadian experts on the Internet, pressure pulses are created due to the vertical movement of the plunger of the pumping unit. The wave power at an average plunger speed of 6 per minute is of the order of 750 W, which is clearly not sufficient to affect the productive formation.

To study the thixotropic properties of oil in laboratory conditions, the shear rate was gradually increased to 300 1/s for 300 seconds, then it was kept constant at the reached value for 300 seconds to completely destroy the inner structure, and then was smoothly decreased to zero in 300 seconds. For thixotropic fluids at a constant shear rate, the shear stress and effective viscosity decrease over time, which is associated with the gradual destruction of the internal spatial structure. When shear rate decreases, oil with viscoelastic properties exhibits them in elastic shape recovery.

The characteristic rheological curves of forward and reverse motion, the so-called hysteresis loops, were thus obtained (Fig. 1). The fact that the forward motion line does not repeat the reverse motion line confirms oil thixotropic structure. The area of the hysteresis loop enclosed within a single measurement cycle characterizes the mechanical energy of thixotropic bonds assigned to the unit of oil volume. With an increase in temperature from 8°C, the hysteresis loop area decreases, thus indicating a decrease in thixotropic effects. It is possible to conclude that the thixotropic properties of oil may be neglected at temperatures above 40°C [10].
For rheological studies, oil was treated with plasma-pulse technology, which creates periodic shocks in the bottomhole zone due to electric discharge. Figure 2 shows that the hysteresis loop area is significantly reduced after impact-pulse treatment [11].

The experiment shows the possibility of destructing the spatial structure of high-viscosity oil by wave-pulse treatment. After treatment of viscous oil with impact pulses with power, which allows creating the plasma-pulse technology, the shear voltage decreases by 20-30%, and effective viscosity of oil – by 20-25% compared to the value of initial oil. It should be noted that at 20°C temperature the effective viscosity decreases by an average of 1-3%, the shear stress decreases by 3-7%, and at 40°C the shear stress decreases by 15-25% and the effective viscosity decreases by 10-40%, therefore, the intensity of change in the thixotropic properties of oil resulting from pressure pulses depends on temperature.

Moreover, according to the results of laboratory experiments, the capillary pressure of the water-saturated sample after wave-pulse treatment increased by 1.5-2 times, which indicates an increase in filtration resistance with respect to the aqueous phase. The effect is explained by reservoir
hydrophobization, in particular by the change in the nature of wettability, which allows reducing the watering of the extracted product.

The greatest effect can be achieved by combining the thermal and pulse wave treatments, which is possible if the effects change in a short time, during which the viscoelastic structure of oil does not have time to recover from thermal and pulse effects, the temperature and viscosity do not change significantly during this time. The methods of wave-pulse treatment can be divided into methods using submersible devices and with wellhead action. The use of submersible equipment is related to the need for its regular removal from the well in order to enable heat treatment. Frequent round-trip operations complicate the work, long-term stops lead to a decrease in the temperature of the well zone of the formation and, therefore, an increase in the viscosity of reservoir oil.

Currently, there are technologies for the transfer of high pressure differences along the well string from the wellhead. The proposed methods are cost effective, environmentally friendly, do not require a well workover team, use of heavy pumping units, can be used both during well workover and operation. The treatment pressure is regulated up to 25 MPa, the power of treatment on the downhole zone depends on a well depth and is up to 200 kW [12].

For complex thermal and wave-pulse treatment, it is necessary to use special wellhead equipment that allows pumping the coolant in a pulse mode. Pulses of varying value and direction of pressure allow developing the fracturing pattern due to compression, stretching, bending, movement of enclosing rock, which leads to loosening and breakouts of low-permeable fragments of the formation skeleton. A fracture pattern radially diverging from the borehole is created. The movement of fluid mass in the bottomhole zone facilitates its washing, separation of adsorption sediments from the walls of pores and cracks.

A branched crack system is artificially created in the downhole zone of the oil reservoir, which becomes a new system of filtration channels. The permeability of this new system of channels can exceed the natural permeability of the reservoir.

The number of pressure increase repetitions in the bottomhole zone, as well as the amplitude and duration of hydraulic impacts are selected based on the physical parameters of a well (depth, reservoir permeability, oil viscosity, etc.). The downhole fluid may contain chemicals for more efficient treatment.

An additional increase in the impact of hydraulic shock can occur due to abnormal amplification of shock waves in fluid with bubble gas. The fact of the matter is that with shocks in a heterogeneous non-Newtonian system, the pressure of the wave front can many times prevail the initial initiated pressure. The causes of the effect have not yet been fully studied. The most likely cause is the flow of nonlinear oscillation processes in a viscoplastic fluid containing gas bubbles. The effect of increasing the pressure of hydraulic shock waves can reach 5-6 times the value of the initiated hydraulic pulse [13].

