ELSEVIER

Journal of Petroleum Science and Engineering 19 (1998) 191–200

JOURNAL OF PETROLEUM SCIENCE & ENGINEERING

Improved oil recovery by application of vibro-energy to waterflooded sandstones

O.L. Kouznetsov [a], E.M. Simkin [a], G.V. Chilingar [b,*], S.A. Katz [c,1]

[a] *Institute of Geological, Geophysical, and Geochemical Systems, Moscow, Russia*
[b] *University of Southern California, School of Engineering, Los Angeles, CA 90089-1211, USA*
[c] *University of Southern California, Center of Applied Mathematical Sciences, Los Angeles, CA 90089, USA*

Received 1 May 1996; revised 24 May 1997; accepted 24 May 1997

Abstract

The final oil recovery of reservoirs after waterflooding usually does not exceed 50%. Therefore, the problem of additional oil production in water-flooded oilfields, or after depletion, is of major importance. A method of enhanced oil recovery based on the use of powerful surface-based vibro-seismic sources is discussed here, and results of laboratory tests and their application at several oilfields in Russia and in other states formed from the former USSR are presented. In laboratory experiments, natural core samples and synthetic sandpacks were used. The rate of displacement of oil by water in the presence of applied vibro-energy was studied and compared to the displacement rate in the absence of vibrations. Dependence of relative permeability to oil and to water on application of vibro-energy was analyzed. Effect of vibro-energy on residual oil saturation in the porous medium was also studied. It was shown that the rate of oil displacement increases and the percentage of residual oil decreases if vibro-energy is applied to the porous medium containing oil. Another important phenomenon studied in the synthetic porous models is the increase in the rate of degassing due to applied vibration energy. Results of both laboratory and pilot-field testing of the proposed enhanced oil recovery method showed an increase in both oil recovery and the producing oil/water ratio. This proposed vibro-seismic methodology will serve as an additional tool for increasing oil recovery, possibly in conjunction with application of direct electric current, chemical floods, and other processes. © 1998 Elsevier Science B.V.

Keywords: oil recovery; vibro-energy; sandstone

1. Introduction

We will describe results of research aimed at studying a new approach to enhanced oil production which relies on the utilization of surface-based vibro-energy sources. A surface vibrator generates seismic energy that is transmitted down to the oil-producing reservoir for a certain period of time using a special device. The interaction of this seismic energy with the fluids in the pores causes changes in (1) the relative permeabilities of the rock to oil and to water, (2) the degree of oil displacement by water, (3) the rate of oil production and water cut, and (4) the total recovery of oil.

* Corresponding author. Tel.: +1 213 9328369.
[1] Tel.: +1-310-5760419. Fax: +1-310-3956857.

PII S0920-4105(97)00022-3

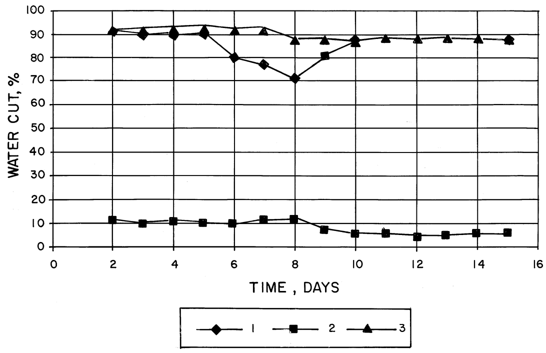

Fig. 1. Decrease in water cut in three wells after an earthquake: *1* = Makhachkalinskoe field, 170 km from the earthquake epicenter; *2* = Shamkal–Bulakskoe field, 130 km from the epicenter; *3* = Novo-Groznenskoe field, 130 km from the epicenter. All fields are located in the northern Caucasus.

Research presented in this paper was initiated partly because of the recorded dependence of the rate of oil production on earthquake occurrences in seismically active areas (Surguchev et al., 1975). It was noticed that several days after the occurrence of an earthquake with the epicenter located in the vicinity of the oil-producing oilfield, the rate of oil production often increased and remained higher than the pre-earthquake level for a considerable period of time. It was also noticed in soil remediation studies (e.g., Sadeghi et al., 1992) that sonic energy applied to soil increases the rate of hydrocarbon removal and decreases the percentage of residual hydrocarbons.

