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Physical and chemical effects of acoustic cavitation in selected ultrasonic cleaning applications

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ABSTRACT

Acoustic cavitation in a liquid medium generates several physical and chemical effects. The oscillation and collapse of cavitation bubbles, driven at low ultrasonic frequencies (e.g., 20 kHz), can generate strong shear forces, microjets, microstreaming and shockwaves. Such strong physical forces have been used in cleaning and flux improvement of ultrafiltration processes. These physical effects have also been shown to deactivate pathogens. The efficiency of deactivation of pathogens is not only dependent on ultrasonic experimental parameters, but also on the properties of the pathogens themselves. Bacteria with thick shell wall are found to be resistant to ultrasonic deactivation process. Some evidence does suggest that the chemical effects (radicals) of acoustic cavitation are also effective in deactivating pathogens. Another aspect of cleaning, namely, purification of water contaminated with organic and inorganic pollutants, has also been discussed in detail. Strong oxidising agents produced within acoustic cavitation bubbles could be used to degrade organic pollutants and convert toxic inorganic pollutants to less harmful substances. The effect of ultrasonic frequency and surface activity of solutes on the sonochemical degradation efficiency has also been discussed in this overview.

1. Introduction

The interaction between bubbles and ultrasonic waves in liquids leads to a number of events that could be beneficially used in various applications [1–10]. Examples include synthesis of nanomaterials in aqueous and non-aqueous solutions either using primary and secondary radicals generated during acoustic cavitation or using the high temperature conditions within cavitation bubbles [1,4]. The physical effects of cavitation have been found useful in the generation of highly viscoelastic micelles [8] and deactivating pathogens in wastewater [10]. Depending upon the choice of ultrasonic frequency, microbubbles of various sizes present in a liquid could be forced to oscillate in response to alternating pressure waves of ultrasound. Such oscillations generate shear forces and enhance fluid flow and mass transfer that could be used in various chemical processes [1–13]. In addition, ultrasound itself generates mechanical agitation that could be used for specific applications that include cleaning of surfaces and various materials. For example, ultrasonic cleaning of microchips, jewellery and large engines is well known. In addition to the direct mechanical forces generated by ultrasound or oscillating bubbles, much stronger forces are generated when the oscillating bubbles cavitate under specific experimental conditions. The oscillating bubbles can be grown by rectified diffusion – after reaching a critical size range (resonance size range), they grow to a maximum size and violently collapse – the process known as acoustic cavitation [1,15,16]. It should be noted that the experimentally observed resonance size range is much smaller than that is theoretically predicted. For example, Levitated SBSL bubbles do collapse, despite their ambient radius (near 4 μm) is much smaller than resonance size [15]. Also, at low frequency, sub-resonant bubbles can also can undergo cavitation and generate physical and chemical effects discussed in this manuscript. The collapse of cavitation bubbles generates extreme temperature conditions within the bubbles – "hot spots" – highly reactive radicals are generated that could be used for redox reactions. High pressure generated within the collapsing bubbles is suddenly released into the liquid medium generating shockwaves that are helpful to enhance mass transfer and shear induced

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processes. In addition, other high energy physical processes such as, microstreaming, microjet formation, acoustic streaming, etc. are generated [1–13].

This overview focuses on the benefits of ultrasound-generated physical effects in cleaning of membranes used in dairy processing, destruction of pathogens in wastewater and degradation of organic pollutants in aqueous environment. Selected reports from our laboratories have been discussed in addition to providing new experimental data on the degradation of organic pollutants in aqueous solutions.

2. Physical effects of ultrasound in cleaning

As has already been mentioned, ultrasound and acoustic cavitation generate various physical effects in a liquid medium. Fig. 1 shows some of these effects schematically or photographically [13–16]. Ultrasonically vibrating surface can make the medium to oscillate back and forth causing a steady streaming away from the piezo location. This flow is compensated with inflow from the sides (Fig. 1a). Due to the liquid movement in opposite directions, acoustic streaming effect is generated (Fig. 1a) that is accompanied by significant mass transfer effects [13–16].

In addition, bubble streamers develop in an acoustic field due to the interaction between sound waves and gas bubbles as shown in Fig. 1b [14]. The development of oscillating gas bubble streamers is due to the primary and secondary Bjerknes forces where bubbles move at high speed towards pressure antinodes. Such microstreaming effect also generates a large amount of physical forces that could be used in various applications. Two other major forces generated during acoustic cavitation are microjets (Figs. 1c and 2) and shockwaves (Fig. 1d) [16]. When cavitation bubbles collapse asymmetrically, for example when collapsing near a boundary, high speed liquid jets are formed that are capable of pitting metal surfaces. When bubbles collapse symmetrically, high intensity shock waves are generated.

