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An experimental study on the motion of water droplets in oil under ultrasonic irradiation

Xiaoming Luo [a,*], Limin He [a], Hongping Wang [b], Haipeng Yan [a], Yahua Qin [c]

[a] College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, PR China
[b] CNOOC Refinery QingDao Engineering Co., Ltd., Qingdao 266100, PR China
[c] Mechanical and Chemical Engineering, The University of Western Australia, Crawley, WA 6151, Australia

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ABSTRACT

The motion of a single water droplet in oil under ultrasonic irradiation is investigated with high-speed photography in this paper. First, we described the trajectory of water droplet in oil under ultrasonic irradiation. Results indicate that in acoustic field the motion of water droplet subjected to intermittent positive and negative ultrasonic pressure shows obvious quasi-sinusoidal oscillation. Afterwards, the influence of major parameters on the motion characteristics of water droplet was studied, such as acoustic intensity, ultrasonic frequency, continuous phase viscosity, interfacial tension, and droplet diameter, etc. It is found that when the acoustic intensity and frequency are 4.89 W cm^{-2} and 20 kHz respectively, which are the critical conditions, the droplet varying from 250 to 300 μm in lower viscous oil has the largest oscillation amplitude and highest oscillation frequency.

1. Introduction

The natural emulsifiers in crude oil and chemicals artificially injected during the oil exploitation adsorb at the oil–water interface and form a strong viscoelastic interfacial film, resulting in kinetic barriers to coalescence of dispersed droplets and invalidation of conventional gravity separation [1]. At present, the general methods of demulsification include heat treatment, chemical demulsification, electrostatic coalescence, ultrasonic demulsification and microbial demulsification, etc. Among these, ultrasonic irradiation is quite simple and effective, which impels water droplets to move directionally, aggregate, then collide and coalesce under the mechanical oscillation and thermal effect of the ultrasonic wave and consequently enhances the separation efficiency [2].

With the help of external energy which drives dispersed droplets in the emulsion to move, the efficiency of collision and coalescence can be promoted. In recent years, electrostatic coalescence technology develops rapidly and breakthroughs have been made in both microcosmic mechanism and industrial application. Under electric field, polarization effect makes the two ends of water droplet carry positive and negative charges respectively, which induces dipole force between the neighboring droplets and accelerates the drainage of liquid film, promoting the efficiency of coalescence consequently. Meanwhile, electrophoresis, oscillatory deformation and dielectrophoresis will increase the collision frequency between the droplets [3–6]. Nevertheless, when the electric field strength is excessively high and the field stress exceeds the critical value, the interface becomes unstable and dispersion occurs [7–11]. Therefore, the dynamic behaviors of water droplets in oil subjected to electric field are mainly affected by electric field parameters and physical properties of water droplets.

About ultrasonic demulsification, currently most researches focus on the evaluation of the demulsification performance. Singh [12] found that ultrasonic had better demulsification effect on certain stable emulsions while the chemical demulsification did not have influence on them. Kotayusov et al. [13] theoretically deduced that the optimum frequency for droplets cohesion was higher than 10 kHz. Check et al. [14] evaluated the effects of ultrasonic power, irradiation time, and temperature on water removal from crude oil and provided optimal parameters theoretically and experimentally. Nii et al. [15] investigated the mechanism of demulsification under ultrasonic irradiation by observing the formation and lifting process of emulsion flocculates. Sun et al. [16,17] found that the cavitation effect of ultrasonic could lead to oil–water emulsification. Thus they suggested acoustic intensity should be controlled under cavitation threshold and the optimum demulsification frequency varied from 21 to 41 kHz. Ye et al. [18,19] systematically investigated the effect of acoustic intensity,

* Corresponding author.
E-mail address: upclxm@163.com (X. Luo).

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ultrasonic frequency, irradiation time and temperature on demulsification. Meanwhile, they indicated that acoustic intensity was more important than other factors. As to the microcosmic mechanism, current researches are mainly about the characteristics of cavitation bubbles under ultrasonic field, while few works reported the mechanism of ultrasonic demulsification [20–27]. However, the physical properties between oil–water system and gas–liquid system are significantly different. Therefore, it is necessary to explore the behavior of droplets in oil under the influence of ultrasonic field, which provides the theoretical foundation for the development of ultrasonic demulsification technology.

In this paper, the motion characteristics of an isolated water droplet in oil under ultrasonic irradiation are studied carefully with the help of high-speed photography. And the effects of ultrasonic parameters and physical properties on droplet motion characteristics are discussed in detail.

