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Short communication

Simulation of the formation and characteristics of ultrasonic fountain

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ABSTRACT

In order to design an ultrasonic apparatus with a high throughput rate for generating atomization, the mechanism of fountain characteristics is important because the throughput rate of the ultrasonic atomization is decided by the area of the fountain surface. The formation of the fountain can be numerically studied by taking into account the effect of surface tension and radiation pressure. We have investigated the shape of the fountain with different ultrasound parameters or different kinds of solutions. When the amplitude of input sound pressure is higher than 1.3×10^5 Pa, the liquid separates from the ultrasonic fountain after irradiation for a very short period. It is further found that the area of the fountain surface increases with the concentration of the ethanol due to its low surface tension, density and sound speed. Finally, we discuss the difference between the ultrasonic fountain and the pump fountain, and find that the velocity field in the reactor induced by the pump is higher than that by the ultrasound.

1. Introduction

When a beam of ultrasound wave passes through a liquid and directed at the liquid–air interface, a fountain arises from the liquid surface and droplets are generated from the fountain [1]. This phenomenon is known as ultrasonic atomization. Nowadays, by the development of ultrasonic technique, ultrasonic atomization has been widely used in air humidifiers, aroma diffusion, fuel combustion, inhalation drug delivery and nanoparticle synthesis [2]. Compared with the conventional pneumatic atomizers, high pressure and orifice is not required in this simple method and the size of droplets is microns or below with a narrow size distribution. Furthermore, size of liquid droplets is tunable by varying the ultrasonic frequency and physical properties of liquids [3].

Ultrasonic atomization has been experimentally investigated by many researchers. It is found that ultrasonic atomization is powerful in enrichment for solutions [4,5] and size-selective separation [3]. The droplet size distributions with different ultrasonic parameters [6] and different kinds of solutions [7] have been investigated. It is proved that the throughput rate of ultrasonic atomization is determined by the area of the vibrating surface of the fountain. However, the selection of the ultrasound frequency to increase atomization efficiency is very difficult because a high frequency of the transducer should lead to the diminishing of the fountain area. At low frequencies, the pressure amplitude is insufficient to achieve liquid sheet or disintegration [8]. In order to enhance the throughput rate of ultrasonic atomization, it is important to understand the mechanism of formation for the acoustic fountain in detail. In fact, the thermal behavior in an ultrasonic fountain with different materials submitted to ultrasound has been experimentally investigated by using an infrared camera [9]. Due to the importance of the fountain area by ultrasonic irradiation, we experimentally investigated the fountain characteristics in our previous papers [10,11]. It is found that the area of the fountain is related to the intensity and the frequency of the ultrasound.

Theoretically, many researchers have investigated the distribution of the acoustic pressure and the radiation pressure in a reactor for generating ultrasonic atomization. In order to optimize the throughput rate of ultrasonic atomization, the effect of the longitudinal oscillations in ultrasonic transducer on the throughput rate of ultrasonic atomization has been theoretically investigated [12]. Rudenko et al. [13] and Kamakura et al. [14] respectively investigated the acoustic radiation force and acoustic streaming induced by a focused Gaussian beam theoretically and numerically. The acoustic radiation pressure on a boundary produced by a beam of ultrasound has been also investigated [15]. One step more, the geometry of the fountain has been described by considering the gravity and the acoustic radiation pressure [16]. Laborde et al. numerically simulated the cavitation bubbles distribution in a sonoreactor. Here, the acoustic streaming and the convective flow have been taken into account. The acoustic fountain formation due

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to the radiation force that acts on the liquid–air interface is calculated [17]. However, the surface tension has never been considered in the formation of the ultrasonic fountain. Although the throughput rate of ultrasonic atomization has been widely investigated, the theoretical or numerical work is seldom carried out. Since the throughput rate is determined by the surface area of the fountain, the simulation of the ultrasonic fountain is necessary to understand the mechanism of the fountain formation.

In this paper, as a first step towards to understand the mechanism of the ultrasonic atomization, ultrasonic fountain has been numerically simulated and the results are compared with the experimental results. The influences of the sound pressure on the formation of ultrasonic fountain have been investigated in the various solutions. The differences between ultrasonic fountain and pump fountain are discussed.

2. Theoretical

In order to calculate the acoustic pressure distribution in a reactor, the inhomogeneous Helmholtz equation is used

$$\nabla\left(-\frac{1}{\rho_c}\nabla p\right)-\frac{\omega^2}{\rho_c c_c^2}p=0, \tag{1}$$

where p represents the acoustic pressure. The angular frequency ω is defined as $\omega = 2\pi f$, where f is the ultrasonic frequency.

