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Study on separation characteristics of water in oil (W/O) emulsion under ultrasonic standing wave field

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ABSTRACT

The separation characteristics of W/O emulsion were investigated under ultrasonic standing wave field in this paper. The effects of the irradiation time, acoustic intensity, frequency, oil viscosity, and oil-water interfacial tension on the separation characteristics of emulsion were studied in details. It was proved that there existed an optimal irradiation time, acoustic intensity and oil-water interfacial tension to achieve the maximum separation efficiency in ultrasonic treatment process. Excessive long irradiation time had little effect on improving the dehydration rate of emulsion but rather increased unnecessary processing time. Excessive high acoustic intensity caused the occurrence of acoustic cavitation phenomenon. The acoustic cavitation would cause the aggregated droplets to be dispersed by oscillating bubbles or even emulsified again by high speed micro jets. The acoustic cavitation threshold is effectively and accurately obtained by a spectral analysis method. The micro acoustic streaming which resulted from the attenuation of acoustic energy occurred with the increase of frequency. It sheared the aggregated droplets, destroyed the stable droplets banding and reduced the separation efficiency of emulsion. The excess surfactant adsorbed on the oil-water interface resulted in the increase of the interfacial film strength, which hindered the coalescence process of droplets and reduced the separation efficiency.

1. Introduction

Separation of the water phase from W/O emulsion is very important in petroleum and chemical processing. In the past decades, emulsion-separation methods based on the use of ultrasonic fields have caused wide attention due to its advantages of efficiency and simplicity. The dispersed droplets would be influenced by acoustophoresis phenomenon [1] under ultrasonic standing wave field, which is similar to the electrophoresis of water droplets in oil under electric field. Because of the difference of density and compressibility between the dispersed droplet and the continuous phase, acoustic standing waves could aggregate homogeneously-suspended droplets at pressure nodal, or anti-nodal planes within a fluid [2]. The migration direction depends on the acoustophoresis coefficient [3]. Those aggregated droplets at pressure nodal or anti-nodal planes will form droplets banding, which could cause droplets to clump together and sediment more rapidly [4]. This banding effect enhances emulsion separation efficiency.

The motion rules of dispersed droplets are very important to emulsion separation characteristics under ultrasonic standing wave field. Mathew et al. [5] developed a two-dimensional dynamic model for tracing the path of microparticles, and found that the microparticles' trajectory consisted of transient and steady phases. Pangu et al. developed a microscopic mathematical model [6] to predict the relative trajectory of binary droplets and further developed a global model [7] of droplets coalescence rates. The trajectory of binary droplets shows two regimes: (a) a fast motion of two droplets primarily due to the gravity and the primary radiation force that pushes both droplets independently toward steady positions near the pressure antinodes; and, (b) the subsequent slow approach toward collision due to the combination of the secondary acoustic and van der Waals forces. Luo et al. [8] studied the single droplet motion and the coalescence law of binary droplets, which revealed that there exists an optimal acoustic intensity for droplets coalescence and the binary droplets show sinusoidal oscillation at the optimal acoustic intensity. These conclusions provide a fundamental understanding of the emulsion separation mechanism under ultrasonic standing wave field.

Based on empirical studies and numerical simulations, a variety of factors impacting separation efficiency have been investigated, including acoustic parameters, such as the type of acoustic field [9,10], acoustic intensity [11,12], frequency and irradiation time [13];

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properties of continuous phase and dispersed phase [14], such as viscosity, interfacial tension, water content, and other operating conditions [15]. Nii et al. [16] investigated the effects of acoustic intensity and irradiation time on emulsion separation efficiency and quantitatively monitored the progress of the separation with the optical absorbance. The effective separation was attained with a low acoustic power input and a long irradiation time. Check et al. [17] used two-stage ultrasonic irradiation for the dehydration and desalting of the heavy crude oil, and found that the settling time required to separate emulsion was remarkably shortened. Garcia-Lopez et al. [18] studied the separation characteristics of mineral and motor oil emulsion. The experimental results indicated that excessive acoustic power would cause acoustic cavitation and acoustic streaming. However, the acoustic cavitation threshold is unclear and needs further study. Trujillo et al. [19] summarized the physical principles and the mathematical models of droplets separation, and proposed that one of several critical problems of acoustic separation was how to control the disturbance of acoustic streaming. Acoustic cavitation [20] and acoustic streaming [21–24], which are the two non-linear phenomena associated with the acoustic wave in the liquid, have a serious impact on the acoustic separation process [25]. Nanoemulsions can be produced by acoustic cavitation [26–32]. The acoustic cavitation causes localized intense turbulence and shear forces that produce violently and asymmetrically imploding bubbles and cause micro jets which effectively break dispersed droplets [33–35].

In this paper, the ultrasonic standing wave field was established and verified firstly. Then, the effects of irradiation time, acoustic intensity, frequency, oil viscosity and oil-water interfacial tension on the separation characteristics of emulsion were investigated and discussed in details. These results would provide insights into the fundamental mechanism of separation process and provide guidance for setting the optimum conditions for emulsion separation.

