Ultrasonics Sonochemistry 25 (2015) 76–81

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

journal homepage: www.elsevier.com/locate/ultson

Sonochemical approaches to enhanced oil recovery

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ARTICLE INFO

Article history:
Received 7 August 2014
Accepted 13 August 2014
Available online 29 August 2014

Keywords:
Ultrasound
Enhanced oil recovery EOR
Oil well treatment
Horizontal well

ABSTRACT

Oil production from wells reduces with time and the well becomes uneconomic unless enhanced oil recovery (EOR) methods are applied. There are a number of methods currently available and each has specific advantages and disadvantages depending on conditions. Currently there is a big demand for new or improved technologies in this field, the hope is that these might also be applicable to wells which have already been the subject of EOR. The sonochemical method of EOR is one of the most promising methods and is important in that it can also be applied for the treatment of horizontal wells. The present article reports the theoretical background of the developed sonochemical technology for EOR in horizontal wells; describes the requirements to the equipment needed to embody the technology. The results of the first field tests of the technology are reported.

1. Introduction

Currently the efficiency of oil recovery from wells is less than 40% and as such is not really satisfactory [1]. Existing technologies for enhanced oil recovery (EOR) are often energy and labor intensive and often not environmentally friendly [2–6]. Thus there is great interest in the modification of established techniques and the development of new technologies. This is particularly important in the case of the newer types of horizontal wells that are generally higher yielding than traditional (vertical) types in that they harvest oil from a number of underground sources through which they pass. In Western Siberia and the Volga region one of the main approaches to the rejuvenation of failing oil wells has been through the use of chemical treatment which is useful for removing blockages. While this method is good for traditional wells it has been shown to be inefficient in the case of horizontal wells. This is because the chemical reagents injected through the wellhead often do not reach the zones along the horizontal part which need to be treated [7].

Over the last few years there has been a developing interest in physical EOR techniques, especially those based on ultrasonic treatment [8–10]. We have developed a method for EOR which includes ultrasonic treatment in the wellbore perforation zone with the simultaneous creation of a zone of lower pressure in that zone [11–12]. The methodology is particularly useful for older wells which are in the later stages of reduced yields.

Laboratory and field tests have shown that acoustical oscillations initiate a variety of chemical and physical processes in oil bearing formations. The most attractive and studied of these processes, which will be described further in this article, are:

1. Destruction of physical bonding on the boundary layer between the pores of the rock and the fluid, which hinders the movement of fluid.
2. Alteration of the fluid rheology by the destruction of the bonding between molecules in the fluid which is important in the cases of viscous and heavy oils allowing the more solid components like resin, paraffin and asphaltene to become mobile.
3. The break-down of mineral salt deposits and deparaffinization.

2. Theoretical background and laboratory scale experiments

The main difference between oil and many other viscous liquids is that its molecules form conglomerates, which account for the

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http://dx.doi.org/10.1016/j.ultsonch.2014.08.014
1350-4177/

higher viscosity of oil. In these conglomerates the molecules are bonded to each other by intermolecular forces. The goal of ultrasonic treatment is to destroy these bonds and to bring the properties of the oil closer to what they would have been if no conglomerates were present.

The description of this process is in many aspects similar to the description of destruction of materials, 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 [13]:

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

In the above Eq. (1) τ_0 is a constant value, which depends on the material properties, σ_c is the static stress, σ_u 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 (Eq. (2)) taking into account the periodic nature of this stress $\sigma(t)$:

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

where $\sigma(t) = \sigma_0 \sin\omega t$ and $\tau = 2\pi/\omega$. Thus Eq. (1) is transformed into Eq. (3):

$$\tau_p = \tau_0 \exp\left\{\frac{E_0 - \gamma\left(\sigma_c + \frac{2\eta N_p \sigma_0}{\pi}\right)}{kT}\right\} \quad (3)$$

where $N_p = 1/(2\pi) \times \omega\tau_p$ is the number of stress cycles needed to destroy the intermolecular bond. η characterizes the percentage of energy of the ultrasonic treatment, which goes to bond destruction.

Eq. (3) is an equation for N_p, which can be changed to

$$N_p = \pi\frac{E_0 - \gamma\sigma_c}{2\gamma\eta\sigma_0} + \frac{kT\pi}{2\gamma\eta\sigma_0}\ln\left(\frac{\omega}{\pi^2}\tau_0\frac{\eta\sigma_0\gamma}{(E_0 - \gamma\sigma_c)}\right) \quad (4)$$

