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Energy changes during use of high-power ultrasound on food grade surfaces

Tirivaviri A. Mamvura, Sunny E. Iyuke, Anthony E. Paterson*

School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Wits, 2050, Johannesburg, South Africa

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ABSTRACT

The energy changes experienced during application of high-power ultrasound in cleaning biofilms from food-grade surfaces was investigated in this study. Laboratory scale experiments were conducted using 24 kHz ultrasound frequency with an ultrasonicator capable of operating in continuous mode at nominal ultrasound intensities up to 105 $W \cdot cm^{-2}$. There are different energy changes that occur during its use; however, three types of energy changes were monitored: electrical to acoustical to cavitation, and the efficiency of conversion rate from one form of energy to the other was determined to ascertain the effectiveness of the process. High-power ultrasound do not leave residual chemicals behind after treatment and they reach hidden spots near and/or welds where biofilms thrives. A Nexus hydrophone was used to determine the electrical input energy and the cavitation energy but the calorimetric method was used to determine the acoustical energy. Values obtained for electrical power density were against the rated maximum amplitude displacement to compare the error when using the hydrophone. Results showed that the energy conversion was low, on average 26% from electrical to acoustical energy and 9% from electrical to cavitation. However, the values were in line with some of those reported in literature. It can be seen that high-power ultrasound does have a strong presence in the future for cleaning biofilms on food-grade surfaces.

1. Introduction

Ultrasound waves usually at low-frequency (high-power ultrasound) are able to inactivate bacteria cells and deagglomerate bacterial clusters (Fellows, 2000). The mechanism of inactivation consists of acoustic cavitation phenomena and associated shear disruption (mechanical), localised heating (physical) and free radical (chemical) formation (Joyce and Mason, 2008). High-power ultrasound is considered a ‘green’ technology that uses sound energy to remove biofilms (Rajasekhar et al., 2012). Ultrasound waves cannot replace CIP systems in food and beverage industry because the process is not 100% efficient. However, they can aid the process and at the same time reduce the chemical quantities and water required thereby making the whole process more environmentally friendly and cost-effective (Joyce and Mason, 2008; Rajasekhar et al., 2012).

Ultrasound waves are finding application because they can access some hidden places where microbial organisms can hide from CIP process, particularly near and/or on welds where there are geometrical discontinuities (Mamvura et al., 2011). The fact that there are three processes that occur at once increases the disinfection efficiency of the process. Elimination or efficient control of biofilms decreases the occurrence of microbial induced corrosion (MIC) and equipment failure by dealing with the root cause of the problem at the source (Medilanski et al., 2002).

When high-power ultrasound is applied in cleaning biofilms, there are energy changes that occur starting from electrical energy. The study was undertaken to determine how much of the initial energy (electrical energy) was converted to thermal energy with a change in amplitude and distance from the ultrasound probe during use of high-power ultrasound in cleaning of biofilms from food-grade surfaces. In addition, sound attenuation was investigated with change in amplitude and distance during cleaning of biofilms as attenuation leads to a decrease in energy conversion with an increase in distance from the ultrasound source.

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* Corresponding author.
E-mail address: tony.paterson@wits.ac.za (A.E. Paterson).

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2. Theory

In food processing industries a distinction is made between low power and high-power ultrasound. Low-power ultrasound (high frequency between 2 and 10 MHz; intensity, $I < 1\ W \cdot cm^{-2}$) is concerned with the physical effect of the medium on the wave and is typically used for analytical purposes while high-power ultrasound (low frequency between 20 and 100 kHz; $10 < I < 1000\ W \cdot cm^{-2}$) is used for cleaning, plastic welding and for sonochemistry by generating cavitation within liquid systems (Ince and Belen, 2001; Laborde et al., 1998; Santos et al., 2009).

High-power ultrasound has the ability to cause acoustic cavitation that can be used to inactivate microbes (Ince and Belen, 2001; Laborde et al., 1998). Acoustic cavitation refers to the formation and subsequent dynamic life of bubbles in liquids subjected to a sufficiently low pressure caused by ultrasound waves (Laborde et al., 1998; Li-xin et al., 2008). Heat is generated in the medium by absorbing the ultrasonic energy from the waves (acoustic energy) resulting in mechanical, physical and chemical effects observed (Miller, 1987). The mechanism of ultrasound interaction involves cavitation phenomena and associated shear disruption, short but intense local heating and free radical formation (Joyce and Mason, 2008; Laurent et al., 2009).