2. Theory

Acoustic radiation force was first investigated by Kundt et al. [36]. Later, this force was described by King [37] for incompressible droplets in details. Considering the effect of droplet compressibility, Yosioka and Kawasima [3] supplemented this analysis which was further developed by Gor'kov [38]. The radiation force acting on a droplet is a second-order nonlinear force and is induced by a non-uniform flux of momentum around the droplet [39]. The time-averaged primary radiation force along with the direction of the propagating wave in an ideal standing wave field is given by [6]

$$F_{1,\mathrm{ac}} = 4\pi k r^3 E_{\mathrm{ac}} K_s(\tilde{\rho}, \sigma)\sin(2kz) \tag{1}$$

where r is the droplet radius, $k = 2\pi/\lambda$ is the wave number, λ is the wavelength in the continuous phase, and z is the position of the droplet relative to the pressure node.

E_{ac} is the time-averaged energy density [40]

$$E_{\mathrm{ac}} = \frac{P_a^2}{4\rho_o c_o^2} \tag{2}$$

where P_a is the acoustic pressure amplitude, ρ_o is the density of continuous phase, and c_o is the sound speed through the continuous phase.

Droplets with an acoustophoresis coefficient $K_s < 0$ will be driven toward the pressure antinodes. On the contrary, when $K_s > 0$, the droplets will be driven toward the pressure nodes. The acoustophoresis coefficient K_s takes the form:

$$K_s(\tilde{\rho}, \sigma) = \frac{1}{3}\left[\frac{5\tilde{\rho} - 2}{2\tilde{\rho} + 1} - \frac{1}{\tilde{\rho}\sigma^2}\right] \tag{3}$$

where $\tilde{\rho}$ is the density ratio of the droplet to the continuous phase, and σ is the sound speed ratio of the droplet to the continuous phase.

As droplets are subjected to a one-dimensional acoustic field, the droplets will scatter that field and the interaction of droplets with the scattered field from a neighboring droplet gives rise to secondary acoustic forces [41,42]. The secondary acoustic force between two droplets is given as [43]

$$F_{2,\mathrm{ac}} = \frac{8\pi k^2 E_{\mathrm{ac}}}{9}\left(1 - \frac{1}{\tilde{\rho}_1\sigma_1^2}\right)\left(1 - \frac{1}{\tilde{\rho}_2\sigma_2^2}\right)\frac{r_1^3 r_2^3}{l^2} \tag{4}$$

where l is the center-to-center distance between the droplets, the subscripts 1 and 2 represent two droplets.

Generally, the magnitude of secondary acoustic force is at least one order smaller than that of the primary radiation force immediately after the acoustic field is applied. But as the droplets are gathered near the pressure nodes (or antinodes) due to the primary radiation force, the secondary acoustic force becomes significant and droplets agglomeration is enhanced.

The net effect of the gravity and buoyancy acting on a droplet is given by

$$F_g = \frac{4}{3}\pi(\rho_w - \rho_o)r^3 g \tag{5}$$

where F_g is the net gravity, ρ_w is the density of droplet and g is the gravitational acceleration.

The drag force F_μ acting on the droplet is given by the Hadamard-Rybczynski formula [44]

$$F_\mu = 4\pi\left(\frac{1 + 3\tilde{\mu}/2}{1 + \tilde{\mu}}\right)\mu_o r v \tag{6}$$

where $\tilde{\mu}$ is the viscosity ratio of the droplet to the continuous phase, μ_o is the viscosity of the continuous phase, and v is the velocity of the droplet.

Under the assumption that inertial forces are negligible, the balance of primary radiation force, net gravity and drag force is given as:

$$F_{1,\mathrm{ac}} + F_g + F_\mu = 0 \tag{7}$$

Substituting Eqs. (1), (5) and (6) to Eq. (7), the droplet velocity v is given by: [45]

$$v = \frac{M(1 - N_{\mathrm{ac}}^2)}{N_{\mathrm{ac}}^2\cos(2L) - N_{\mathrm{ac}}\sqrt{1 - N_{\mathrm{ac}}^2}\sin(2L) + 1} \tag{8}$$

where

$$N_{\mathrm{ac}} = \frac{3kE_{\mathrm{ac}}K_s(\tilde{\rho}, \sigma)}{(\rho_w - \rho_o)g}$$

$$M = \frac{r^2(\rho_w - \rho_o)g}{3\left(\frac{1 + 3\tilde{\mu}/2}{1 + \tilde{\mu}}\right)\mu_o}$$

$$L = kMt\sqrt{1 - N_{\mathrm{ac}}^2} + \tan^{-1}\left(\frac{\tan(kz_0) + N_{\mathrm{ac}}}{\sqrt{1 - N_{\mathrm{ac}}^2}}\right)$$

and z_0 is the position of the droplet relative to the pressure node at $t = 0$.

Fig. 1 displays the sketch of droplets separation mechanism under acoustic standing wave field. The primary radiation force (blue solid line in Fig. 1) and its direction (black solid arrow in Fig. 1) are also displayed. The droplets' trajectory consists of transient and steady phases. The transient phase is described as follows: the droplets migrate to the pressure nodes due to the primary radiation force. The steady phase is described as follows: the droplets gather in the banding zone (green zone in Fig. 1) under the balance of the net gravity F_g and the primary radiation force $F_{1,\mathrm{ac}}$. The aggregated droplets collide and coalescence due to the secondary acoustic force $F_{2,\mathrm{ac}}$.