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Acoustic and sonochemical methods for altering the viscosity of oil during recovery and pipeline transportation

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ABSTRACT

Reduction of oil viscosity is of great importance for the petroleum industry since it contributes a lot to the facilitation of pipeline transportation of oil. This study analyzes the capability of acoustic waves to decrease the viscosity of oil during its commercial production. Three types of equipment were tested: an ultrasonic emitter that is located directly in the well and affects oil during its production and two types of acoustic machines to be located at the wellhead and perform acoustic treatment after oil extraction: a setup for ultrasonic hydrodynamic treatment and a flow-through ultrasonic reactor. In our case, the two acoustic machines were rebuilt and tested in the laboratory. The viscosity of oil was measured before and after both types of acoustic treatment; and 2, 24 and 48 h after ultrasonic treatment and 1 and 4 h after hydrodynamic treatment in order to estimate the constancy of viscosity reduction. The viscosity reduction achieved by acoustic waves was compared to the viscosity reduction achieved by acoustic waves jointly with solvents. It was shown, that regardless of the form of powerful acoustic impact, a long lasting decrease in viscosity can be obtained only if sonochemical treatment is used. Using sonochemical treatment based on ultrasonic hydrodynamic treatment a viscosity reduction by 72,46% was achieved. However, the reduction in viscosity by 16%, which was demonstrated using the ultrasonic downhole tool in the well without addition of chemicals, is high enough to facilitate the production of viscous hydrocarbons.

1. Introduction

The reserves of heavy and viscous oil and natural bitumen are several times greater than the reserves of medium and light oil; therefore, all over the world, much attention is paid to their commercial development. New technologies that facilitate their production and transportation are developed and applied.

The main methods of developing high-viscosity oil fields are as follows [1]:

- thermal: steam soaking (cycling, water drive, hot water drive, fire flooding, electromagnetic heating);
- gaseous: miscible and immiscible displacement (using hydrocarbon gases, CO2, nitrogen, flue gases);
- chemical: surfactants, polymers, diluents, microbiological products;
- physical: treatment by physical fields.

For the transportation of such high-viscosity fluids, different methods for increasing fluidity are used: heating, mixing of high-viscosity oil with low-viscosity oil and their joint pumping, mixing and pumping with water and addition of various reagents, for example, depressants [2]. These methods are rather expensive, since they require either considerable energy or the use of a considerable amount of various substances and the subsequent additional treatment of oil.

The effects of cavitation induced by ultrasound in liquid media and its influence on chemistry and processing have been studied for many years under the umbrella title of sonochemistry [3]. Ultrasonic treatment is one of the most promising alternative

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methods for affecting a fluid both under well conditions and on surface. It is known, that under well conditions ultrasonic treatment can lead to such effects as increase of fluid penetration into capillaries due to the sonocapillary effect, increase of fluid mobility, detachment of paraffinic and other deposits from the rock [4–6]. Under well and surface conditions, ultrasound can lead to de-emulsification [7–9] and to viscosity reduction [10–12].

Various effects can cause the viscosity reduction of oil under the influence of ultrasound. First, ultrasonic oscillations of the media lead to a temperature increase due to energy dissipation. Apart of that ultrasonic waves increase the surrounding pressure, which in turn also leads to a temperature increase. These two effects were described in [10]. The authors of [10] suggested a model, which enables to evaluate these effects numerically. In the article, the modelling results were compared with results of experiments, in which the oil recovery from a saturated core sample was measured. In these experiments, the oil recovery was measured and calculated each 10 min after start of ultrasonic treatment of the core sample. The experiments lasted 60 min. During the first 30 min of the experiments authors report a mismatch between the experimental and calculated results, which they explain by the instability of the output power of the ultrasonic generator. After the 30 min, the calculated and measured results show relatively good agreement. While the model and the experimental results are a good evidence for the change of viscosity of oil due to pressure and temperature changes, there are also another aspects, which contribute to the increase of oil recovery in the presence of an acoustic field, which should be taken into account. These are the increase of fluid mobility, the decrease of interfacial tension and the redistribution of pressure and temperature.

The experiments, described in [10], were performed on oil with 50 API gravity. However, it is known from the literature, that at a temperature of 20 °C, the viscosity and density of residual fuel oil under wave treatment at a constant temperature decreases to values that correspond to thermal treatment at temperatures above 40 °C [13]. This was not studied in [10] and did not affect the agreement between the model and the experiment, since the viscosity change not caused by temperature changes, is not so meaningful for not viscous oil. However, due to its nature viscosity change of oil not caused by temperature changes is much more meaningful for heavy and high-viscous oil [14]. The nature of this effect is explained below.

The main difference between oil and many other viscous liquids is that its molecules form conglomerates, which account for the higher viscosity of oil. In these conglomerates, intermolecular forces bond the molecules to each other. The goal of ultrasound is to destroy these bonds and to bring the properties of oil closer to what they would have been if no conglomerates were present [14].