The acoustic absorption coefficient is not directly related to the physical properties of the media. It is expressed by the complex density ρ_c and the complex sound speed c_c as follows,

$$\rho_c=\frac{Z_c k_c}{\omega},\, c_c=\frac{\omega}{k_c}. \tag{2}$$

Here, the complex wave number k_c and the impedance Z_c are shown as

$$k_c=\frac{\omega}{c_s}-i\alpha \text{ and } Z_c=\rho_0 c_s, \tag{3}$$

where α is the absorption coefficient of the media, c_s and ρ_0 denote the sound speed in the media and the density of media, respectively.

The boundary condition of transducer surface is set as pressure. The pressure distribution is decided from the experimental data measured by a hydrophone. The liquid surface is set as the impedance boundary which indicates the reflection property at the interface between two materials. It can be expressed as

$$\vec{n}\frac{1}{\rho_c}\nabla p+\frac{1}{Z_e}\frac{\partial p}{\partial t}=0, \tag{4}$$

where $Z_e = \rho_e c_e$ is the acoustic input impedance for the external domain, and ρ_e and c_e are the density and the sound speed of the external domain, respectively.

The side wall of the reactor is made of quartz glass. The temperature is set as ambient temperature (293 K). The Young's modulus, density and the Poisson ratio of the quartz glass are 7.4×10^{10} Pa, 2200 kg/m^3 and 0.3, respectively. The liquid is set as water (density: 1000 kg/m^3, sound speed: 1482 m/s) unless claimed. Geometry with boundary and domain conditions for simulation of pressure distribution in the reactor is shown in Fig. 1(a).

In order to calculate the formation of the acoustic fountain, the liquid flow distribution in the reactor should be obtained. The liquid flow field can be calculated by the momentum transport equation and the continuity equation:

$$-\nabla\cdot(-p_L\vec{I}-\tau)+\rho_0(\vec{u}\cdot\nabla)\vec{u}=\vec{F}, \tag{5}$$

$$\nabla\cdot\vec{u}=0, \tag{6}$$

where $\tau=-\mu(\nabla\vec{u}+(\nabla\vec{u})^T)$ is the viscous stress tensor. Superscript T denotes the transpose matrix. $\vec{I}$, μ, $\vec{u}$ and p_L indicate the unit matrix, the particle velocity, liquid viscosity and pressure in the liquid, respectively. $\vec{F}$ represents the volume force. According to our previous paper [18], the flow field induced by ultrasonic attenuation during propagation can be expressed as the form of volume force:

$$F=\frac{2\alpha}{\rho_0 c_s^2}|p|^2. \tag{7}$$

The no slip wall is used as the boundary condition to specify a stationary solid wall and the transducer surface. This boundary condition is prescribed as

$$\vec{u}=0. \tag{8}$$

In order to consider the formation of a fountain, the liquid surface is set as an external fluid interface with a free deformation. This boundary condition is represented as

$$n\cdot T=p_{in}-\sigma(\nabla_t\cdot\vec{n})\vec{n}-\nabla_t\sigma, \tag{9}$$

where σ is the surface tension. The inner pressure (p_{in}) exerted on the boundary is calculated as

$$p_{in}=p_r+p_0, \tag{10}$$

where p_0 shows the atmosphere pressure. The radiation pressure p_r is calculated as [19]

$$p_r=\frac{p^2}{2\rho_0 c_s^2}. \tag{11}$$

Geometry with boundary and domain conditions for simulation of flow field is shown in Fig. 1(b). Since the pressure and the liquid flow velocity near the corner of the reactor are low, the simulation is conducted in cylindrical coordinates and with axial symmetry. In simulation, the maximum mesh size is limited to 2×10^{-4} m.

It should be noted that a discontinuity of the geometry is unable to be calculated due to the limitation of the FEM for the liquid flow calculation. Thus, the atomization procedure due to the break of the fountain is not calculated in this study. Moreover, the temperature rise is not obvious since the atomization does not occur. Thus, the phase change is neglected in the simulation.

3. Experimental

Experiments are carried out in a rectangular vessel [$0.05\times0.05\times0.08$ (height) m^3] made of quartz glass with a disk-shaped transducer (radius: 0.005 m) mounted at the central position of the vessel bottom. The thickness of the quartz glass is 0.002 m. In experiment, the height of liquid is fixed at 0.01 m. In order to understand the pressure distribution on the transducer plate, a hydrophone (ONDA Model, HNP-400, EASTEK CORPORATION) is used to measure the pressure amplitude on the transducer plate in a pulsed wave mode. Fig. 2 shows the experimental data (scatter) of pressure distribution on the transducer plate. Because the obtained point-by-point data are discontinuous, the Gaussian distribution (solid-line curve) is assumed to fit the data.

4. Results and discussion

4.1. The formation of the ultrasonic fountain

The formation of the ultrasonic fountain is investigated. The amplitude of the emitted pressure wave at the center of the transducer plate is 9×10^4 Pa. Fig. 3 shows the simulation results of the variation of the fountain with different irradiation times. The color