2. Theoretical background

There are two main forces when droplets are exposed to the ultrasonic field: one is the primary acoustic force which helps to agglomerate the droplets at the pressure nodes or antinodes; the other is the secondary acoustic force which will be an attractive force when two drops have identical compressibility. In this paper, our main purpose is to explore the law of motion of one isolated droplet under ultrasonic irradiation. Accordingly, we mainly focused on the primary acoustic force.

It is widely accepted that in the standing wave acoustic field, the smaller droplet would be subjected to a time-averaged force in the direction parallel to the propagation of the sound field known as the primary acoustic force, which is given for a one-dimensional field as [28]:

$$F_{1,ac} = 4\pi a^3 \kappa E_{ac} F \sin(2\kappa x) \tag{1}$$

where a is the droplet radius, κ is the wave number of the acoustic field, E_{ac} is the energy density of the acoustic field, x is the distance between the droplet and a pressure antinode of the standing wave and F is the acoustic contrast factor which is crucial in determining the direction of droplet motion. F is given by [29]:

$$F = \frac{\rho_r + (2/3)(\rho_r - 1)}{(1 + 2\rho_r)} - \frac{1}{(3\sigma^2 \rho_r)} \tag{2}$$

with ρ_r being the ratio of the droplet density to the continuous phase density and σ being the ratio of the speed of sound through the drop phase to that through the continuous phase. It could be inferred from Eqs. (1) and (2) that the droplet motion will be significantly influenced by the size of droplet and the frequency and intensity of the acoustic field, which will be discussed in detail in this paper. In addition, drag force opposes the relative motion of a droplet through the continuous phase. Therefore, the viscosity is another main factor which is to be discussed in this paper as well (see Fig. 1).

3. Experiment

3.1. Experimental apparatus

The experimental apparatus, as shown in Fig. 2, are composed of an ultrasonic generator, a transparent test cell, a high-speed digital video camera system, an LED light source, and a data

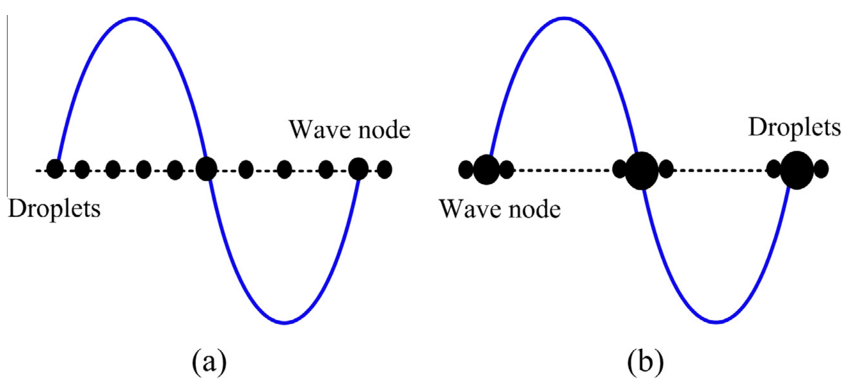

Fig. 1. Schematic of displacement effect for water droplets in oil [16]. (a) The initial distribution of water droplets. (b) The motion of droplet under ultrasonic irradiation.

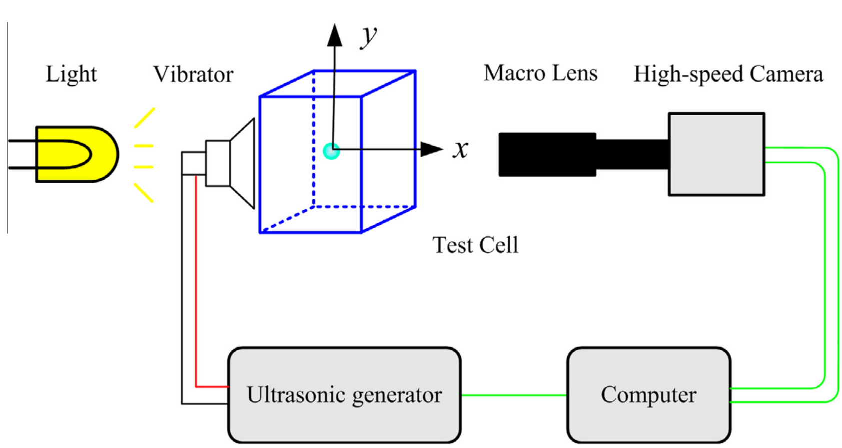

Fig. 2. Schematic of microscopic test system of droplet under ultrasonic irradiation.