The description of this process is in many aspects similar to the description of material destruction, where the kinetics of link opening depends on the temperature of the material T, the energy of bond breaking E_0 without external influence etc. The main formula of the theory of material destruction, which describes the destruction time of one bond τ_p, can be generalized for the case of intermolecular interaction [14]:

$$\tau_p = \tau_0 \exp\left\{\frac{E_0 - \gamma(\sigma_c + \sigma_u)}{kT}\right\} \tag{1}$$

In the above Eq. (1) τ_0 is a constant value, which depends on the material properties, σ_c is the static stress, σu is the stress produced by ultrasonic treatment, γ characterizes the degree of transmission of the average stress to one bond and is structure dependent and k is the Boltzmann constant.

σ_u is determined taking into account the periodic nature of this stress $\sigma(t)$ (Eq. (2)):

$$\sigma_u = \frac{1}{\tau}\int_0^{\tau_p} dt\sqrt{\sigma^2(t)} \equiv \int_0^{\tau_p} dt|\sigma(t)| \tag{2}$$

Based on assumptions described in [14], it was possible to calculate the treatment time needed to destroy the intermolecular connections using an acoustical wave. The parameters of the wave, used in the calculation, were as follows: the frequency was 20 kHz and the amplitude was 2 μm. According to the estimation, the time, needed to destroy the intermolecular connections, was 30 s.

The presented data indicate the expediency of using acoustic methods to decrease the viscosity of oil and facilitate its production and pipeline transportation. In comparison with simple heating, the acoustic treatment of a fluid requires considerably less energy [14]. The effect of ultrasonic irradiation on oil viscosity has been verified by a large number of experimental studies [11,12]. However, for the practical use of this method, it is necessary to study the effect of ultrasonic vibrations on oil flows, not on static oil, and to investigate the changes of rheological properties of the fluid in a well after ultrasonic treatment of the near-wellbore area.

The alternative to constant ultrasonic irradiation is ultrasonic hydrodynamic treatment (UHT). It is an intensive treatment of a media stream caused by an instantaneous pressure drop (the approximate time of pressure change should be 1–100 μs) [15]. Instantaneous gas release occurs in the zone of the sharp pressure drop during the movement of the medium. Under certain conditions, generation of high-intensity pressure pulsations occurs due to hydrodynamic effects. Pressure pulsations generated in the narrow zone of the flow induce a flow breakdown. In addition, there is a pressure jump caused by the transition of the medium motion mode from supersonic to subsonic flow. The collapse of gas-vapor bubbles takes place in the effective area of the pressure jump, which is accompanied by a powerful mechanical effect on the liquid.

In order to achieve the necessary effect of hydrodynamic oil treatment, a setup that ensures a working fluid delivery pressure in the range of 8.0–16.0 MPa [15] should be used. During medium flow, a vacuum equal to the saturation pressure of the lowest-boiling fraction at a given temperature should be created in the working zone of the setup. Such flow begins to boil and forms a homogeneous two-phase medium with gas-vapor bubbles, the diameters of which are between 0.1 and 4 μm [16]. The obtained two-phase medium should be supplied to a mixing chamber. Due to an increase in the cross-sectional area of the channel, the flow of the two-phase medium comes off the channel walls at the beginning of the channel and a free flow with a free outer boundary occurs. A complex intensive vortex motion of a vapor-gas-liquid mixture is established in such a way between the channel walls and the jet boundary. In the vortex zone, high-frequency longitudinal flow pulsations in a wide pressure range of up to tens of thousands of atmospheres can be generated [17]. This leads to the destruction of high-molecular compounds.

The consequence of such treatment is the destruction of micellar compounds and the partial cracking of high-molecular compounds, which makes it possible to increase the yield of light fractions during oil distillation. To consolidate and enhance the oil viscosity reduction, supply of various reagents to the mixing chamber is possible. Experimental studies and comparative analysis of viscosity variation with and without reagent addition are necessary to determine the expediency of reagent introduction after UHT.

Ultrasonic hydrodynamic treatment of oil is less energy consuming than constant treatment of an oil stream with ultrasonic waves, in which an electroacoustic transducer generates the oscillations. Thus, it is the preferable technology for decreasing oil viscosity in case of sufficient efficiency of the technology. However, the technical implementation of this method under well conditions during production is considerably more complex. Therefore, we propose to use an integrated approach in production and transportation of high-viscosity oil. In oil production, submersible ultrasonic emitters can be used for ultrasonic treatment of the near-wellbore area. Such emitters would contribute to the reduction of oil viscosity directly in a well (this would make it possible to decrease the load on the pump during lifting of the fluid from the well). Prior to and during oil transportation, we propose to use ultrasonic hydrodynamic treatment of oil. Ultrasonic treatment of oil during transportation in a flow-type ultrasonic reactor with addition of chemical agents is also possible; however, it is necessary to perform a comparative analysis of the efficiency of this technology and UHT, on the basis of which the expediency of using this method can be determined.

To study the potential of this approach, we have carried out three series of experiments:

- Studies of the effect of ultrasonic hydrodynamic treatment and chemical agents on the rheological characteristics of oil.
- Studies of the effect of ultrasonic treatment in a setup with a flow-type waveguide system and chemical agents on the rheological characteristics of oil (to compare the efficiency of the two technologies on the surface).
- Studies of the effect of ultrasonic treatment on the rheological properties of oil under well conditions.

2. Materials and methods

To study the effect of UHT on crude oil and petroleum products, an experimental setup was assembled. The setup made it possible to vary the pressure at the inlet of the reactor. The maximum inlet pressure was 50 MPa, the maximum capacity of the setup was 1200 L/h.