In order to estimate N_p, which obviously determines the time needed to destroy the conglomerates of the molecules, one needs to know the parameters E_0 and γ, which characterize the type of the intermolecular bond. A rough estimation of N_p can be done if we use the approximate equality $E_0 \approx \gamma\,\sigma_T$, where σ_T is the stress of bond destruction. Assuming $\sigma_c = 0$ (which is the typical case), Eq. (4) simplifies to Eq. (5):

$$\begin{aligned} N_p &= \pi\frac{\sigma_T}{2\eta\sigma_0} - \frac{kT\pi\sigma_T}{2E_0\eta\sigma_0}\ln\left(\frac{\pi^2}{\omega\tau_0}\frac{\sigma_T}{\eta\sigma_0}\right) \\ \tau_p &= \pi^2\frac{\sigma_T}{\eta\sigma_0\omega} - \frac{kT\pi^2\sigma_T}{E_0\eta\sigma_0\omega}\ln\left(\frac{\pi^2}{\omega\tau_0}\frac{\sigma_T}{\eta\sigma_0}\right) \end{aligned} \quad (5)$$

The energy of the intermolecular bond is related to the stress of the bond destruction is given by Eq. (6):

$$E_0 = \pi R_c^2 R_{cr}\sigma_T \quad (6)$$

where R_c is the typical "radius" of one molecule, which is about 0.5 nm for oil and R_{cr} is the critical distance required to break the connection, which was considered to be 0.5 nm (the size of molecule) for the estimation.

The stress produced by the acoustical field is equal to the acoustical pressure (Eq. (7)):

$$\sigma_0 = 2\pi f\rho cA\sqrt{\frac{\pi}{\omega}} \quad (7)$$

where f is the frequency of ultrasound, A is the amplitude of the signal, c is the speed of sound and ρ is the density of the media.

In the case of low temperatures the second quantity is low; the temperature rise due to ultrasonic treatment can be neglected as ultrasonic treatment is usually accompanied by pumping out the well by a jet pump, thus creating a continuous flow.

Thus the treatment time may be roughly estimated using Eq. (8):

$$\tau_p = \frac{E_0}{2R_c^2 R_{cr}\eta\sqrt{\pi\omega}f\rho cA} \quad (8)$$

The following numerical values were used for the estimation: $f = 20{,}000$ Hz, $E_0 = 1.7 \times 10^{-20}$ J (typical value for non polarized molecules), $\rho = 900$ kg/m^3 (for oil), $c = 620$ m/s, $\eta = 0.3$ and A near the downhole tool was determined experimentally and was equal 2 μm. In order to calculate the amplitude of the pressure depending on the distance from the acoustical emitter r Eq. (9) was used:

$$A_r = Ae^{-\alpha r}, \quad (9)$$

The damping coefficient is dependent on the frequency of the signal (Eq. (10)):

$$\alpha = \omega/c \times 1/Q, \quad (10)$$

Q is the quality factor. For materials of the earth's crust Q is usually about 300. However it should be taken into account that in case of oil formation we deal with a porous media, thus the signal is damped more. As recommended in Ref. [14] for this case we assumed that the quality factor is equal 30. Thus in our case the damping coefficient α may vary from 4 up to 5.2 depending on the structure of the porous media.

Based on the assumptions described above we have been able to calculate the treatment time needed to destroy the intermolecular connections. Near the downhole instrument it is 30 s. However depending on the structure of the porous media this time reaches 20–55 min for zones which are 1 m away from the tool (based on experiments in a barochamber it was determined that the acoustical signal is damped almost completely within 1 m of formation, thus the treatment time was calculated for this case).

The theoretical model described above was tested experimentally by studying the effect of ultrasound on the viscosity of oil. A schematic of the equipment used is shown on Fig. 1. We have used the generator TS4M1, the waveguide system had an operating frequency 20 kHz with an emitting surface 6.6 cm^2.

We have studied the viscosity changes of oil after 3 min of treatment. The power of the generator was 3 kW. In order to avoid the

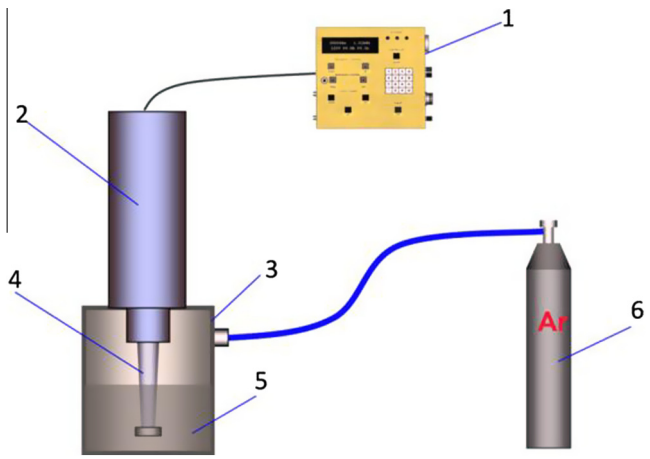

Fig. 1. Equipment scheme for studying the effect of ultrasound on the viscosity of oil: 1 – ultrasonic generator, 2 – magnetostrictive transducer, 3 – sealed reactor for treatment of oil, 4 – waveguide system, 5 – oil, 6 – compressed gas cylinder to maintain the pressure in the reactor.