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A comparative fluid flow characterisation in a low frequency/high power sonoreactor and mechanical stirred vessel

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ABSTRACT

This study aims at analysing the jet-like acoustic streaming generated under low-frequency and high-power ultrasound irradiation and comparing it with fluid streaming generated by traditional mechanical mixing. The main characteristics of fluid flow, which include radial, axial and tangential terms of velocity and their effects on fluid flow pattern, pressure distribution, axial mixing time and turbulence intensity were considered at different power inputs. Both 3D CFD simulation and Particle Image Velocimetry (PIV) were used in this study. The CFD results indicated that the jet-like acoustic streaming reached the velocity magnitude of 145 cm/s at 400 W, which reduced the mixing time to 1.38 s. However, the minimum mixing time of 3.18 s corresponding to the impeller rotational speed of 800 RPM was observed for mechanical stirring. A uniform axial flow pattern was generated under ultrasound irradiation whereas the tangential flow pattern was more prominent in the stirred vessel. Besides, the highest turbulence was observed in the vicinity of the ultrasound transducer and impeller with the values of 138% and 82% for the ultrasonicator and stirred vessel, respectively. The predicted fluid flow pattern under ultrasound irradiation was in a reasonable agreement with that obtained from PIV, with a reasonable accuracy.

1. Introduction

Recently, high-power ultrasound irradiation has been introduced as an effective method for accelerating industrial processes that require mixing. Apart from generation of "micro-streaming", "cavitation", "shock wave" and "hot spot" [1], the sinusoidal pressure waves (the elements of ultrasound energy) may also cause a flow within the fluid, which is known as acoustic streaming. Acoustic streaming is inversely proportional to the speed of sound in the medium and the medium viscosity but it is proportional to the surface area of the ultrasound source, ultrasound power intensity and attenuation coefficient of the liquid bulk.

Eckart streaming, Gedeon streaming and Rayleigh streaming are types of acoustic streaming [2,3]. Eckart streaming (also known as "quartz wind") originates from dissipation of acoustic energy in the fluid. It applies to large-scale phenomena and is generally found at frequencies above 1 MHz. Gedeon streaming is normally observed in thermoacoustic travelling wave systems. In Gedeon streaming, a non-zero net mass transport occurs because of the phase difference between acoustic velocity and density. Rayleigh streaming, which is the focus of this study, is a sub-category of boundary layer driven acoustic streaming. It originates from the action of Reynolds stresses developing in the boundary layer near a solid wall in the fluid. Rayleigh streaming appears as a pair of symmetrical vortices extending along a quarter wave length. The scale of this type of streaming is characterised by the acoustic wavelength. The theoretical analysis of acoustic streaming was introduced by Rayleigh [4], and further developed by Riley [5] and Lighthill [6] who emphasised ways to dissipate the acoustic energy to the momentum flux gradient. [3,7] produced among the most complete reviews of different categories of acoustic streaming and their characteristics. Moreover, another critical review of nonlinear acoustics was presented by Beyer [8].

Propagation of acoustic waves in gas mediums and determination of their effects i.e. pressure balance or fluid flow within the medium have been extensively studied. A brief review of the numerical and computational works on acoustic streaming in gas and liquid mediums (from 2000 to 2015) is presented in Tables 1 and 2, respectively. As observed, most of the numerical and analytical researches have been conducted in micro scales with one-dimensional tubes, rectangular-channels-enclosed tubes or chambers or open-scape gaps filled with an ideal gas.

This study presents a numerical and comparative study on propagation of acoustic streaming in the liquid medium inside a

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Table 1
Summary of investigated acoustic streaming under ultrasound irradiation in gas medium.