Fig. 1 shows the dependence of water cut in wells located at three different oilfields in Northern Caucasus several days after an earthquake. The earthquake epicenter was located at a distance of 130–170 km from the producing wells. In all three cases, a decrease in water cut and a respective increase in oil production was recorded in about a week after the earthquake. Decrease in the water cut, in one of the wells, was followed by an increase. Nevertheless, on the average, decrease in the water cut was about 4% for all three wells for a considerable period of time. This and other similar facts led to extensive laboratory and field studies of artificial vibro-seismic enhancement of oil production. Theoretical and experimental aspects of this phenomenon and the mechanism of enhanced oil recovery due to the presence of elastic waves generated by surface-based vibrators have been studied during the last ten years by Surguchev et al. (1984), Simkin and Surguchev (1991), Simkin (1992), and Kouznetsov and Simkin (1994).

2. Laboratory experiments of enhanced oil recovery

Laboratory experiments were done using (1) natural sandstone cores, (2) sandpacks prepared from quartz sand, and (3) sandpacks prepared from quartz sand and bentonite. The following aspects of production were studied:

(1) Variation of residual oil saturation with time in natural core samples and sandpacks (a) in the presence of elastic waves generated by a vibrator and (b) when no vibrations were applied to the cores.

(2) Variations in the speed of displacement of oil by water while subjecting, and not subjecting, cores to vibration.

(3) Variations in the relative permeability to oil and to water due to effect of elastic vibrations.

(4) Change in water cut when imposing elastic waves.

(5) Variations in the rate of degassing of fluids in cores and sandpacks due to action of elastic waves.

In all laboratory and field experiments, the frequency of the vibro-sources was in the range of 100–200 Hz, which is close to the range (10–100 Hz) utilized in seismic prospecting. As a result, seismic waves generated by these vibro-sources could travel considerable distances (in the range of 1–2 km) without significant attenuation.

2.1. Oil and water saturations of the porous medium exposed to elastic waves

To study the effect of elastic waves on recovery, core samples from the Elabuzhskiy oilfield and sandpacks prepared from quartz sand were used. Kerosene ($\rho_k = 820$ kg/m^3) and water ($\rho_w = 1000$ kg/m^3) were used as model fluids. The kerosene–water interfacial tension was 25×10 N/m, and the initial water saturation was 5%. Natural core samples were 0.05–0.26 m in length, with a diameter of 0.03 m. The permeability of core samples to nitrogen was 1.0 μm^2. Sandpacks had a length of 0.25 m, diameter of 0.02 m, and permeability of 9.3 μm^2.

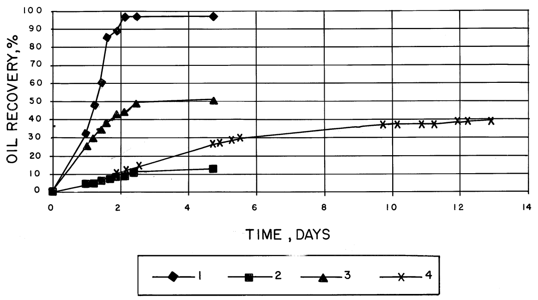

Fig. 2. Rate of oil recovery from natural core samples in the presence and absence of elastic waves (vibration–stimulation). *1* = capillary saturation in the direction of fluid flow, no vibro-energy; *2* = capillary saturation in the direction of fluid flow, vibro-energy applied; *3* = capillary saturation against direction of fluid flow, no vibro-energy; *4* = capillary saturation against direction of fluid flow, vibro-energy applied.

Capillary saturation was measured at natural conditions and on applying vibro-energy at an acceleration of 7.8 m/s^2. After completion of each experiment, the initial conditions in the sandpacks were restored.

Fig. 2 shows the effect of vibro-energy on the oil recovery and the rate of capillary water saturation. Two modes of capillary saturation were tested in combination with the applied vibro-energy and in its absence: (a) direct-flow capillary saturation when the direction of water movement in the process of capillary saturation coincided with direction of the fluid flow caused by the pressure gradient; and (b) inverse-flow capillary saturation when the direction of the water movement in the process of capillary saturation was opposite to the direction of fluid flow caused by the pressure gradient.

As shown in Fig. 2, the rate of oil recovery and the displacement of hydrocarbons by water considerably increase in the case of direct-flow capillary saturation when vibrations are applied to the cores and sandpacks. In the absence of vibrations, oil recovery from sandstone was at a level of about 32% after 300 hours of monitoring oil saturation. In the presence of elastic waves, the oil recovery increased to 60% in 51 hours.