Fig. 1(a) shows the scheme of the experimental setup for UHT. The setup consisted of a pump, a working section (reactor), a tank for the untreated oil, a receiving tank, an electric heater, an emergency discharge tank, control and stop valves, and instrumentation (pressure gages, a compound pressure and vacuum gage and temperature meters, namely, chromel-alumel thermocouples). The working section contained a hydrodynamic emitter, a scheme of which is shown in Fig. 1(b). The operation of the emitter is based on the generation of oscillations in a liquid media, when the jet from the nozzle interacts with a barrier of a certain shape and size. The perturbations caused by the obstacle affect the jet base, causing autooscillations. In the experimental setup we used an annular slotted nozzle, which was formed by two conical surfaces. The barrier had the shape of a hollow cylinder, dissected along the elements. Thus, the barrier consisted of cantilever plates, arranged circumferentially. The frequencies of the oscillations, caused by that emitter, were in the range of 15–35 kHz. The fundamental frequency was 22 kHz. The electric heater in the setup was used to maintain constant temperature of the treated oil. During the experiments, the heater was not used, since the necessary temperature of 20 °C was maintained in the laboratory.

The oil from the feed tank was supplied to the working section (reactor) using the pump. The pressure of the medium before the reactor was between 8.0 and 50.0 MPa and was set by the valve B1, the pressure in the reactor was between 0.05 and 0.09 MPa, and the pressure after the reactor was between 3.5 and 8.0 MPa. The pressure after the reactor was set by the valve B4. A check valve was used to protect the compound pressure and vacuum gage. Table 1 shows the technical characteristics of the setup for UHT.

To study and compare the effect of ultrasonication and chemical agents on the rheological characteristics of an oil flow with the effect of UHT, a unit with a flow-type waveguide system was used. A photograph and a schematic of the setup with the flow-type waveguide system are shown in Fig 2(a) and (b) respectively. The unit is a cylindrical steel reactor, the outer side of which is connected to two electroacoustic transducers that generate vibrations of the reactor. The oscillations were transmitted to the flow of the liquid in the reactor. The diameter d of the waveguide system was 145 mm. The power of ultrasonic irradiation was 6 kW, and the frequency of ultrasonic vibrations was 20 kHz.

The dynamic viscosity of oil samples after ultrasonic and hydrodynamic treatment was determined using an INPN SX 850 rotational viscosimeter (a measuring instrument for the low-temperature characteristics of petroleum products). The torsional moment in the viscosimeter was measured at a constant shear rate of 250 rad/s. The accuracy of determining the dynamic viscosity of samples was 2%, the temperature measurement accuracy was ±0.5 °C. The requirements of the international standard ASTM D4684 and GOST 1747–91 were taken into account during the

Table 1
Technical characteristics of the experimental setup for UHT.

No.	Characteristics	Unit of measure	Value
1.	Pump	kW	7.5
2.	Operating pressure	atm	8.0 ÷ 50.0
3.	Operating temperature	°C	0 ÷ 80
4.	Setup capacity	m^3/h	1.0 ÷ 1.2
5.	Installation area	m^2	1.5
6.	Weight	kg	250

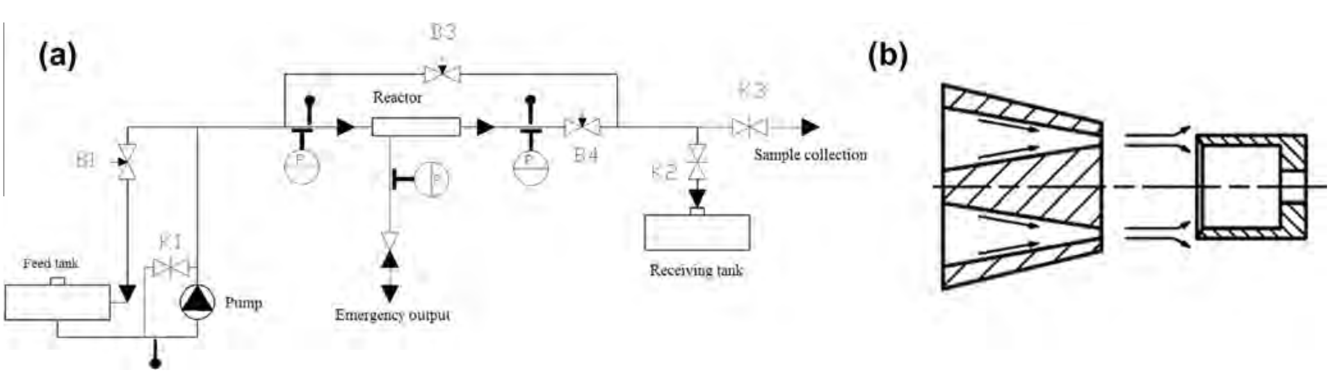

Fig. 1. a) Schematic of the experimental setup for ultrasonic hydrodynamic oil treatment; b) Schematic of the hydrodynamic emitter in the setup for UHT.

