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Review

Phase separation technology based on ultrasonic standing waves: A review

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ABSTRACT

The current understanding and developments of phase separation technology based on ultrasonic standing waves (USWs) are reviewed. Most previous reviews have focused on microscale applications of this technology in the fields of biological materials and food processing. This review covers different applications of ultrasonic separation technology, especially in petrochemical industry. The kinetic mechanism of ultrasonic, design of reactors, separation principles, and related applications are discussed in detail. We lay special stress on the motion characteristics of particles in USWs. According to the particle numbers, particle properties, and frequency characteristics, the separation principles are reasonably categorized as: (1) Bands effect; (2) Acoustophoretic coefficient; (3) Particle density; (4) Sweep frequency. Diverse separation principles improve the universality of ultrasonic separation technology. However, acoustic streaming and acoustic cavitation are two of the main challenges in the application of ultrasonic separation. Based on the current research, the future research can focus on the following aspects: (1) Explore the mechanism of ultrasonic demulsification; (2) Establish unified evaluation criteria for acoustic separation systems; (3) Develop the basis for determination of acoustic cavitation and non-cavitation.

1. Introduction

Phase separation technology has a significant impact on the development of many industries. Developing an efficient, energy-saving and environment-friendly separation method has been the main work of engineers, and is also an urgent demand for industrial applications. It is difficult for the traditional separation methods to meet the harsh requirements in some research fields, such as biological cell separation, emulsion separation, fat separation, etc. Ultrasonic separation method has been widely researched because of its simplicity, high-efficiency and environment-friendliness.

Chladni patterns [1] have attracted increasing attention from researchers because the acoustic waves have the ability to move particles directionally. Several studies have shown that the motion of particles is predictable and controllable under the action of ultrasonic standing waves, which is known as the displacement effect of standing waves. Therefore, scholars of different fields have carried out extensive research on this separation method. Nowadays, phase separation methods based on USWs are widely used in food processing [2], biological [3], pharmaceutical [4], environmental [5], and petrochemical industries [6].

The directional motion of particles under the action of USWs is known as acoustophoresis [7], which is similar to the electrophoresis of particles in an electrostatic field [8]. Due to the differences in density and compressibility between the particle and continuous phase, acoustic standing waves can promote homogeneously-suspended particles to aggregate at pressure nodal or anti-nodal planes in continuous phase [9]. Direction of particle motion depends on the sign of acoustophoretic coefficient [10]. In addition, this method can achieve non-contact separation, making it more suitable for precise and gentle separation. The acoustophoresis phenomenon is applicable to all kinds of dispersions. Table 1 shows the common characterization of dispersions according to the physical state of the dispersed phase and the continuous phase.

Trujillo et al. [12] reviewed the separation of suspensions and emulsions via USWs. However, the review was mainly focused on the applications of USWs in microfluidic separation. Few researchers have systematically discussed this technology focusing on large scale systems, especially in the field of petrochemical separation.

This review focuses on the phase separation technology based on USWs, which is carefully organized into six sections. Section 2 begins with the background theory and illustrates the particle separation process under the action of USWs. Section 3 provides a guide to design reactors based on USWs. Sections 4 and 5 analyze and summarize the

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Table 1
Different dispersions [11].

Dispersed phase	Continuous phase	
	Liquid	Gas
Solid particle	Suspension	Smoke
Droplet	Emulsion	Mist
Gas	Dispersed bubble	

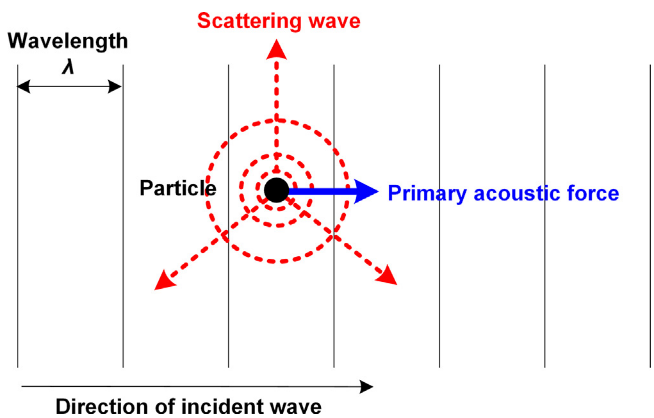

Fig. 1. Schematic diagram of primary acoustic force acting on the particle in USWs.

separation principles and corresponding applications, respectively. The final section discusses the main challenges of ultrasonic phase separation technology and future research recommendations.