Geometry/media	Scheme/ coordinate	Parameters investigated	Objective/comments	Ref.
Air-filled rigid-walled tube	FDM/L	• Displacement amplitude • Pressure waveforms • Pressure amplitude • Pressure distribution	• Objective: Analysed the effect of non-linear standing wave • A multi-time-step, 6-point finite-numerical model was used • A second-order 1-D wave equation was considered • Conservation of the mass and momentum was considered	[17]
Air-filled rigid-walled tube	FDM/L	• Displacement waveforms • Pressure waveforms • Amplitude distribution	• Objective: Analysed the standing wave ranging from linear to strongly nonlinear and weak shock • The isentropic state equation of Tait-Kirkwood was used • Differential equation was solved without truncation • Mass and momentum conservation and absorption were considered	[18]
Rectangular channel	FDM/L	• Harmonic distortion of pressure field effects • Nonlinear attenuation of pressure field effects	• Objective: Evaluated the behaviour of strongly and complex nonlinear waves in thermoviscous fluid • Two-dimensional wave equation was considered • Redistribution effect of rms pressure inside a 2-D cavity was analysed	[19]
Enclosed chamber	FDM	• Pressure distribution inside the axisymmetric resonator • Pressure waveform at the centre of the reflector	• Objective: Analysed strongly nonlinear standing acoustic waves in axisymmetric cavities at complicated modes of axisymmetric cavities • The wave equation was directly obtained from the conservation laws and state equation, by assuming an irrotational fluid	[20]
Enclosed chamber	FDM	• Pressure distribution in • (i) 2-Dresonator • (ii) Axisymmetric resonator • (iii) Planes of the 3-dresonator	• Objective: Analysed nonlinear acoustic phenomena in high-power ultrasonic resonators • Possibility of modelling complicated nonlinear fields was illustrated in the one- two- and three-dimensional cases, including the axisymmetric configuration	[21]
An air-filled tube	FDM FVM/L	• Decomposition of the nonlinear pressure wave • Distribution of non-linear pressure wave • Displacement distribution	• Objective: Calculated the linear to strongly non-linear (weak shock) acoustic field inside a 1-D resonant cavity • 3 1-D numerical models in the time domain were employed i. Model 1. Implicit and conditionally stable model based on finite-difference schemes for both time and space derivatives ii. Model 2. Implicit and unconditionally stable model based on finite-difference scheme for time derivatives and a finite-volume scheme for approximating the spatial rates of change iii. Model 3. Based on the development of explicit techniques of high-order for the time integration	[22]
Enclosed chamber	FEM/Eu	• Acoustic radiated corresponds to resonance • far from resonance	• Objective: Analysed the partial differential equations of 3-D linear and nonlinear acoustics in absorbing fluids • A formulation for coupling the Kuznetsov equation with the equations of motion of an elastic solid was also derived	[23]
Cavitating flow	FVM/L	• Unsteady/steady shock waves • Nonlinear steepening of the waves • Damping effects	• Objective: Analysed the cavitating flow caused by the oscillating wall • The 1-D model was based on coupling of conventional continuity and momentum equation into a Rayleigh–Plesset equation • Damping of the bubble volume oscillations was restricted to a simple "effective" viscosity. Damping of the bubble volume oscillations was restricted to a simple "effective" viscosity	[24]
Two coaxial cylinders	FDM/Eu	• Waveform distortion • Shock wave formation	• Objective: Analysed the resonant oscillation of large amplitudes • The wave phenomena were characterised by the non-D geometrical parameter (R_i/R_o) and the acoustic Mach number	[25]
2 coaxial cylinders 2 concentric spheres	FDM/Eu	• Resonant oscillation with/without damping	• Objective: Analysed nonlinear shock free resonant oscillation of cylindrical and spherical standing waves • A cubic nonlinear equation for complex wave amplitude derived from the method of multiple scales	[26]
Liquid bubbly flows	FDM	• Acoustic pressure amplitude, variation of bubble volume	• Objective: Analysed strongly nonlinear acoustic wave propagation in a bubbly liquid by coupling the nonlinear bubble vibration equation with the wave equation • Equations were coupled through the force terms. Then, nonlinear vibration of bubbles and pressure harmonic distortion were coupled and feeding-up	[27]

Note: Eu: Eulerian, L: Lagrangian, FVM: Finite Volume Method, FDM: Finite Difference Method, FEM: Finite Element Method.

macro-scale sono-reactor. Two analyses were conducted: (i) numerical analysis of jet-like acoustic streaming using 3D CFD simulation; investigation of its effect on pressure balance within the system, axial, radial and tangential velocity compounds of liquid flow and mixing time; and (ii) practical analysis of jet-like acoustic streaming through Particle Image Velocimetry (PIV). The results were further compared with that of stirred vessel. In this study, the word "jet-like acoustic streaming" refers to high-speed fluid flow generated by ultrasound energy. This flow is initiated from the surface of the transducer toward the bottom of the vessel, exerting an impinging force on the liquid and pushing it to circulate in the vessel.

2. Experimental

2.1. Vessel configuration

A Pyrex cylindrical-vessel (Diameter: 7.4 cm and Height: 9.3 cm) was used as a sono-reactor in the study. It was equipped with an ultrasonic horn, a condenser (to prevent evaporated liquid