In the case of inverse-flow capillary saturation, vibro-energy caused not only a considerable increase in the rate of oil displacement but also resulted in the recovery of practically all oil from the sandpacks. In the absence of vibrations, 56% of the initial oil was recovered from the sandpacks over 325 hours. In the presence of elastic waves, the oil recovery increased to 96% in 92 hours.

These experiments show that in both cases, direct flow and inverse-flow capillary saturation, utilization of vibration energy not only increases the total oil recovery, but also increases the rate of oil production. In the presence of vibrations, the speed of oil flow was about three times higher than that in its absence.

2.2. Rate of displacement of oil by water and effect of elastic waves on relative permeability to oil

We also studied the gravitational flow of kerosene in the (a) presence and (b) absence of vibro-energy. The experiments were conducted using vertical sandpacks having a length of one meter and a diameter of 35 cm. The sandpacks, which were prepared from quartz sand, had a porosity of 0.33 and permeability of 5.4 μm^2. At first, the model was saturated with water ($\rho_w = 1000$ kg/m^3), which was then displaced by kerosene ($\rho_o = 820$ kg/m^3). After that, oil was displaced by water to produce a natural level of residual oil saturation. After completing displacement of oil by water, the oil saturation stabilized at a level of 50%.

The model was installed vertically and the gravitational redistribution of oil in the two series of experiments was monitored when: (1) vibro-energy was not applied to the model (gravitational displacement of oil by water alone); and (2) elastic waves with an acceleration of 37.4 m/s^2 (combination of gravitational displacement and the effect of elastic waves) were applied.

In the absence of vibro-energy, the water/oil ratio was 0.6 at the top of the model and 1.37 at the bottom of the model after 20 days.

When gravitational redistribution of oil and water phases was combined with applied vibro-energy, a higher degree of oil–water gravitational separation was achieved in a time period about 500 times shorter than that in the case of natural gravitational redistribution alone. This illustrates a radical increase in the relative permeability of the porous medium to oil in the presence of elastic waves.

2.3. Degassing of fluids in porous models due to applied vibro-energy

Degassing of formation fluids under the influence of elastic waves is important because the volume of free gas is increased. Fig. 3 shows the dynamics of degassing of water containing CO_2 on application of elastic waves. Before beginning the vibration, the volume of gas separated from the water grew at a rate of about 0.2% per minute. Immediately after initiation of vibrations, this rate increased to 3–4% per minute. After the relative volume of free gas reached 40%, the rate of degassing stabilized once again at the rate of 0.2% per minute.

Degassing is related to local instantaneous ruptures in the formation fluid due to the effect of elastic waves. Nuclei of bubbles are formed in these ruptures, and gas diffusion from fluid into these bubbles takes place. The bubbles periodically contract and expand due to the periodic variation of pressure caused by elastic waves. During contraction, gas migrates from the bubbles into the surrounding fluid, whereas during expansion, gas migrates from the fluid to the bubbles. Because during the expansion gas migration takes place through a larger surface area of the bubble compared to that during contraction, more gas moves into the bubbles from the fluid than out of the bubbles into the fluid. This causes a systematic increase in the size of the bubbles with a corresponding increase in the degassing rate.

Experimentally, degassing of oil in the field of elastic waves was evidenced by an increase (up to 20–30%) in the gas-saturation pressure. Gas bubbles released from the fluid due to seismic energy may plug some of the pore throats and channels and change the relative permeabilities to water and to oil. Whereas the relative permeability to water always decreases due to the release of free gas into the formation, the relative permeability to oil may either increase or decrease, depending on the water saturation.

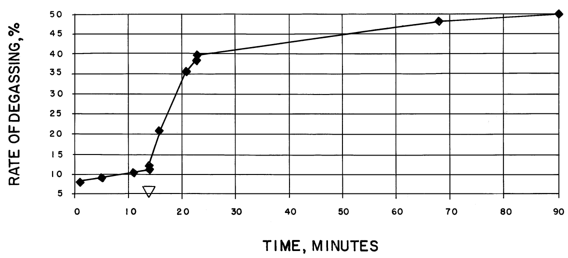

Fig. 3. Degassing of CO_2-saturated water in the presence of elastic waves.

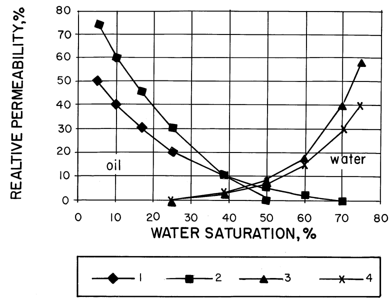

Fig. 4. Relative permeabilities to oil and to water (three-phase fluid flow). *1* = gas saturation = 10% (permeability to oil); *2* = gas saturation = 0% (permeability to oil); *3* = gas saturation = 10% (permeability to water); *4* = gas saturation = 0% (permeability to water).