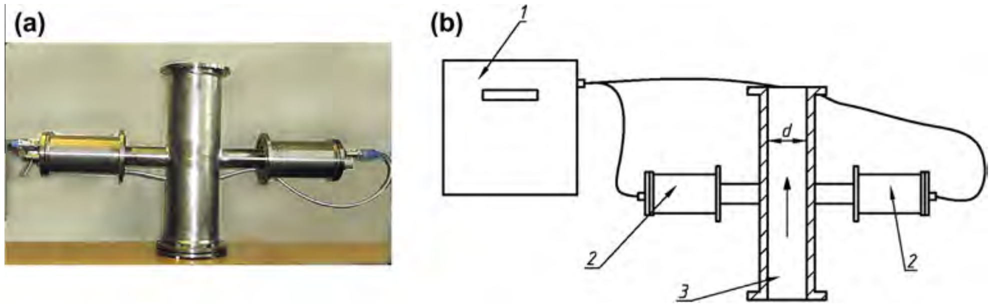

Fig. 2. a) Photograph of the setup with the flow-type waveguide system; b) Schematic of the setup with the flow-type waveguide system: 1 – ultrasonic generator; 2 – electroacoustic transducers; 3 – flow-type waveguide system.

measurement procedure. The arithmetic average of the results of two parallel determinations was taken as the outcome of measurement.

Experiments on ultrasonic treatment of oil under well conditions were carried out in the producing well No. 4620 at the Demkinskoe oil field. The well had the following characteristics: 168 mm production casing, C1bb formation, perforated interval depth 1309.3–1312 m, fluid production before treatment was 1.82 m^3/day, oil production before treatment was 1.51 tons/day, bottomhole pressure (on average during the last month before treatment) was 25.6 atm, temperature was 23 °C, water cut was 10.3%, formation pressure was 49 atm, and the production coefficient was 0.071.

To study the effect of ultrasound on the rheological properties of oil under well conditions, an ultrasonic tool was placed into the perforation zone of the well. The tool was attached to the tubing and was powered through a cable, attached to the outer surface of the tubing using cable bands. An ultrasonic generator was installed near the wellhead on the surface to power the downhole tool through the cable. The output power of the ultrasonic generator was 9 kW. The power of the ultrasonic downhole tool was 5 kW. The scheme of the equipment arrangement in and near the well is shown in Fig. 3.

The outer diameter of the downhole tool was 102 mm, and its length was 700 mm. The downhole tool contained three annular magnetostrictive transducers that generated an ultrasonic field at a frequency of 19 kHz.

The vibration amplitude distribution at a distance of 500 mm from the lateral radiating surface of the downhole tool is shown in Fig. 4. The distribution was measured in a cylindrical tank with

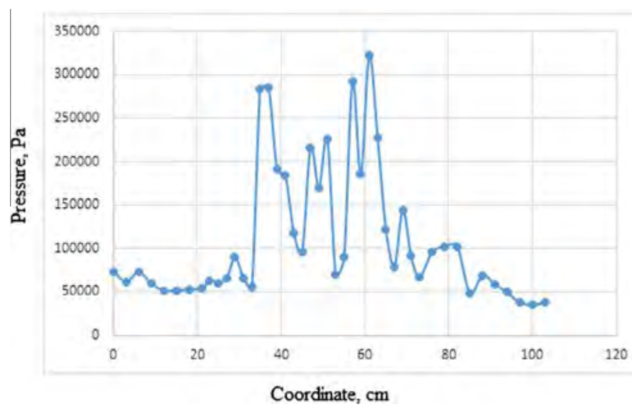

Fig. 4. Distribution of the acoustic field near the downhole tool with a diameter of 102 mm according to the studies performed using a hydrophone at a distance of 500 mm from the lateral radiating surface.

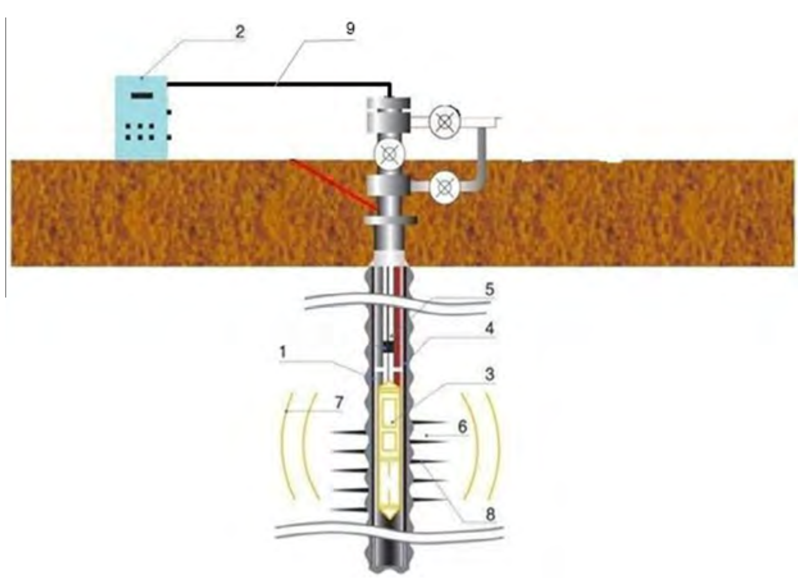

Fig. 3. Arrangement of ultrasonic equipment in the well during field tests: 1 – anchor, 2 – ultrasonic generator, 3 – downhole tool (102 mm), 4 – casing, 5 – tubing, 6 – reservoir, 7 – area of acoustic impact, 8 – perforation zone, 9 – cable.