A recent study by Leong et al. [17] has shown the random movement of solid particles under the influence of oscillating bubbles. Using particle image velocimetry, streaming velocities around cavitation bubbles could be calculated to be about 100 μm/s. It should be noted that a much higher instantaneous velocities than this value could be expected. Fig. 2b probably shows the time-averaged (acoustic streaming) velocity, which can be a few orders of magnitudes smaller. The observed random motion near to the bubble may be too fast to measure for the PIV system.

Together, the physical forces shown in Figs. 1 and 2 have been found useful in cleaning applications.

2.1. Cleaning of ultrafiltration membranes

Several industrial processes use membrane separation processes. For example, ultrafiltration is a common technique used in dairy, biochemical and pharmaceutical industries [14]. Ultrafiltration is heavily used in dairy industry to concentrate whey proteins. Due to high solid loading, membranes used in such processes foul very quickly leading to a significant reduction in flux. In a conventional process, fouled membranes are removed, soaked in a strong alkaline solution containing detergents/surfactants, washed and re-used. In an industrial process, such cleaning procedures lead to production downtime and the use of expensive chemicals is undesirable from both economical and environmental contamination points of view. The use of ultrasound in membrane cleaning has been extensively studied by different groups [18–28]. Kentish and co-workers [18–21] used a laboratory cleaning bath for ultrasound-assisted cleaning of polymeric membranes fouled (pre-fouled as well as during filtration) by whey solutions. The experimental setup is shown in Fig. 3 [20]. A Minitan S unit containing a polysulfone flat sheet membrane was immersed in an ultrasonic bath to study the effect of ultrasound on cross-flow filtration efficiency.

Using the experimental setup shown in Fig. 3, flux enhancement by ultrasound was evaluated. By studying the permeate flux (6% w/w whey solution) in the absence and presence of ultrasound, authors could show that the use of ultrasound enhanced the flux by ~40–70% under various cross-flow rates (550–975 ml/min). Muthukumaran et al. [21] and Ho and Zydney [29] used a combined pore blockage/cake resistance model to fit experimental data and found that ultrasonication lowered the compressibility of protein deposits. They also observed that pore blockage is not significantly affected by sonication. The authors have also published detailed reviews of applications of ultrasound in membrane cleaning processes [14,18,19], where it has been noted based on the outcomes of several investigations that ultrasound increases membrane permeation by reducing the depth of foulant layer and by increasing turbulence in the concentration polarisation layer. They have also mentioned that the economic viability of ultrasonic cleaning of ultrafiltration membranes has not been considered in the literature. One of the main issues is the availability of custom made large scale ultrasonic equipment. Thus, despite extensive studies on ultrasonic cleaning of ultrafiltration membranes in lab scale, pilot scale or industrial scale processing has not been explored.

2.2. Destruction of pathogens

Water purification is another area where membrane filtration is heavily used, in particular to remove pathogens [30]. In order to see if ultrasound can be used to deactivate pathogens in drinking water, an effort was made to treat water contaminated with Cryptosporidium oocysts [31]. Cryptosporidium is a well-known pathogen that causes diarrhoea. Cryptosporidium oocyst is the

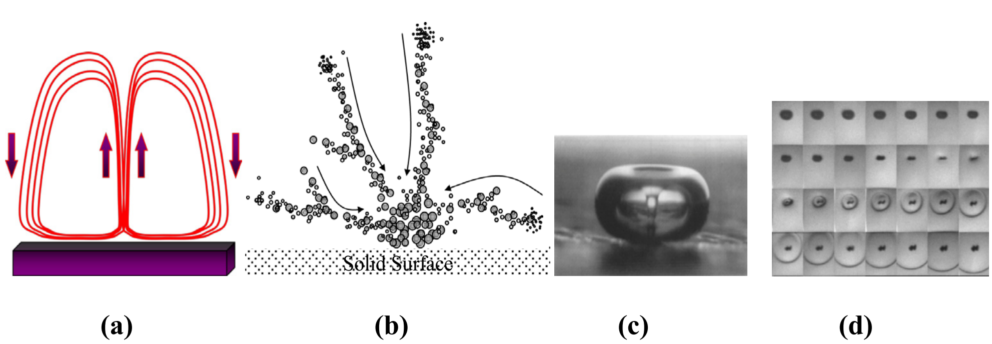

Fig. 1. (a) Acoustic streaming (oscillator is located at the bottom and liquid surface is at the top), (b) microstreamers, (c) microjet and (d) shockwaves generated by ultrasound and acoustic cavitation. Images adapted from Refs. [13–16].