Fig. 4 shows dependence of relative permeability to oil and to water on water saturation at conditions when gas saturation is equal to (a) zero and (b) 10%. For the same water saturation, the relative permeability to water is always lower when the gas saturation is higher. When water saturation is between 0 and 40%, the relative permeability to oil is lower when the gas saturation is higher. When water saturation exceeds 40%, an increase in gas saturation leads to an increase in the relative permeability to oil. It is important to note that in the case of zero gas saturation, the relative permeability to oil decreases to zero at a water saturation of 50%, whereas for 10% gas saturation, the relative permeability to oil is zero at a water saturation of 70%. This means that at high water saturation, degassing effects due to the application of elastic waves will increase the relative permeability to oil, which will lead to an increase in the oil production rate and a decrease in water cut.

2.4. Displacement of oil by gas-free water in the presence of elastic waves

The effect of elastic waves on the rate of oil displacement by water was studied using transparent sandpack cylinders measuring 0.35 × 0.95 × 0.01 m.

The models were filled with quartz sand resulting in a porosity of 45% and permeability of 18–20 μm^2. Initially, the models were saturated with gas-free formation water, which was then displaced by oil. Experiments were conducted in two steps. First, vibration energy was not applied to the model. Oil displacement continued until the oil output stopped. After that, the same model was subjected to the vibration energy which resulted in the additional displacement of oil by water (additional recovery). An additional 10% of oil was recovered from the model, which is equal to about 20% of the residual oil remaining in the formation after waterflooding.

2.5. Displacement of oil by CO_2-saturated water in the presence of elastic waves

Experiments were also conducted to analyze the effect of vibro-energy on the rate of oil recovery when oil is displaced by CO_2-saturated water. As a first step in these experiments, oil was displaced by CO_2-saturated water, and the displacement process continued until oil content in the produced fluid decreased to zero. After that, the process of oil displacement resumed with vibro-energy applied to the model. Elastic waves caused extensive release of carbon dioxide, leading to the complete degassing of water. Fig. 5 shows dependence of oil recovery from the quartz sandpack on the cumulative fluid produced. Percentage of the recovered oil is presented as a function of the total cumulative volume of fluid for two cases: (a) when oil is displaced by gas-free water; and (b) when oil is displaced by CO_2-saturated water. In both cases, the displacement process was started in the absence of vibro-energy and then continued with vibro-energy applied to the sand pack. In the case of CO_2-saturated water, magnitude of the oil recovery was systematically higher than that in the case of gas-free water. Subjecting the sandpack to elastic waves resulted in a further increase in oil recovery in the cases of gas-free and CO_2-saturated water.

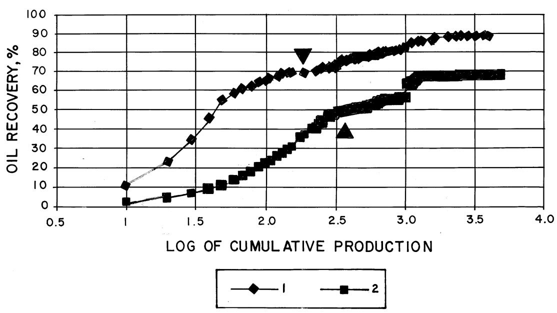

Fig. 5. Cumulative fluid production (cm^3) as a function of oil recovery (%) before and after initiation of vibro-stimulation for (*1*) CO_2-saturated and (*2*) degassed water.

2.6. Modeling of oil displacement by water in clayey sandstones

Analysis of the effect of elastic waves on displacement of oil by water in clayey sandstones was done using sandpacks of 40 cm long and 2.8 cm in diameter. The sandpacks were prepared with quartz sand having grain sizes of 0.05–0.2 mm and a bentonite admixture. The permeability of the sandpack was 0.2–0.4 μm^2, whereas porosity was 25%. Distilled water with dissolved NaCl (30–200 g/l) was used for displacement of oil, which was imitated by a mixture of kerosene with transformer oil having viscosity of 5.0 MPa s.

Prior to the experiments, residual water saturation was attained in the sandpacks. Saline water (200 g/l) was displaced by the oil until water was no longer produced from the sandpack.

