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Short Communication

Effects of ultrasonic waves on the interfacial forces between oil and water

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Abstract

The effect of ultrasound on flow through a capillary using the pendant drop method was investigated. Water was injected into a 0.1 mm Hastelloy C-276 capillary tube submersed into several mineral oils with different viscosity, and kerosene. The average drop rate per minute was measured at several ultrasonic intensities. We observed that there exists a peak drop rate at a characteristic intensity, which strongly depends on oil viscosity and the interfacial tension between water and the oil. The semi-quantitative results reveal that the remarkable change in the interfacial forces between oil and water could be the explanation to the enhancement of oil recovery when the ultrasonic waves are applied.

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1. Introduction

Field tests and laboratory investigations have demonstrated that high intensity acoustic stimulation may enhance oil recovery in rocks [1–8]. Despite a vast body of empirical and theoretical support, this technology lacks sufficient understanding to make meaningful, consistent engineering predictions. This is in part due to the complex nature of the physical processes involved, as well as the shortage of fundamental/experimental research.

Our recent research showed that the ultrasonic waves influence capillary forces in porous media [9–11] causing remarkable changes in the shape of the interface between two immiscible fluids [12,13]. More efforts are needed in clarifying the type and level of this influence on the interfacial properties such as interfacial tension and wettability.

Many researchers have investigated the rise of liquid level within a capillary tube subjected to an ultrasonic field. Most of the investigations attribute this rise to ultrasonic cavitation at the tip of the capillary. A collapsing vapor bubble can exert thousands of pounds per inch of pressure locally, causing a temporary increase in phase pressure. When such bubbles collapse rapidly, the cumulative pressure increase results in a rise in fluid level. It was also shown that the wettability of liquids on solid ultrasonically driven surfaces is enhanced [14]. Therefore, applying ultrasonic radiation onto a capillary may increase capillary forces, and alter the wetting properties of a vibrating capillary.

The drop formation at a capillary tip has been studied extensively. Two types of flow regimes have been identified to describe fluid ejection from a capillary. At high rates, drops exit the capillary in form of a jet (connected set of drops), while at low rates, distinct droplets form at the tip. An excellent experimental treatise on this topic may be found in the thesis of Cramer [15]. Drop formation is usually divided into two stages: (a) early static growth at

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the capillary, and (b) necking/detaching. These mechanisms are described in greater detail elsewhere [16–18].

Graham [19,20] and Graham and Higdon [21,22] studied the motion of fluid droplets in harmonically forced capillary tubes. They observed remarkable enhancement in mobility for large droplets (droplet diameter exceeding the diameter of the capillary) when oscillatory forcing is strong, and the drop capillary number is low. They attributed this enhancement to the increased droplet deformation and observed that frequency, amplitude and type of waveform play a critical role on it as well.

Zaslavskii [23] performed experiments to study the motion of small droplets in a capillary. They applied a static pressure on the droplet to control the level of the fluid within the capillary, and altered the frequency of vibration. They noticed a hysteretic dependence of surface tension forces on the velocity of the meniscus.

In a series of experiments, Tamura et al. [14] showed that liquids may adhere to flat ultrasonically driven surfaces. The shape of the droplet depends on the amplitude of vibration. After investigating the effects of intrinsic surface tension and intensity, they developed a simple model to predict drop shapes. The predicted drop dimensions matched closely with the experimental observations.

In this study, a series of pendant drop experiments were performed to explore the effect of ultrasound on drop rate within narrow capillaries. The drop rate is a strong function of both viscosity and interfacial tension. The drop experiments may explain various observations made during the imbibition experiments. In essence, the capillary represents a pore throat. When applying ultrasound to porous media, a series of physical mechanisms, such as change in the wettability and vibrations of ganglia at the pore throat, may induce a higher capillary snap-off threshold. This mechanism may considerably improve the percolation of oil ganglia into adjacent pores, and ultimately lead to higher oil recovery.

