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A technique for evaluating the oil/heavy-oil viscosity changes under ultrasound in a simulated porous medium

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ABSTRACT

Theoretically, Ultrasound method is an economical and environmentally friendly or "green" technology, which has been of interest for more than six decades for the purpose of enhancement of oil/heavy-oil production. However, in spite of many studies, questions about the effective mechanisms causing increase in oil recovery still existed. In addition, the majority of the mechanisms mentioned in the previous studies are theoretical or speculative. One of the changes that could be recognized in the fluid properties is viscosity reduction due to radiation of ultrasound waves. In this study, a technique was developed to investigate directly the effect of ultrasonic waves (different frequencies of 25, 40, 68 kHz and powers of 100, 250, 500 W) on viscosity changes of three types of oil (Paraffin oil, Synthetic oil, and Kerosene) and a Brine sample. The viscosity calculations in the smooth capillary tube were based on the mathematical models developed from the Poiseuille's equation. The experiments were carried out for uncontrolled and controlled temperature conditions. It was observed that the viscosity of all the liquids was decreased under ultrasound in all the experiments. This reduction was more significant for uncontrolled temperature condition cases. However, the reduction in viscosity under ultrasound was higher for lighter liquids compare to heavier ones. Pressure difference was diminished by decreasing in the fluid viscosity in all the cases which increases fluid flow ability, which in turn aids to higher oil recovery in enhanced oil recovery (EOR) operations. Higher ultrasound power showed higher liquid viscosity reduction in all the cases. Higher ultrasound frequency revealed higher and lower viscosity reduction for uncontrolled and controlled temperature condition experiments, respectively. In other words, the reduction in viscosity was inversely proportional to increasing the frequency in temperature controlled experiments. It was concluded that cavitation, heat generation, and viscosity reduction are three of the promising mechanisms causing increase in oil recovery under ultrasound.

1. Introduction

One of the mechanisms through which ultrasound improves the recovery of oil from porous media is viscosity reduction [1–4]. Viscosity is one of the controlling factors in areal sweep efficiency of any EOR project as it controls the mobility of the moving front as follows:

$$M = \frac{K_{r1}}{K_{r2}} \frac{\mu_2}{\mu_1} \tag{1}$$

In which K_{r1}/K_{r2} is ratio of relative permeability of displacing fluid (EOR agent) to displaced fluid (oil) and μ_2/μ_1 is the ratio of viscosity of displaced phase (oil) to viscosity of displacing phase (EOR Agent). The less the viscosity ratio the lower the mobility (M) is results in more uniform displacement and higher recovery in EOR operations.

In a pioneering study, Duhon and Campbell [1] stimulated a porous medium with ultrasound waves of 45 and 65 kHz frequency and inferred that reduction in viscosity of oil as a result of ultrasonic stimulation contributes in increasing the recovery.

Fairbank and Chen [5] observed reduction of surface tension, density and viscosity as a consequence of heating by ultrasonic radiation. The same result was highlighted also by Sokolov and Simkin [6] mentioned that surface tension and viscosity were decreased (with frequency and time) due to heat generation by ultrasonic radiation.

Beresnev and Johnson [7] concluded after a careful review of the literature, that no clear evidence was available about the mechanisms responsible for the flow stimulation by acoustic irradiation. They suggested that the following mechanisms might be involved: (1) the acoustic wave field may considerably reduce the influence

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of capillary forces on the oil percolation, resulting in an increased rate of migration through the porous material, (2) non-linear effects such as acoustic streaming, may give the liquids extra momentum, (3) reduction of the surface tension and the viscosity of the liquids due to a temperature increase caused by energy dissipation may result in an apparent change in permeability, (4) peristaltic transport. One of the possible explanation for enhancement of flow in porous media under ultrasound is that ultrasonic waves traveling along the tube walls may cause displacement of fluid similar to "peristaltic transport" [8–10]. This mechanism was first proposed by Ganiev et al. [8]. They suggested that ultrasonic radiation deforms the pore walls in a porous medium in the shape of traveling transversal waves. However, they do not analyze the influence of the ultrasound power output and the material properties of the porous medium and the liquid. Furthermore, they do not refer to a validation of the mechanism by experiments. Aarts and Ooms [11] proposed that the peristaltic transport mechanism works only at ultrasonic frequencies, and is only significant near the wellbore due to the high attenuation of the ultrasound. Later, Aarts et al. [9] discussed the role of peristaltic transport mechanism in fluid flow enhancement by a comparison between the trends observed in the experiments and the theoretically predicted trends. The numerical results showed that the fluid flow inside a capillary tube made by rubber (small shear modulus G) is proportional to the power output W generated at the source. Furthermore, they observed that for a softer porous medium (which has a smaller shear modulus G), the induced velocity is larger. They concluded that the size of the pore has only a slight effect on the induced flow velocity, whereas the hardness of the porous medium has a huge effect. The experimental results showed that fluid flow is proportional to the power output W which shows that the trend is in agreement with the theoretically predicted trend. However, the experiments also showed that the ultrasonically induced flow velocity is nearly independent of the hardness of the rubber, which is in contrast to the theory of peristaltic transport due to the deformation of the capillary wall in the shape of a traveling wave. Thus, whether the induced flow is a result of peristaltic transport has become doubtful.