The experiments showed that increasing the salinity of water to 150 g/l led to lower swelling of clay than that at a salinity of 50–100 g/l. Lower swelling results in an increase of the permeability to oil and to water. Thus, subjecting clayey sandstone to elastic waves leads to more effective oil displacement in the case of 150 g/l water salinity. Experiments showed that the oil recovery at this salinity level reached 86.8%.

Dependence of the rate of oil recovery on the salinity of water (50, 100, 150 and 200 g/l) that displaces the oil was also studied. The intensity and frequency of the elastic waves were the same for all salinity values. Experimental results showed that the influence of elastic waves on the oil production changed with changing salinity of the injection water, with maximum oil recovery attained at a water salinity of 150 g/l. Effect of elastic waves on the oil recovery is illustrated in Fig. 6, which shows dependence of oil recovery on the water salinity in the presence and absence of elastic waves. One can

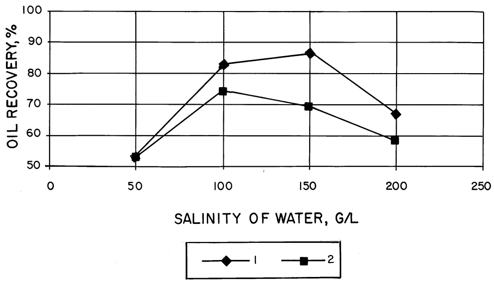

Fig. 6. Dependence of the oil recovery on water salinity (*1*) in the presence of elastic waves, and (*2*) in the absence of elastic waves.

observe that the application of elastic waves increases the oil recovery at all salinity levels.

3. Producing well experiments

Field experiments were conducted using vibrators located at the Earth's surface in the vicinity of oil-producing wells. Vibro-energy generated by vibrators traveled down as elastic waves to the oil-bearing formation. The goal of the experiments was to study the effect of elastic waves on the relative permeability to oil and to water, water saturation, oil production rate, and the rate of oil displacement by water. Generally, it was found that the presence of elastic waves increased the relative permeability to oil, decreased the relative permeability to water, decreased the water cut, and enhanced the oil production.

In terms of industry application, the use of vibro-energy for enhancement of oil recovery is acceptable only if the amount of generated vibro-energy is smaller than the amount of energy contained in the additionally recovered oil.

The writers studied the energy balance between the generated vibro-energy and energy contained in the additional oil produced by using vibrators. Calculations show that the amount of vibro-energy applied to one unit of rock volume does not exceed 1.5% of the energy contained in the oil present in this unit volume (calculations were based on the fact that the energy content of 1 kg of oil is 4.2×10^7 J). Therefore, for this process to be economically feasible, it is necessary to increase the oil production by a minimum of 1.5% (Vahitov and Simkin, 1985). To study feasibility of enhanced oil recovery based on the use of vibro-energy, field experiments were conducted in several old oilfields in Russia, Uzbekistan, and Kirgizstan. The following is a review of major results obtained in these experiments.

3.1. Abuzy oilfield

1. The first field experiments with vibrators located at the surface were started in 1987 at the Abuzy oilfield in the Krasnodarskiy Region of Russia. Two 50 kW vibrators were placed 50 m apart. Water saturation of the reservoir rock was 97%, whereas the depth of the oil-bearing formation was 1500 m. These experiments were the first ones to demonstrate the improvement in oil production due to use of vibro-energy. On the average, the water cut decreased by 20–26%, whereas for some boreholes the drop in water cut reached 50% and more. Degassing of formation oil was observed in the following ways: (1) volume of the hydrocarbon gases in the air samples at a depth of 45–100 m increased as much as 10–110 times; (2) volume of the hydrocarbons in gas samples at a depth of 1150–2500 m in the oil-bearing formations increased 28–40 times; and (3) the values of the light absorption coefficients for the oil samples decreased from the producing wells in productive intervals (depth interval of 1150–2500 m).

3.2. Changirtash oilfield

Another cycle of experiments was conducted at the Changirtash oilfield, Kirgizstan, in 1986. The Changirtash oilfield is one of the oldest fields in Kirgizstan, where oil production started in 1938. Its length from north to south is 4.5 km, whereas its width is 3.1 km. The oil-bearing formation is represented by light-gray, fine-grained sandstones with thin layers of clay. Average depth is 410–570 m, porosity is 10.5–23%, permeability is 0.1–30 μm^2, and the initial oil saturation was 60%. Total thickness of the oil-bearing formation is 25 m, whereas the pay zone thickness is 5.7–6.4 m. Initial production rates of the boreholes were 2–3 tons/day, whereas at the time of these experiments they were 0.5–1 tons/day. There were 89 wells across the oilfield, and waterflooding was done through 25 boreholes. Total oil production from the oilfield was 1,150,000 tons of oil, when water saturation reached 90%, and the oil recovery was 31%.