2. Experimental setup

Equipment: A Hastelloy C-276 0.1 mm capillary was used to inject water at a constant pressure into various oleic fluids. A tear drop shaped glass vessel was utilized to maintain injection at a constant hydrostatic head pressure of 10 cm H_2O (0.1422 psi). A 3/4" ultrasonic horn was employed to deliver continuous ultrasound at a broad range of intensities at an angle of approximately 45°. The oleic phase was contained in a 2 mm thick glass cylinder (5 cm diameter) which was sealed with a rubber stopper at the bottom end. The glass container served to protect the capillary from the intense cavitation zone generated by the horn, and ensured that the observed drop rate was entirely due to ultrasound alone. It also reduced the level of emulsification which may alter the rheological properties of the oleic phase. One inch of the capillary was immersed into the oleic phase. Images of the falling drops were recorded using a Canon Xi video camera, and digitized using Windows Moviemaker. The experimental setup is presented in Fig. 1. Snap shots of the droplets just before detachment are shown in Fig. 2 for increasing ultrasonic intensities.

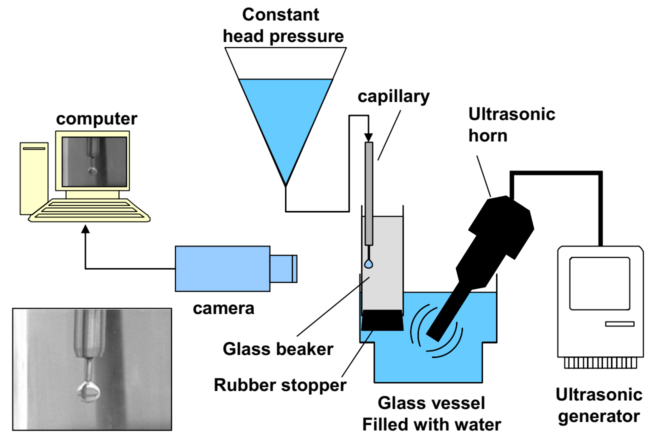

Fig. 1. Experimental setup of the pendant drop experiments.

Fluid properties: Three types of refined mineral oils and kerosene were used in the experiments. The fluid properties are shown in Table 1. Fluids were chosen to cover a broad range of interfacial tension and viscosity. N350 (Canon Instruments calibration oil) is a high viscosity, low IFT

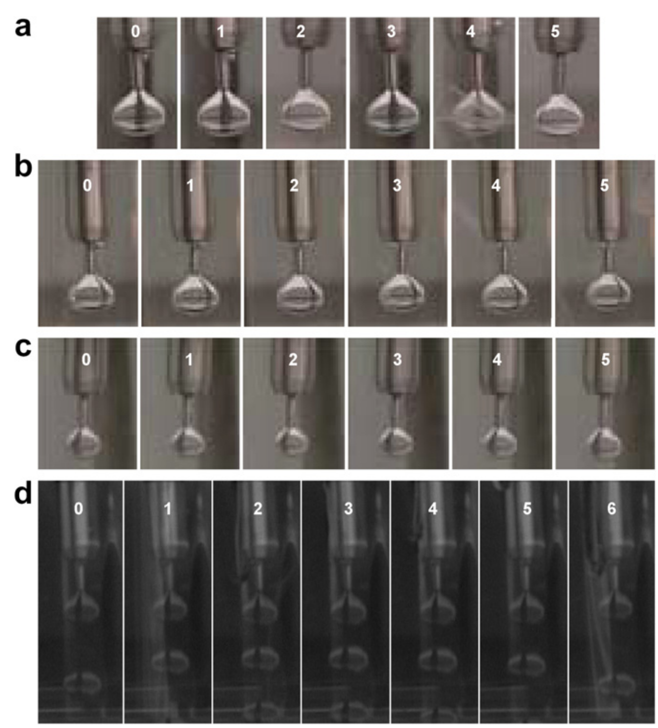

Fig. 2. Snap shots of pendant drops just before detachment. A wide range of viscosity and interfacial tension was investigated by using: (a) light mineral oil, (b) heavy mineral oil, (c) kerosene, and (d) high viscosity processed mineral oil (N350). Numbers at the top of each image indicates the ultrasonic setting [0 = no ultrasound; 5 = high ultrasound]. After inspecting the shape of the drops visually, it can be readily concluded that interfacial tension does not noticeably change with ultrasonic intensity.