Poesio et al. [12] speculated reduction in pressure gradient of fluid trapped in a Berea sandstone. The effect was attributed to reduction in fluid viscosity resulted from exposure to ultrasound waves. However, one can argue that the latter conclusion is valid only if other parameters such as relative permeability remain the same pre and post radiation. Nevertheless, alteration in relative permeability as a result of ultrasound stimulation was observed by Amro et al. [13].

Xiao et al. [2] reported that reduction in the viscosity is a temporary effect; the viscosity values will return to their initial values as the media cools down (emission of sound waves stops). Also, the effect of acoustic field on dynamic viscosity of oil was investigated by Sokolov and Simkin [6]. They concluded that the oil viscosity reduced by 20–25% after 30–60 min radiation. However, the viscosity gradually returned back to the preradiation step in about 120 h.

Poesio and Ooms [14] suggested that reduction in liquid viscosity was due to the heat generated by the dissipation of ultrasound energy in media and as a result, the pressure gradient decreased at constant liquid flow rate.

On the other hand, increase in viscosity of fluid is observed in case of radiation ultrasonic waves to heavy oil by Najafi [15]. Scaling of high molecular components such as wax and asphaltene as a result of ultrasonic radiation was considered as the reason for increase in the viscosity of heavy oils. The same effect is also reported in research conducted by Mohammadian [16] in a temperature-controlled experiment to prove the scaling of heavy molecules is only due to effect of the waves on the oil rather than temperature effects.

In addition to laboratory studies, some field studies have been carried out. Yan and Yaping [17] have studied using ultrasonic and surface active agent to change viscosity of heavy oil in Gudao oil field. The results showed that ultrasonic wave can effectively decrease the viscosity of heavy oil, increase fluid flow ability, which aids to produce additional oil and transport heavy oil at long distance. Xiao et al. [2] conducted a series of experiments to study the feasibility of using ultrasound technology into heavy oil field to enhance oil recovery. In the first series of experiments, they measured the variation of viscosity of the crude oil with temperature without vibration. These tests were performed at the same vibration frequency. The results showed that the viscosity decrease with increase in temperature. Also, they measured the change in viscosity of the crude oil with time that vibration of ultrasound conducted when temperature is 35 °C, 43 °C, and 48 °C. The results showed that (a) the viscosity of the vibrated oil increases again with extension of recovering time.

In spite of numerous studies, it is not yet clear that whether the viscosity reduction in ultrasonic stimulated fluids is due to the thermal effect of waves or due other reasons. For example Poesio et al. [12] convincingly demonstrated that, the only reason for reduction of viscosity is temperature increase in the media. Mohammadian et al. [4] considered viscosity reduction as one of the possible contributing mechanisms in the recovery. They further concluded that viscosity of brine and oil are reduced as a result of sonication. They also inferred that the reduction in viscosity of fluids is not solely due to heat generated as a result of sonication. Table 1 summarizes more details about previous studies on viscosity changes of fluids as they are being irradiated with ultrasound waves.

In all of the previous mentioned studies the viscosity was measured using either indirect methods i.e. calculating the viscosity from temperature changes or it was measured in a static condition. The aim of the current study therefore is to investigate changes in the viscosity of various liquids exposed to radiation of ultrasonic waves of various frequency and power outputs measured by a novel method. Moreover, in previous researches the effects of properties of waves (frequency and power output), as an independently factor, has not been discussed on viscosity. In the other word, viscosity reduction was reported as a side effect of ultrasonic radiation. The area therefore could be explored further. The current study aims to investigate the changes in viscosity of various liquids as they are exposed to ultrasound waves of various frequency and power outputs in porous media. The findings of this research could be used in development of models which could be further implemented in simulation studies concerning simulation of ultrasonic waves for enhanced oil recovery purposes.

2. Experimental setup and procedure

2.1. Experimental setup

In this study, an ultrasonic generator provided the energy which was emitted to a water bath through an immersible transducer. The generator used was Genesis™ XG-500-6 ultrasonic processor which emits ultrasonic waves with maximum power of 600 W and different frequencies of 25, 40, and 68 kHz. A 25-cm stainless steel smooth capillary tube with dimension of 0.2×20 cm ($D \times L$) was used as a single pore system in the fluid flow experiments. The water bath with dimension of $21 \times 50 \times 30$ cm ($W \times L \times H$) was designed to make a suitable surrounding for application of ultrasound. The bath efficiency was measured by calorimetric method [18]. For instance, the bath efficiency for maximum power of 500 W is 35.4% which shows actual power dissipated in bulk solution is 176.9 W. The tube was fixed on a holder