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the dimensions Ø500 × 1800 mm filled with water, which was positioned horizontally. In the top part of the tank there was a rectangular window with the dimensions 260 × 1500 mm to put in the tool. The tool was fixed horizontally in the tank. The temperature of the water during the measurement was 35 ± 1 °C. The vibration pressure amplitude was measured using a pressure sensor PS02 with the measurement limits 0,1–250 MPa and with a frequency range of up to 80 kHz. For the distribution the Root Mean Square value of the pressure was used, pressure units, calculated based on it are shown in Fig. 4. The Axis X of Fig. 4 refers to the coordinate, measured parallel to the tool. Thus, the Figure shows the amplitude distribution lengthwise the tool. The power of the tool during the measurement was 3 kW, it worked in the cavitation mode.

3. Results and discussion

Fluid from one of the Samara region fields was used to study experimentally the effect of ultrasonic hydrodynamic treatment and chemical agents on the rheological characteristics of extremely viscous oil. The fluid had the following characteristics: the density was 0,953 g/m^3, the effective viscosity at 20 °C was 1014 mPa*s, the freezing point was 17 °C. The fluid contained 64,05% of oil, 28,6% of resins, 6,1% of asphaltenes.

100 L of oil were treated using the setup for UHT under the following conditions:

- The temperature was 75 °C.
- The pressure at the inlet of the reactor was 20–40 atm.
- The pressure at the outlet of the reactor was up to 10 MPa.
- The treated flow was 1.1 m^3/h.

Table 2 and Fig. 5 show the results of oil distillation before and after treatment. After activation of oil by UHT, the initial boiling point decreased by 3.5 °C, the yield of fractions below 350 °C increased by 5.6%, and the absolute yield of fractions below 320 °C increased by 11% (Table 3, Fig. 5).

Following the experiments on the effect of UHT on the rheological properties of oil, the effect of a reagent for viscosity reduction, which was added to the reactor during treatment, on the oil viscosity was studied. The reagent R-12, which was used during the research, had the following composition: butyl acetate – 30%, toluene – 60%, and xylene – 10%. Its density at 20 °C was 850 kg/m^3, and its viscosity was 0.640 mPa*s.

We have determined, that while during UHT, kinematic viscosity decreased by 34.4%. In case of UHT with addition of the R-12 solvent (2%) we observed a decrease in viscosity by 72.5%. The results are shown in Table 3.

We have monitored the duration of the viscosity reduction by measuring the viscosity 1 and 4 h after the treatment was finished. The values of viscosity after 1 and 4 h changed insignificantly. For comparison, we have also measured the viscosity values of the oil mixed with the solvent. In this case, the mixing was done using an ordinary lab scale magnetic mixer. It was necessary to use the mixer in order to ensure proper mixing of the two substances. For this case we have observed a viscosity decrease of 30,72% and 30,18% after 1 and 4 h respectively. Taking into account these results, we can conclude that in case of the use of both, the UHT and the solvent, we observe a synergetic effect. It should be also taken into account, that in a flow-through reactor on an industrial scale it would not be possible to organize proper mixing of the solvent with the oil without the use of ultrasonic or hydrodynamic methods or a special mixing device.

For comparison, studies of the effect of ultrasonic treatment on the oil flow in a setup with a flow-type waveguide system were carried out. In this experiment, the oscillations were induced into the oil flow by two magnetostrictive transducers. We have used the same oil from the Samara region. The treatment time in the reactor shown in Fig. 2 was 3 min. The time was chosen in such a way, to ensure the treatment of equal oil flow in both cases and to be able to compare the results of the two experiments. The flow was 1.1 m^3/h in both cases, 55 L of oil were treated in the flow-type reactor. The changes of oil viscosity after ultrasonic treatment and after ultrasonic treatment with addition of the R-12 reagent (2%) were studied.

The viscosity of the samples directly after treatment and in 2, 24, and 48 h after treatment was measured. The oil was not affected by any physical forces and no chemicals have been additionally added during the relaxation period of 2, 24 and 48 h. Fig. 6 shows the viscosity reduction after 3 min of treatment and the restauration of the viscosity after treatment, which was measured in order to estimate the duration of the viscosity reduction.

As it can be seen on Fig. 6 and 3 min of ultrasonic treatment reduced the viscosity of oil by 19.2%. The joint effect of ultrasound and the solvent caused a decrease in viscosity by 26.2%, which is considerably lower than the reduction after UHT. Already in 2 h after treatment, the reduction in viscosity decreased to 9.1 and 17.0%, respectively. After that, the relaxation of viscosity was observed during 48 h: in case of ultrasonic treatment, viscosity almost reached the initial values, and, in the case of sonochemical treatment, the viscosity reached a level that was 7% lower than the initial one.

