Wave thermal flooding when designing high-viscosity oil reservoirs

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Abstract. The article describes an environmentally friendly and energy-saving method for increasing the volume of oil recovery - thermal flooding of a high-viscosity oil reservoir integrated with wave actions in injection wells. Heating of a remote formation zone to the effective temperature and wave impacts improve the conditions for effective oil displacement. The integrated use of associated gas and waste water from the oil treatment plant increases the energy efficiency and improves the environmental friendliness of small high-viscosity oil fields. For geological and physical conditions of high-viscosity oil deposits, it is recommended to employ the method of wave thermal flooding.

1. Introduction
The water cut of produced fluid by oil producing wells of "old" fields and a large share of conventional oil reserves production make to pay attention to hard-to-recover reserves (HTRR), associated with high-viscosity oils (HVO), natural bitumen (NB), low-permeability reservoirs, residual reserves, etc. [1-6]. Thus, the role of small deposits, deposits associated with HTRRs, is increasing; to maintain and stabilize the level of oil production, it is necessary to apply new environmentally friendly and energy-saving technologies [1, 2].

Enhanced oil recovery (EOR) methods have been used for more than half a century in a large number of oil-producing countries and regions [1]. In recent decades, modern technologies of enhanced oil recovery and production intensification have been developed [2, 7, 8]. EORs have been used at fields with different geological and physical conditions, and this made it possible to evaluate their effectiveness and predict effective use for various hydrocarbon fields. The effect of the same enhanced oil recovery technologies at one of the fields decreased. With a decrease in the efficiency of an EOR and an increase in the water cut of fluid and reference of residual oil to the HTRR category, the volume of application decreased. At this time, fields with a complicated geological structure containing explosives began to be exploited. Their reserves belong to the HTRR [1, 9]. This caused the need to search for energy-saving and innovative methods for the development of fields with HTRR under different geological conditions [2, 7–12]. A technical and economic assessment of the use of various oil recovery processes is required [13].
The aim of the study is to determine the effectiveness of maintaining the reservoir temperature in combination with wave action on the productive reservoir for small deposits of high-viscosity oil and to develop recommendation for using the method.

2. Materials and methods
This goal was achieved by analyzing the temperature regime of the productive formation, studying viscosity properties of oil, measuring the flow rates of liquid and oil in wells of the experimental section of the Soldatovskoye field.

3. Results and Discussion
A significant number of studies on the applicability of various EOR for the development of HTRR have been carried out [1, 2, 9, 10]; criteria for the applicability of EOR have been found [1, 2, 11]. Using modern techniques, several types of EOR that are applicable to high-viscosity oil deposits confined to the South Tatar arch and Melekess depression have been determined [10, 12]. In world practice, a significant number of technologies are used for the development of HTRR [1, 13]. Among other methods of well stimulation and EOR, a wave action was recommended. It can be used for the Bobrikovskaya high-viscosity oil reservoir at the Soldatskoye field (oil viscosity is more than 200 mPa s).

At the Soldatskoye field, thermal flooding was implemented based on the scheme that can reduce the technogenic load on the environment [11]. Hot waste water (temperature up to 60–65°C) obtained from the oil treatment unit was used for injection into the formation. Energy for technological heating was consumed using associated petroleum gas. This scheme made it possible to avoid emissions into the atmosphere and, accordingly, environmental payments (fines) for such emissions. The laboratory experiments determined the effective temperature for the field. It is +29.7°C. Thus, in order to achieve the best oil displacement effect, hot water injection temperature must be +29.7°C.

Field studies have shown that in the reservoir conditions, there was a decrease in oil viscosity by about 30 mPa·s. This means that the development indicators for the Bobrikovskaya deposit of the Soldatskoye field have been obtained due to the thermal effect on this deposit. The forecast of changes in viscosity made on the basis of laboratory studies shows (the correlation coefficient is close to "1") that oil heated to more than 40–50 ºC has a lower energy efficiency than oil heated to 30–40 ºC. In fact, the temperature was 29.5–30 ºC.

This mode provided an increase in oil production and achievement of the oil recovery factor design (ORF).

Injection well No. 4 (figure) was selected for the wave action (WA), into which hot water is injected to maintain reservoir pressure and temperature. It was expected that the wave action would increase the injectivity of the well due to the inclusion of idle intervals of the productive formation in the filtration process and cleaning the bottomhole zone from clogging material.

![Figure 1. Scheme of the wave thermal flooding section](image-url)

The bottom hole was treated with a hydraulic generator using the cavitation method. The generator has a design that allows you to create radiation in high and low frequency ranges. BHZ treatment is
carried out in each perforation interval, i.e. the generator worked at two points. The operation of the generator was confirmed by recording with a deep self-contained pressure gauge. The processing was carried out for more than 8 hours. Then injection well # 4 was launched with a wave hydraulic generator installed on the tubing shoe above the upper perforation interval.

After the wave impact on the bottomhole formation zone and the start of the wave thermal flooding (WTF) process, the injectivity of the well exceeded the initial one by 25%. In the reacting wells, 2018 tons of oil were additionally produced after the beginning of the wave thermal flooding (table)

Table 1. Results of implementation of the wave thermal flooding method at the site of the Soldatskoye deposit

| No of wells | Additional oil production per year after wave treatment, tons | Average current gain in oil production rate, t / day |
|-------------|-------------------------------------------------------------|-----------------------------------------------|
| 12C         | 453                                                         | 1.3                                           |
| 13          | 459                                                         | 1.3                                           |
| 14          | 821                                                         | 4.1                                           |
| 18          | 218                                                         | 0.7                                           |
| 28          | 67                                                          | 0.2                                           |
| **Total**   | **2018**                                                    | **1.5**                                       |

The average monthly technological efficiency of WTF (in comparison with simple thermal flooding) per one production well was 33.6 tons. The smallest increase in oil production was observed in wells # 18 and # 28, which are the farthest from the stimulating injection well # 4.

Experimental works on the thermal wave water flooding technology confirm theoretical and experimental studies, which identified and described the processes and effects arising from wave and resonance impacts on porous and fractured oil gas reservoirs [12, 14]. The movement of fluids is accelerated. There appear new ones. There are differences between porous blocks-fractals and cracks, due to which the previously immobile fluid is involved. It is obvious that the use of wave technologies has significant potential and can allow one to involve in the cost-effective development of HTRR.

4. Conclusion
The complex system of RPM and PPT allows solving environmental and energy saving issues. The reservoir pressure and temperature maintenance system is able to maintain the initial reservoir temperature and prevent complications due to the cool reservoir containing high-viscosity oil. The use of associated gas as an energy carrier increases the energy efficiency and improves the environmental friendliness of high-viscosity oil fields.

Thermal wave waterflooding, which is a modification of thermal flooding, provides an increase in production and final oil recovery.

For the geological and physical conditions of the HVO deposits, the method of wave thermal flooding can be used. It will increase the energy efficiency of the HTRR recovery and oil recovery.

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