Non-Newtonian oils treated with pressure drops exhibit Newtonian properties over a period of time from minutes to several days. The variable pressure created by periodic hydraulic impacts destroys the molecular viscoplastic structure of oil and increases its fluidity.

The creation of high pressure drops in the contact zone of the displacing agent and oil contributes to the following:
- setting in motion the viscous reservoir oil;
- formation and development of cracks of the enclosing rock;
- penetration of a hot agent through cracks deep into the formation;
- destruction of a viscous oil space lattice due to its regular deformation, change of its rheological properties with gradual reduction of viscosity.

The technology includes a series of hydraulic shocks in the contact zone of the displacing agent and oil by periodically connecting the wellhead with a source of fluid under high pressure and using the inertia of the well fluid mass to develop fractures and affect the rheological properties of reservoir oil.

After a series of hydraulic impacts, the coolant is added. A heat carrier is pumped into bed cracks formed during hydraulic impacts, and the hydraulic resistance of the reservoir after pressure treatment decreases due to the destruction of viscoelastic molecular structure of oil.

The increase of bed temperature due to heat carrier injection facilitates the destruction of viscoelastic
structure of oil at the next series of pressure pulses, etc. [14].

Oil is extracted from a treated well during periods between complex treatment of a deposit by heat and hydraulic shock treatment, or oil is extracted through adjacent wells.

It is possible to ensure the simultaneous treatment of a high-viscosity oil deposit with thermal and pulse treatment by pressure, at which a heat carrier is supplied through tubing, and pressure pulses – through the annular space. Wave-pulse simulation additionally accelerates the movement of heat carrier, contributes to intensive heating of the reservoir.

The mathematical description of changing the viscosity from the mechanical impact of hydraulic impacts may be as follows. The pressure at any point along the well depth is determined by the formula

\[
P(t, x) = P_{\text{ex}} \left(t - \frac{x}{c}\right) - t_r \frac{dP_{\text{ex}}}{dt} + t_r^2 \frac{d^2P_{\text{ex}}}{dt^2} - \ldots
\]

where \(P_{\text{ex}}\) – free surface pressure; \(x\) – distance from the wellhead; \(c\) – shock-wave speed.

The change in pressure on the free surface can be presented by the sinusoidal law:

\[
P_{\text{ex}} \left(t, \frac{x}{c}\right) = P_o \sin \omega \left(t - \frac{x}{c}\right),
\]

where \(\omega\) – circular frequency of hydraulic shock recurrence from the wellhead.

\[
P_{\text{ex}} \left(t, \frac{x}{c}\right) = P_o \sin \omega \left(t - \frac{x}{c}\right) - \omega t_r \cos \omega \left(t - \frac{x}{c}\right) - \omega^2 t_r^2 \sin \omega \left(t - \frac{x}{c}\right) + \ldots
\]

where: \(t_r = \frac{\mu}{k}\) – relaxation time; \(\mu\) – fluid viscosity; \(k = 2 \times 10^9 \text{ Pa}\) – volume elasticity modulus.

Fluid velocity at any point along the well depth:

\[
u = \frac{P_0}{k} \left[\cos \omega \left(t - \frac{x}{c}\right) + t_r \omega \sin \omega \left(t - \frac{x}{c}\right) + \ldots\right]
\]

\[
P(t, x) = \int_0^\infty P_{\text{ex}} \left(t - \frac{x}{c} - zt_r\right) e^{-z} \, dz.
\]

where \(z\) – integration variable.

The viscosity of oil being a non-newtonian fluid decreases as hydraulic impacts are carried out, therefore, the relaxation time is reduced.

4. Conclusion

The thixotropic properties of high-viscosity oils are highly dependent on temperature and pressure treatment. As the temperature increases, the efficiency of the wave-pulse method to reduce the thixotropic properties of high-viscosity oil increases.

The application of steam treatment is associated with significant economic costs and environmental pollution. The destruction of high-viscosity oil space lattice promotes the penetration of a heat carrier and a surfactant into reservoir thickness. The wave effect on the productive formation decreases in time, and after 3-7 days the well must be treated again to ensure its operation in an intensive mode. The wave-pulse treatment facilitates the separation of light fractions from high-viscosity oil and hydrophobization of the reservoir.

The method of wave-pulse treatment should have sufficient power and cyclicity of action with the recurrence rate optimal for the destruction of high-viscosity oil space lattice. Heat and pulse wave treatments complement each other and contribute to a complex effect on high-viscosity oil, but they must be carried out simultaneously or alternated with minimal interruptions in order to avoid the
restoration of the space lattice.

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