Abstract

Microbubbles, along with ultrasound waves (frequency > 20 kHz), play an essential role in biomedical and engineering applications, e.g. the medical imaging of internal organs, permeabilization of tissues, food/dairy processing, and nanoparticle generation. For example, tissue-permeabilization is made possible when oscillating bubbles in the presence of sound waves produce recirculation flows in the surrounding fluid (commonly known as microstreaming). Alongside, bubble-collapse generates high temperature and pressure that can help break down molecules into free radicals, triggering chemical reactions. But, there is a dearth of information and understanding of the relationship between these physical and chemical effects with applied power and frequency of the ultrasound, when the amount of dissolved gas is less and surplus gas intrusion from outside is checked.

This study addresses some of these issues through different experimental and numerical techniques. An experimental sonoreactor setup is fabricated to connect to a degassing setup and different frequency plates, thereby allowing the measurement of radical generation during bubble oscillation. Sonochemiluminescence and iodide dosimetry tests are conducted in the water in this setup without overheating or gas-intrusion. Again, the same liquid is transferred without any agitation to another in-house fabricated glass cell connected to a frequency transducer. This arrangement facilitates the levitation of a single bubble registering stable oscillation, thereby generating flow structures in the adjacent liquid. These are captured using particle image velocimetry (PIV) for different cases of applied power. In addition, computational fluid dynamics is performed to closely resolve these flow features and explore these phenomena over a broader applied power and frequency parameter space.

It has been observed from our chemical investigations in water that at low dissolved gas conditions, limited radical generation occurs that is governed by acoustic cavitation (not by "ordering effect") irrespective of applied frequency. Our results suggest the absence of undesirable chemical reactions under low gas conditions. The concept of "cavitation-free" radical generation in liquids is also clarified. The PIV experiments for a single bubble reveal that periodic shape evolution of the bubble takes place beyond an acoustic pressure amplitude, known as threshold for onset of surface or shape mode oscillation. This results in a mean motion in the adjacent liquid leading to unique flow patterns characteristic to microstreaming. Through CFD models, attempts have been made to understand these flow patterns exhibited by the formation of a certain number of vortices at the bubble interface due to the subharmonic behaviour of the bubble, where the radial amplitude varies periodically. Additionally, different significant modes of bubble oscillation are identified for various combinations of applied power and resting radii of the bubble. The modal decomposition of each such significant mode provides further insight into the zonal harmonics of bubble oscillation.

This phenomenon is simulated in inert and homogenous liquid nitrogen (LN2), where nitrogen vapour bubbles oscillate at relatively higher surface modes in the presence of ultrasound without any harmful reactions and simultaneously generate shear stresses. All these make controlled oscillating bubbles suitable for ultrasound-aided cryosurgical operations to remove cancerous tissues efficiently. Furthermore, a numerical investigation on the interaction of multiple bubbles in LN2 has been performed to gain insight into the erosive potential of bubbles on solids.

Keywords: bubble dynamics, acoustic cavitation, cavitation-free radical generation, oscillating bubbles, ultrasound standing wave, microstreaming