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Influence of ultrasound power on acoustic streaming and micro-bubbles formations in a low frequency sono-reactor: Mathematical and 3D computational simulation

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ABSTRACT

This paper aims at investigating the influence of ultrasound power amplitude on liquid behaviour in a low-frequency (24 kHz) sono-reactor. Three types of analysis were employed: (i) mechanical analysis of micro-bubbles formation and their activities/characteristics using mathematical modelling. (ii) Numerical analysis of acoustic streaming, fluid flow pattern, volume fraction of micro-bubbles and turbulence using 3D CFD simulation. (iii) Practical analysis of fluid flow pattern and acoustic streaming under ultrasound irradiation using Particle Image Velocimetry (PIV). In mathematical modelling, a lone micro bubble generated under power ultrasound irradiation was mechanistically analysed. Its characteristics were illustrated as a function of bubble radius, internal temperature and pressure (hot spot conditions) and oscillation (pulsation) velocity. The results showed that ultrasound power significantly affected the conditions of hotspots and bubbles oscillation velocity. From the CFD results, it was observed that the total volume of the micro-bubbles increased by about 4.95% with each 100 W-increase in power amplitude. Furthermore, velocity of acoustic streaming increased from 29 to 119 cm/s as power increased, which was in good agreement with the PIV analysis.

1. Introduction

Use of ultrasound energy (a combination of sinusoidal pressure waves with a frequency of >20 kHz) in a system affects the pressure balance within the media, producing a large number of micro-bubbles and micro jets in micro scale and creating a special fluid flow pattern in macro scale. Furthermore, a large number of localized over-heated regions named as hotspots are produced by vigorous collapses of these bubbles. Therefore, regions with pressure of about 1000 atm and temperature of 10,000 K are generated within only a microsecond. Generally, the formation, growth, and implosive collapse of microbubbles are known cavitation. These phenomena may increase mixing intensity and mass transfer within the system. Hence, ultrasound is frequently and successfully employed in liquid mixing, wastewater treatment, extraction, crystallization, emulsification, chemical reactions and etc. Many researchers have also studied such applications. However, most of the previous researches have only focused on modality, quality of heat propagation and temperature profile within the system. Analytical or simulation analysis of ultrasound irradiation and acoustic streaming have rarely been investigated [1–3] and this is one of the major restrictions in optimization of ultrasound applications in industries.

The numerical simulation of acoustic streaming was initiated and accomplished by Rayleigh and Nyborg [4] who indicated that acoustic streaming could be a second-order nonlinear result of acoustic wave propagation. They calculated the streaming through Navier–Stokes equation and neglected the inertia term (convective acceleration term). Later, Lighthill established a model to show that acoustic streaming took the form of inertia dominated turbulent jet at powers above 4×10^{-4} W. In the Lighthill [5] model, the horn tip is an inlet where all the acoustic energy absorbed by the liquid is converted into turbulent motion or jet. Besides, Lighthill [6] reported that neglecting the inertia term of the Navier–Stokes equation was true only for “creeping motions” where there were very slow flows with Reynolds numbers <1 and low power.

Based on the theory presented by Lighthill on the Navier–Stokes and κ–ε turbulent equations, Trujillo et al. [7] tried to simulate the acoustically induced ultrasound streaming at powers higher than or equal to 30 W. Nastac [8] also developed an ultrasound modeling approach to predict the acoustic streaming and ultrasonic cavitation. His approach was based on the numerical solution of Lighthills’s acoustic analogy, fluid flow and heat transfer equations

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Nomenclature

Cp_g	specific heat [J/kg]
F_v	vapor mass fraction [–]
F_g	noncondensable gases mass fraction [–]
F	force [kg m/s^2]
F_{vap}	empirical constant [–]
F_{cond}	empirical constant [–]
G	gravity acceleration [m/s^2]
I_{us}	ultrasound intensity [W/cm^2]
K_g	thermal conductivity [W/m K]
Pe	Péclet number [–]
P	driving pressure [kg/m s^2]
P_{gas}	internal pressure of bubbles [kg/m s^2]
p_0	driving pressure [kg/m s^2]
P	local far-field pressure [kg/m s^2]
P_{sat}	saturated vapour pressure [kg/m s^2]
R	bubble radius [m]
R_c	condensation rates [kg/s m^3]
R_e	evaporation rates [kg/s m^3]
T_b	bubble temperature [K]
T_0	ambient temperature [K]
u	liquid velocity [m/s]
Γ	diffusion coefficient [m^2/s]
k	turbulent kinetic energy [m^2/s^2]
ε	turbulent dissipation rate [m^2/s^3]
μ_t	turbulence viscosity [kg/m s]
ρ	fluid density [kg/m^3]
σ	surface tension [N/m]
ν	shear viscosity [kg/m s]
γ	polytropic coefficient [–]
Γ	adiabatic coefficient [–]
χ_g	thermal diffusivity [m^2/s]
α	volume fraction [–]
λ	evaporation rate [kg/s m^3]
μ	fluid viscosity [kg/m s]