2. Background theory

2.1. Primary acoustic force

The schematic diagram of primary acoustic force acting on the particle in USWs is shown in Fig. 1. The particle will stimulate the scattering wave in USWs. Due to non-uniform of acoustic pressure distribution around the particle, the particle will be subjected to primary acoustic force under the superposition field of standing wave and scattering wave.

Primary acoustic force was first investigated by Kundt et al. [14]. Later, this force was described by King [15] for incompressible particles in detail. Considering the effect of the compressibility of particles, Yosioka and Kawasima [16] supplemented this analysis and it was further developed by Gor'kov [17]. The radiation force acting on a particle is a second-order nonlinear force and is induced by a non-uniform flux of momentum around the particle [18]. The time-averaged primary acoustic force along with the direction of the propagating wave in an ideal standing wave field is given by: [19]

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

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

E_{ac} is the time-averaged energy density [20] which can be expressed as follows:

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

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

The acoustic intensity I is often used to represent the magnitude of acoustic energy. The relationship between E_{ac} and I is given as: [21]

$$I = 2E_{ac}c_o \tag{3}$$

The acoustophoretic coefficient K_s takes the form: [20]

$$K_s(\tilde{\rho}, \sigma) = \frac{1}{3}\left[\frac{5\tilde{\rho}-2}{2\tilde{\rho}+1} - \frac{1}{\tilde{\rho}\sigma^2}\right] \tag{4}$$

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

Particles with $K_s < 0$ are driven towards pressure antinodes. On the contrary, when $K_s > 0$, the particles are driven towards pressure nodes. Particles will aggregate into bands when the acoustic intensity exceeds a threshold level [22,23].

Fig. 2 shows the primary acoustic force, which is calculated as a function of frequency and particle radius. An acoustophoretic coefficient K_s of 0.205 and acoustic pressure amplitude P_a of 1.5×10^4 are used in the calculation. The primary acoustic force increases with the increase in particle radius and frequency.

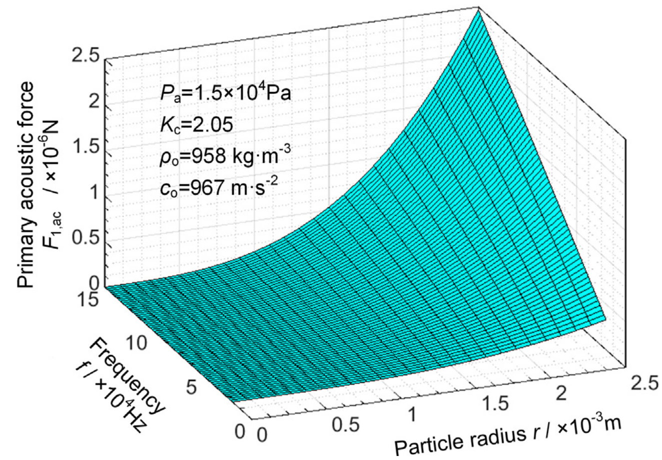

Fig. 2. Primary acoustic force calculated as a function of frequency and particle radius.

The primary acoustic force acting on the particles in the continuous phase can also be calculated from the force potential $\langle U \rangle$, which is usually used in finite element simulations (COMSOL, MATLAB, FLUENT, etc.). The formula is convenient for computer calculation with various analysis methods. The primary acoustic force is given as: [13]

$$F_{1,ac} = -\nabla\langle U\rangle \tag{5}$$

$$\langle U\rangle = 2\pi r^3 \rho_o \left(\frac{1}{3}\frac{\langle p^2\rangle}{\rho_o^2 c_o^2} f_1 - \frac{\langle v^2\rangle}{2} f_2\right) \tag{6}$$

$$f_1 = 1 - \frac{\rho_o c_o^2}{\rho_w c_w^2} f_2 = 2\frac{\rho_o - \rho_w}{2\rho_o + \rho_w} \tag{7}$$

$\langle p^2\rangle$ and $\langle v^2\rangle$ are the mean square fluctuations of the pressure and velocity of the ultrasonic standing waves, respectively.

2.2. Secondary acoustic force

Owing to the primary acoustic force, particles move to pressure nodes. After the formation of particle bands, particles approach each other gradually and the interparticle forces tend to be significant. Following the method developed by Yosioka and Kawasima [16], Zheng et al. [24] proposed the secondary acoustic force. Considering the superposing contributions of rigid-sphere and compressibility, the secondary acoustic force was expressed by Crum as: [25]

$$F_{2,ac} = 4\pi r_1^3 r_2^3\left[\frac{(\rho_w-\rho_o)^2(3\cos^2\theta - 1)}{6\rho_o l^4}v^2(z) - \frac{\omega^2\rho_o(\beta_w-\beta_o)^2}{9l^2}p^2(z)\right] \tag{8}$$