To study the effect of ultrasonic irradiation on the viscosity of the fluid under well conditions, we performed a 24-h well treatment with an output power of the surface generator of 9 kW and a frequency 19 kHz. During the treatment, an increase of the bottomhole pressure by 2 atm was observed. The downhole tool was equipped with a temperature sensor, which switched off the tool, if the temperature exceeded 65 °C. During the treatment the tool worked continuously, thus the temperature did not exceed 65 °C. The oil production Q_{oil} increased by 0.4 tons/day. The production coefficient K_{prod} was 0.094 at the moment of treatment.

After treatment, a sample was taken and delivered within 4 h to the TGRU laboratory in Almetyevsk for the study of its rheological characteristics. According to the measurement during treatment, the viscosity of oil decreased from 183 mPa*s to 154 mPa*s. Thus, there is a reduction in oil viscosity by 16%, which is in good agreement with the results of laboratory experiments taking into account the time of sample delivery (4 h).

Table 2
Yield of fractions at different temperatures of the original oil from the Samara region field and oil after treatment in the setup for UHT.

Fraction, °C	∑ vol%, original	∑ vol%, subjected to UHT	∑ vol%, difference between original and treated
Initial boiling point, °C	**71**	**67,5**	
– below 100 °C	1,0	1,0	0
– below 120 °C	3,0	3,0	0
– below 150 °C	4,0	5,0	1,0
– below 160 °C	5,0	6,0	1,0
– below 180 °C	6,0	8,0	2,0
– below 200 °C	8,0	9,0	1,0
– below 210 °C	9,0	10,0	1,0
– below 220 °C	9,5	11,0	1,5
– below 240 °C	11,0	13,0	2,0
– below 260 °C	13,0	14,5	1,5
– below 280 °C	16,0	16,5	0,5
– below 300 °C	19,0	20,0	1,0
– below 310 °C	21,0	26,0	5,0
– below 320 °C	24,0	35,0	11,0
– below 330 °C	28,0	40,5	12,5
– below 340 °C	34,5	47,0	12,5
– below 347 °C	41,5	47,1	5,6

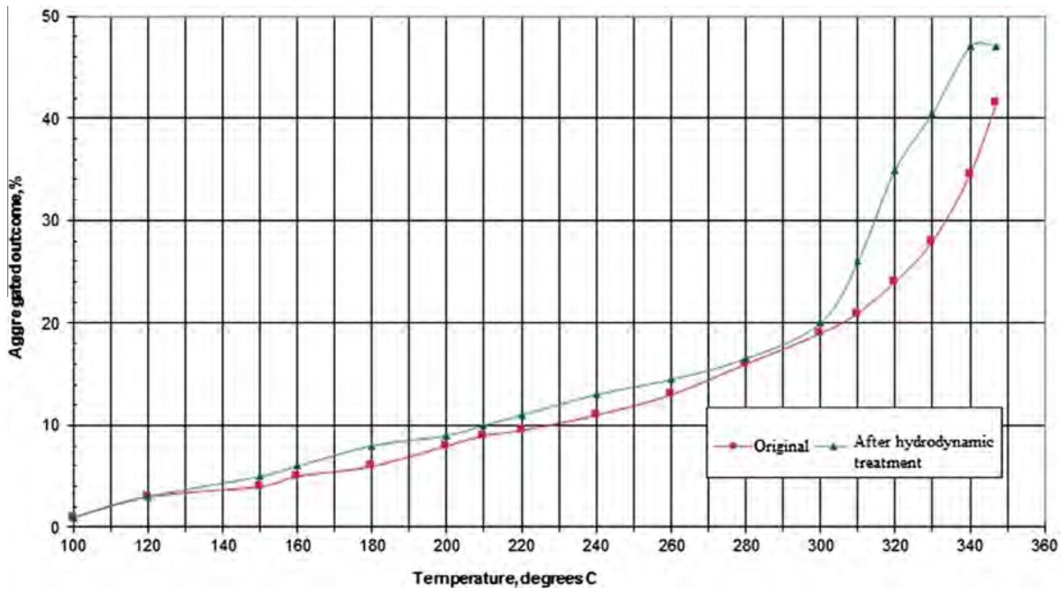

Fig. 5. Yield of fractions at different temperatures of the original oil from the Samara region field and oil after treatment in the setup for UHT.

Table 3
Time variation of oil viscosity (20 °C) after UHT and addition of R-12.

Treatment method	Time after oil treatment, h	Viscosity							Relative variation of viscosity, %
		1	2	3	4	5	6	Avg	
Original oil	1	1031	1012	1030	1018	996	999	1014	
Oil + UHT	1	683	678	669	654	659	648	665,2	34,42
Oil + R12(2%)	1	703	699	710	695	700	708	702,5	30,72
Oil + R12(2%) + UHT	1	273	277	280	285	278	283	279,3	72,46
Oil + UHT	4	709	712	714	708	711	715	711,5	29,86
Oil + R12(2%)	4	706	704	711	701	709	717	708,0	30,18
Oil + R12(2%) + UHT	4	284	283	282	278	287	292	284,3	71,97

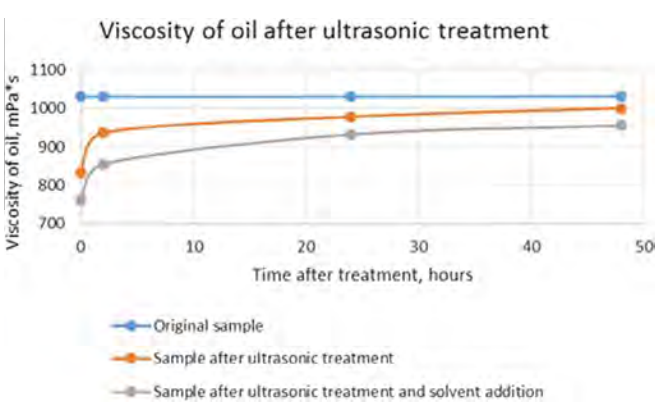

Fig. 6. Viscosity of oil after ultrasonic treatment and after sonochemical treatment in the setup with the flow-type waveguide system.