along with mesoscopic modeling of grain structure. He applied this model to control the solidification microstructure and improve the quality of cast ingots under ultrasound irradiation. He reported that the predicted acoustic streaming was strong while the ultrasonic cavitation was relatively small and meaningless in solidification process.

The velocity potential of the far-field and near-field of these micro bubbles also named as cavitation bubbles should be modified in order to improve the Rayleigh model. This is considered in the Rayleigh–Plesset model using radial sound wave emitted from the bubbles. Niazi et al. [9] focused on pressure and temperature distribution in acoustic cavitation based on the Rayleigh–Plesset theory. Wave propagation was assumed linear and shear stress was ignored in their simulation. Finally, they successfully predicted the collapse temperature (3200 K) and pressure (3000 atm) in the active cavitation zones of a liquid bulk.

However, sound radiation enhances the order of the Rayleigh–Plesset equation. Therefore, Rayleigh–Plesset model has an unstable spurious solution which grows exponentially in time and causes numerical errors. In order to eliminate this problem, Keller and Miksis suggested calculating $d^2/dt^2\left(R^2\dot{R}\right)$ by the Rayleigh equation and inserting the value into the Rayleigh–Plesset equation. A more complex model for characterizing bubble dynamics using the Rayleigh–Plesset equation was proposed by van Wijngaarden [10]. This model is able to represent transient shock waves in a bubbly mixture by capturing inertial effects. Commander and Prosperetti [11] established an equation for wave propagation in a bubbly liquid by adding a nonlinear term to the model presented by Wijngaarden [10] to account for the damping effect of bubbles caused by thermal, viscous and acoustic effects. Jamshidi et al. [12] added three different assumptions to the model in order to demonstrate the sensitivity of the Wijngaarden model: (i) a linear wave with a constant volume fraction of bubbles; (ii) a linear wave without consideration of bubbles; and (iii) a linear wave with an assumed linear relationship between the acoustic pressure amplitude and the volume fraction of bubbles. They reported that acoustic excitation/cavitation should be utilized as a source term for the momentum transfer since micro bubbles significantly affected wave propagation. This analytical method involved homogenous/inhomogeneous Helmholtz equation, as employed by the other researchers who had focused on the effects of system hydrodynamic on acoustic streaming in low/high frequency low-power sonoreactors [13,14]. In two other works, Rahimi et al. [15] and Liu et al. [16] used a similar model to investigate acoustic streaming in a high-frequency sono-reactor and an airlift sonobioreactor by using CFD simulation. Both substituted the plane form of sound pressure waves using the Helmholtz equation with compressible Navier stocks equations along with the Rayleigh–Plesset equation. Recently, Jiao et al. [17] have investigated the influence of ultrasound irradiation on mass transfer coefficient by using the same model along with the inhomogeneous Helmholtz equation. They did not report any original graph from their simulation results. However, they reported that mass transfer coefficient increased with temperature, ultrasound power and frequency but decreased with decreasing transducer diameters and distance between the reactors and ultrasound sources.

However, analysis of ultrasonic wave distribution in liquid media and generation of micro bubbles are challenging since not all phenomena are quantified and well understood [10].

Generally, in mathematical modelling of the mechanic of the bubble's interior, different approaches and corresponding models can be employed.

Assuming that there is a full-compressible gas dynamic in the bubble, the motion of gas should be described by the Navier–Stokes equation and equations of mass and energy. The boundary conditions at the moving bubble wall $r = R(t)$ can be predicted by either Rayleigh–Plesset equation or fluid-dynamic equations. According to the aforementioned discussion, three analytical approaches can be employed in which the bubbles are considered spherically symmetric:

i. Inviscid models, which do not predict the effects of total energy balance of the bubble.
ii. Dissipative models, which present some estimation of heat conduction and energy-loss.
iii. Dissipative models which include phase change, in which the water vapour inside the bubble plays an important role in regulating the bubble heat transfer across the bubble wall.

However, when the sophisticated interplay of physical effects inside a bubble is involved, spatial inhomogeneities inside the bubble are not very pronounced. Therefore, in the other approach, it is assumed that there is a uniform bubble interior and thus