Experiments with vibrators were conducted in two areas:

(1) The size of the first study area was 600 × 600 m. The oil-bearing formation is represented by homogeneous fine-grained sandstone with permeability of 0.2 μm^2. The depth of the oil-bearing formation is 240–448 m and its thickness is 4–10 m with a dip of 35°. The oil-bearing formation was penetrated by 6 boreholes with oil production rates ranging from 0.08 to 0.9 tons/day. Total yearly production in this area was 800 tons, with a water cut of 69%.

Two surface vibrators were installed at the center of the area, 20 m apart. Power of the vibrators was 50 kW each, and elastic waves were continuously generated during a one-month period (October, 1988). During this time and later, samples of oil and gas were taken and oil production rates were recorded. Considerable increase in the content of light components was reported in the gas samples (for example, percentage of ethane increased from 45.3 to 53.3%). In the oil samples, the initial boiling point decreased and the amount of residuals increased due to the effect of elastic waves. This indicates enrichment of oil in light fractions. This phenomenon is similar to the one recorded at Abuzy oilfield. The water cut decreased by 25–30%, and the additional oil produced was greater than 300 tons. It is also important to note that this effect continued after vibrations were discontinued.

(2) In the second field experiment, the area was larger (1500 × 1500 m), the depth of the oil-bearing formation was greater (511–708 m), and the permeability (0.15 μm^2) of the producing formation was lower. The formation was penetrated by 16 boreholes having a total oil production of 2540 tons. Water cut for the recovered oil was 89%. For the efficient transfer of vibration energy from the surface-located vibrators to the oil-bearing formation, a special wave-direction technique was used. Loss of energy using this technique ranged from 5 to 10% for 1 km of depth.

Fig. 7 shows the relationship between the cumulative oil production and cumulative water production for two conditions: (a) absence of vibrations and (b) presence of vibrations. The start of vibrations is marked by ∇. Data are presented for both pilot tests and show the relationship between cumulative oil production and cumulative water production. For both pilot tests, the decrease in water cut due to effect of elastic waves was in the range of 20–25%. Total increase in the oil production for the first pilot test for the period of 4 months from the beginning of vibration was greater than 300 tons, whereas for the second pilot test, the additional production exceeded 1000 tons.

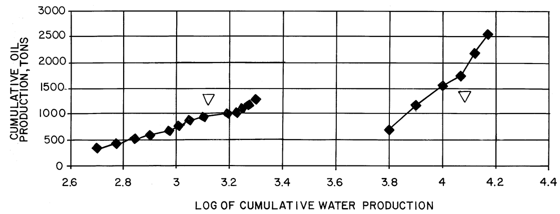

Fig. 7. Cumulative oil production as a function of cumulative water production before and after stimulation by vibro-energy at Changirtash oilfield at two pilot sites.

3.3. Jirnovskiy oilfield, first stage

First stage experiments at Jirnovskiy oilfield (Volgogradskiy region, Russia) were conducted between 1991 and 1993. According to the previously conducted hydrodynamic investigations, productive layer in the pilot experimental area, in spite of high water saturation in the oil-producing boreholes, contained an oil lens with total oil reserves of about 250,000 tons. During experiments, the vibrator was placed at a borehole located approximately at the center of the area. The vibration energy was transmitted from the surface to the oil-bearing layer (depth of about 1000 m) via a specially designed wave-transmitting system which was lowered into the borehole. The monitoring radius of vibrations was 2.2 km. During the period of vibration, 35 wells located in the vicinity of the vibrator were monitored, and variations in the oil recovery were recorded for each borehole. Among these, 26 boreholes showed improved oil recovery. The remaining nine boreholes did not react.

During the first stage of experiments on the effect of vibro-energy on oil production, measurements of the intensity of transmitted seismic energy to the producing horizon were conducted. Recording of the seismic vibrations was done in a well located 850 m from the well through which the seismic energy was transmitted to the formation. The magnitude of seismic waves during vibration at the level of oil-producing formation was about 200 times greater than the background noise. In the neighboring formations, the magnitude of seismic waves was about 1.5 to 2 times lower than that in the oil-producing formation. This illustrates the efficiency of transmitting the seismic energy from the surface down to the geologic section and of focusing the energy on the oil-producing formation. After vibrations were stopped, the level of seismic energy in the oil-bearing formation slowly decreased.