4. Conclusions

Ultrasonic treatment by a downhole tool located directly in the perforation zone leads to a decrease of the viscosity of oil and simultaneously to an increase in oil production. Both effects were demonstrated during field experiments in Tatarstan: a viscosity reduction by 16% 4 h after treatment was observed, simultaneously an oil production increase by 26,5% was demonstrated. As a result, the velocity of oil rise from the well increased. Consequently, the oil, which is supplied to the pipeline near the well, was hotter and the aggregated viscosity change was based on two factors: the change of the rheological properties of oil due to ultrasonic treatment and the temperature factor. Thus, in addition to an increase in the well production rate, ultrasonic treatment performed inside the well can facilitate the pipeline transportation of oil.

Furthermore, experiments have shown that the use of ultrasonic hydrodynamic treatment is the most promising acoustic method for further decreasing the viscosity of oil after its recovery. Such treatment makes it possible not only to reduce oil viscosity (by more than 30%), but also to change the fractional composition of oil. In addition, treatment in the designed setup allows a chemical agent to be effectively introduced into the oil. Introduction of a chemical agent during UHT lead to a synergetic effect and cause a further reduction of viscosity by 58%, compared to the viscosity of oil after UHT only.

Taking into account the mentioned above, ultrasonic treatment, which takes place in the well near the perforation zone, is a promising technology for viscosity reduction. To maintain the effect achieved in the wellbore, the fluid can be additionally treated in a setup for UHT with the introduction of chemical agents as it is shown in Fig. 7. In this case, it would be possible to facilitate the recovery and further transportation of oil and achieve a long lasting viscosity reduction.

The economic effect of this technique would be based on the possibility to transport high pour-point oil at reduced

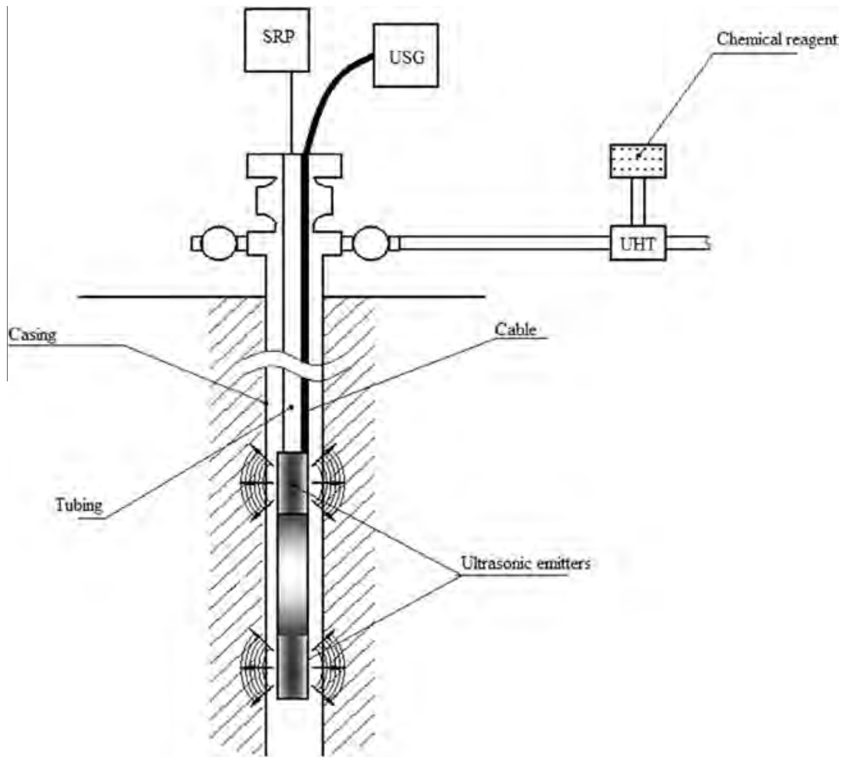

Fig. 7. Flow diagram of the proposed industrial setup.

temperatures and, consequently, on a decrease in energy consumption. In addition, the use of the proposed technology will make it possible to increase the safety of oil pipelines operation.

To increase the efficiency of the method, it is also necessary to consider the possibility of adding chemical agents directly to the perforation zone during treatment. As we demonstrated in laboratory studies, the addition of R-12 makes it possible to increase the viscosity reduction of oil by a factor of 1.5–2.