However, cavitation has been responsible for damage to proper blades on ships, inside surfaces of engine blocks amongst other issues. In these cases, it is more of a nuisance than a technology to be applied to solve some of the challenges we are facing (Epps et al., 2014; Sulaiman et al., 2012).

2.1. Basics of ultrasound waves

Ultrasound waves are described by displacement or acoustic pressure. Acoustic pressure (P_a) or displacement (x) produced by sound waves is time (t) and frequency (f) dependent. At any given time, t, the displacement, x, of an individual liquid molecule from its mean position is represented by equation (1) and Fig. 1 (Blitz, 1964):

$$x = x_o \sin(2\pi ft) \tag{1}$$

where x_o is maximum displacement of the particle.

Differentiation of equation (1) once gives particle velocity, and differentiation twice gives particle acceleration (Kinsler and Frey, 1962a):

$$v = \frac{dx}{dt} = v_o \cos(2\pi ft) \tag{2}$$

where v_o ($=2\pi f x_o$) is maximum velocity of particle

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2} = -a_o \sin(2\pi ft) \tag{3}$$

where a_o ($= - 4\pi^2 f^2 x_o$) is maximum acceleration of the particle.

Besides the variation in molecules' position when the sound wave travels through the liquid, there is variation in pressure (Fig. 1). As with displacement, pressure is calculated as follows (Einhorn et al., 1989; Leong et al., 2011):

$$P_a = P_A \sin(2\pi ft) \tag{4}$$

where P_A is maximum pressure amplitude.

The pressure is higher than normal where the molecules are in compression and lower than normal, where the molecules are in rarefaction implying displacement and pressure are out of phase (see Fig. 1) for a wave of 24 kHz frequency (Capote and de Castro, 2006).

Ultrasonic processors, which can be used to produce high-power ultrasound, are designed to deliver constant amplitude and when adjusted, they cause changes in ultrasound intensity i.e. when the resistance to the movement of the probe increases, additional power will be delivered by the power supply to ensure that the excursion at the probe tip remains constant (Kobus and Kusińska, 2008).

Combining equation (A.8) (Appendix A) and $v_o = 2\pi f x_o$ allows determination of x_o from maximum pressure amplitude as (Mason and Lorimer, 2002):

$$x_o = \frac{P_A}{2\pi f \rho c} \tag{5}$$

where ρ is the density of the liquid, c and f are the velocity and frequency of the wave which remain almost constant in water at $1500\ m \cdot s^{-1}$ and 24 kHz respectively.

2.2. Energy changes during use of high-power ultrasound

An ultrasonic processor transforms electrical energy into other kinds of energies during its operation (Fig. 2).

Electrical energy from the power supply is converted into mechanical energy in the form of oscillations of the piezoelectric crystal when the processor is switched on (Löning et al., 2002). The mechanical energy is then converted into acoustical energy in the form of ultrasonic waves which progress through a liquid medium resulting in liquid molecules oscillating about their mean position until the average distance between them exceed the critical molecular distance necessary to hold the liquid in contact leading to its breakdown (Catallo and Junk, 1995). In the process cavitation bubbles are formed, that is, energy transition is from acoustical to cavitation; and finally to heat estimated by monitoring the rate of temperature change (Kobus and Kusińska, 2008; Löning et al., 2002). Certain assumptions need to be considered when analysing the energy changes during use of high-power ultrasound:

(i) Conduction provides the only means of heat transfer (Hoffmann et al., 1996)
(ii) The effects of cavitation are approximately the same for every position in the reactor (Son et al., 2009)
(iii) A uniform temperature is attained within the bubble immediately after collapse (Hoffmann et al., 1996)

The relationship between I and P_A has been shown(equation (A.9), Appendix A) as (Ierselvan, 2008; Kang et al., 2014; Rueter and Morgenstern, 2014):

$$I = \frac{(P_A)^2}{2\rho c} \tag{6}$$

The equation enables the determination of power intensity from measurements of P_A at a particular setting. Acoustic impedance ($=\rho c$) is characteristic of a liquid and it is always constant regardless of any change in the frequency (Ierselvan, 2008). Adjusting the amplitude setting of the ultrasonicator results in a change of all the six types of energy, as such knowledge of its actual influence is essential particularly on the conversion efficiency.

There are three types of energy changes that can be determined easily (electrical, acoustical and cavitation energy) that can be used to quantify energy conversion efficiency by measuring either primary or secondary effects caused by the propagation of the waves in the liquid medium (Kobus and Kusińska, 2008). The power is expressed in watts per unit area of the emitting surface ($W \cdot cm^{-2}$), known as power intensity, or as watts per unit volume of the