3.4. *Jirnovskiy oilfield, second stage*

The second-stage experiments at the Jirnovskiy oilfield were conducted during the period of May 18–July 13, 1992. The length of the period of generation of vibro-energy was the same as that used during the first-stage experiments at this field.

Analysis of results during the first and second stages of experiments showed that oil production increased in about 40 wells on application of vibro-energy. In some boreholes, the decrease of water cut was 2- to 4-fold, whereas oil production increased 2- to 5-fold. Fig. 8 shows two examples (wells 231 and 1056) of decrease of water cut due to effect of elastic waves. Before initiation of vibration, the recovered oil/water ratio was very low. Soon after starting the vibration this ratio considerably increased.

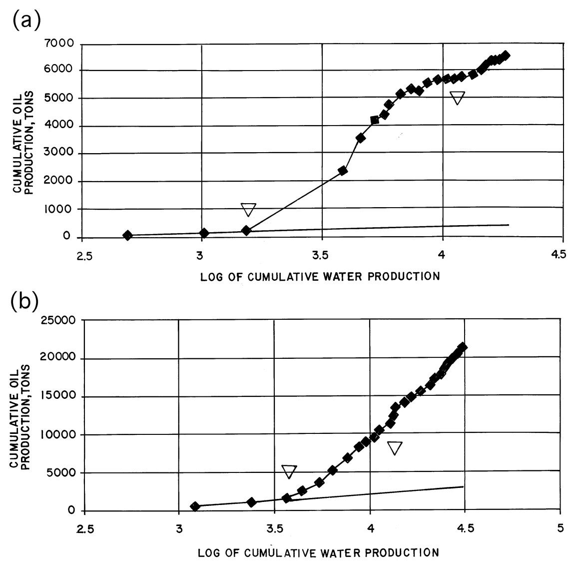

Fig. 8. Cumulative oil production as a function of cumulative water production before and after start of vibro-stimulation for boreholes No. 231 (a) and No. 1056 (b).

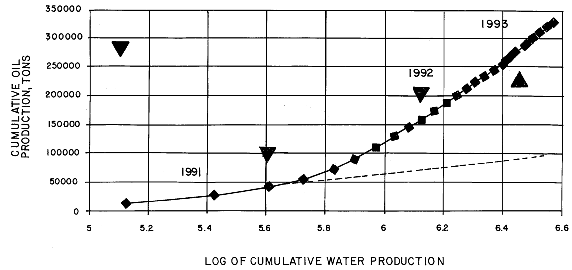

Fig. 9. Cumulative oil production as a function of cumulative water production before and after initiation of vibro-stimulation at Jirnovskiy oilfield (first pilot test). ∇ is the start of the vibro-stimulation.

Average data for 40 boreholes are given in Fig. 9, which shows that during two years after starting vibration, the recovered oil/water ratio remained much higher than that prior to the vibro-stimulation. Total increase in oil production was about 250,000 tons. Fig. 10 shows the average change in the water cut for the Jirnovskiy field (during approximately one year). One can see that as a result of application of vibro-energy, average water/oil ratio decreased from 9.7 to 8.3, although later, possibly due to exhaustion of the oil-producing lens, water/oil ratio increased.

It is important to note that the increase in oil production owing to effect of vibration energy is due

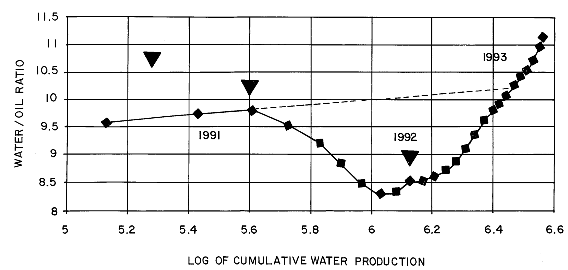

Fig. 10. Water/oil ratio as a function of cumulative water production before and after start of vibro-stimulation at Jirnovskiy oilfield (first pilot test). ∇ is the start of the vibro-stimulation.

to change in the relative permeabilities (and decrease in the water cut) and due to reduction in the contact angle, interfacial tension between oil and water and greater dispersion of oil in water. For theoretical discussion see Langnes et al. (1972, pp. 225–230).