Technologically, this can be implemented, if a combined cable that also makes it possible to deliver chemical agents to the perforation zone is used to power the tool. One of the possible designs of such a cable is presented in Fig. 8. The cable consists of a three-core conductor (to the left) and an armored channel for injection of chemical reagents (to the right). The three-core conductor is used to power the ultrasonic downhole tool. Such a cable could be permanently fixed on the tubing of an oil well and be used upon requirement to power the ultrasonic tool or to inject chemical reagents. The use of such cable would prevent the necessity of stopping and opening the well to perform a sonochemical treatment.

Fig. 8. Possible design of a cable for sonochemical treatment of wells with high-viscosity oil on a permanent basis.

References

[1] A.V. Abramova, V.O. Abramov, S.P. Kuleshov, E.O. Timashev, Analysis of the modern methods for enhanced oil recovery, in: Energy Science and Technology, vol. 3: Oil and Natural Gas, Studium Press LLC, USA, 2015, pp. 118–148.

[2] V.I. Klimoko, Justification of rational temperature mode of pipeline transport of highly viscous and high solidifying oil (in Russian: Обоснование рационального температурного режима трубопроводного транспорта высоковязкой и высокозастывающей нефти) (Thesis for the degree of candidate of technical sciences), 2014, Sankt-Petersburg.

[3] T.J. Mason, A.J. Cobley, J.E. Graves, D. Morgan, New evidence for the inverse dependence of mechanical and chemical effects on the frequency of ultrasound, Ultrason. Sonochem. 18 (2011) 226–230.

[4] V.O. Abramov, A.V. Abramova, V.M. Bayazitov, A.V. Marnosov, S.P. Kuleshov, A. S. Gerasin, Selective ultrasonic treatment of perforation zones in horizontal oil wells for water cut reduction, Appl. Acoust. 103 (2016) 214–220.

[5] M.S. Mullakaev, V.O. Abramov, A.V. Abramova, Development of ultrasonic equipment and technology for well stimulation and enhanced oil recovery, J. Petrol. Sci. Eng. 125 (2015) 201–208.

[6] V.O. Abramov, M.S. Mullakaev, A.V. Abramova, I.B. Esipov, T.J. Mason, Ultrasonic technology for enhanced oil recovery from failing oil wells and the equipment for it's implementation, Ultrason. Sonochem. 20 (2013) 1289–1295.

[7] M. Mohsin, M. Meribout, Oil-water de-emulsification using ultrasonic technology, Ultrason. Sonochem. 22 (2015) 573–579.

[8] J.D. McLean, P.K. Kilpatrick, Effects of asphaltene solvency on stability of water-in-crude-oil emulsions, J. Colloid Interface Sci. 189 (1997) 242–253.

[9] F.G. Antes, L.O. Diehl, J.S.F. Pereira, R.C.L. Guimarães, R.A. Guarnieri, B.M.S. Ferreira, V.L. Dressler, E.M.M. Flores, Feasibility of low frequency ultrasound for water removal from crude oil emulsions, Ultrason. Sonochem. 25 (2015) 70–75.

[10] M. Mohsin, M. Meribout, An extended model for ultrasonic-based enhanced oil recovery with experimental validation, Ultrason. Sonochem. 23 (2015) 413–423.

[11] H. Hamidi, E. Mohammadian, R. Junin, R. Rafati, A. Azdarpour, M. Junid, M. Savory, The effect of ultrasonic waves on oil viscosity, Pet. Sci. Technol. 32 (19) (2014) 2387–2395.

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[12] É.M.M. Flores, F.G. Antes, R.A. Guarnieri, R.C.L. Guimarães, B.M.S. Ferreira, J.S.F. Pereira, L.O. Diehl, Feasibility of low frequency ultrasound for crude oil demulsification, in: Program and Book of Abstracts of the 14th Meeting of the European Society of Sonochemistry in Avignon, France, 2014, pp. 74–75.
[13] A.I. Vladimirov, Development of a wave technology and equipment for the transport of highly viscous oil and oil products (in Russian: Разработка волновой технологии и оборудования для транспорта высоковязких нефтей и нефтепродуктов), Patent # 01200307565, 17.01.2005.
[14] V.O. Abramov, A.V. Abramova, V.M. Bayazitov, L.K. Altunina, A. Gerasin, D.S. Pashin, T.J. Mason, Sonochemical approaches to enhanced oil recovery, Ultrason. Sonochem. 25 (2015) 76–81.
[15] V. Abramova, D. Asylbaev, D. Baranov, M. Mullakaev, G. Oganyan, Yu. Skakunov, Transonic jet activation of diesel fuel in the catalytic hydropurification (In Russian: Трансзвуковая струйная активация дизельного топлива в процессе каталитической гидроочистки), Neftepererabotka i neftechimiya, Nauchno-technicheskie dostigheniya I peredovoy opyt 7 (2009) 15–19.
[16] Y. Savchenko, Supercavitation – Problems and Perspectives. 4th International Symposium on Cavitation, Pasadena, USA, June 20–23, 2001.
[17] A. Schmid, Feinblasige Beluftung durch Sauerstoffeinspreisung unter «Superkavitation», Kommunalle Abwasserbehandlung 11 (2006) 1139–1144.

Please cite this article in press as: V.O. Abramov et al., Acoustic and sonochemical methods for altering the viscosity of oil during recovery and pipeline transportation, Ultrason. Sonochem. (2016), http://dx.doi.org/10.1016/j.ultsonch.2016.10.017