4. Mechanisms of interaction of fluid flow with vibro-energy in porous media

Laboratory and field experiments discussed in the previous sections demonstrate the dependence of fluid flow and character of oil displacement by water on application of vibro-energy. Results of experiments demonstrate that k_{ro}/k_{rw} and the rate of water displacement by water increase on application of vibro-energy. The effect of vibro-energy on fluid flow in porous media is defined by a number of nonlinear factors.

(1) Application of vibro-energy causes periodic or quasi-periodic movements of oil and water phases in pore channels with periodically changing directions. Due to these periodic movements, molecules of oil and water stick to a lesser degree to the solid phase. Accelerations of the oil phase and water phase are related to each other as (Kouznetsov and Simkin, 1994):

$$\frac{\rho_o}{\rho_w}\frac{\partial^2 x_o}{\partial t^2} = \frac{\partial^2 x_w}{\partial t^2}, \qquad (1)$$

where ρ_o and ρ_w are densities of oil and water, respectively, x_o and x_w are distances traveled by the oil droplet and water droplet, respectively, and t is time.

Eq. (1) shows that the acceleration of the oil phase, which has a lower density than water, will be larger than the acceleration of the water phase. The lower the density of oil, the higher will be the ratio of acceleration of oil to that of water due to applied vibro-energy. Thus, the time of possible static contact of oil molecules with a solid phase will decrease with decreasing density of oil. In turn, this will lead to a decrease of adhesion of oil molecules to the walls of the pore channels and better mobility of the oil phase. Mobility of the water will also increase, but to a lesser degree than that of the oil.

(2) Periodic movements of the oil and water in pore throats and variable pressure gradient caused by the applied vibro-energy lead to the destruction of water films blocking fluid flow through narrow pore throats. This leads to a general increase of the relative permeability both to oil and to water. The molecules of oil are much larger than those of water. Therefore, destruction of water films sealing pore throats and increasing the size of the open part of pore throats should produce a larger effect on the relative permeability of rock to oil than that to water.

(3) The relative permeability to oil also increases due to reduction in the interfacial tension and contact angle between oil and water on application of vibro-energy. As a result, the size of oil globules decreases.

5. Conclusions

The results of vibro-stimulation tests for enhanced oil recovery, using powerful surface-based vibroseismic sources, indicate that the rate of displacement of oil by water increases and percentage of nonrecoverable residual oil decreases if vibro-energy is applied to the porous medium containing oil. Tests on sandpacks showed an increase of degassing rate due to application of vibro-energy.

Results of both laboratory and field tests of the proposed enhanced oil recovery method showed an increase in recovery of oil and oil/water ratio. Decrease in water cut is caused by the reduction in oil/water interfacial tension and increase in the relative permeability to oil (and to water).

This proposed vibro-seismic methodology will serve as an additional enhanced oil production recovery technique. Vibro-energy reduces interfacial tension, increases the relative permeability to oil, and increases the produced oil/water ratio. Possibly, this technique can be used in conjunction with other methods, such as thermal recovery, application of direct electric current, and chemical floods.

References

Kouznetsov, O.L., Simkin, E.M., 1994. Transformation and Interaction of Geophysical Fields in the Lithosphere. Oxford and IBH Publ., 271 pp.

Langnes G.L., Robertson, J.O., Chilingar, G.V., 1972. Secondary Recovery and Carbonate Reservoirs. Elsevier, New York, NY, 304 pp.

Sadeghi, K.M. et al., 1992. A new bitumen recovery technology and its potential application to remediation of oil spills. J. Pet. Sci. Eng. 8, 105–118.

Simkin, E.M., 1992. Hydrodynamic description of oil displacement by water process within the elastic vibration field. In: Proc. Int. Conf. Flow through Porous Media: Fundamentals and Reservoir Engineering Applications, pp. 171–175.

Simkin, E.M., Surguchev, M.L., 1991. Advanced vibroseismic technique for waterflooded reservoir stimulation, mechanism and test results. Sixth European Symp. on Improved Oil Recovery, Norway.

Surguchev, M.L., Kouznetsov, O.L., Simkin, E.M., 1975. Hydrodynamic, Acoustic, and Thermal Cyclical Processing of Oil Layers. Nedra Publ., Moscow, 320 pp.

Surguchev, M.L., Zheltov, U.V., Simkin, E.M., 1984. Physicochemical Micro-processes in Oil-Gas-Bearing Formations. Nedra Publ., Moscow, 215 pp.

Vahitov, G.G., Simkin, E.M., 1985. Utilization of Physical Fields for Enhancement of Oil Recovery. Nedra Publ., Moscow, 231 pp.