Ultrasonic and Megasonic Processing of Foods

Kai Knoerzer*  
CSIRO Food and Nutrition Flagship, 671 Sneydes Road, Werribee, VIC 3030, Australia

Abstract

This manuscript will briefly discuss the fundamentals of ultrasound technology, i.e., the effects of ultrasound at low and high frequencies, including stable and unstable sound-induced cavitation, microstreaming, biochemical stress responses and effects achieved through standing waves. Furthermore, it will touch on current applications and highlight the research and advances in low and high frequency ultrasound at CSIRO (The Commonwealth Scientific and Industrial Research Organisation, Australia), e.g., airborne ultrasound for defoaming and enhanced drying, low frequency ultrasound for altering casein micelle characteristics in dairy processing, high frequency ultrasound (megasonics) for non-solvent separation in oil extraction processes and separation of milkfat, as well as texture modification of processed vegetables.

Keywords: ultrasound, ultrasonics, megasonics, dairy processing, separation, palm oil, texture modification

Due to the versatility and flexibility of ultrasound technology over a wide frequency range, spanning over more than two orders of magnitude from 20 kHz to >2 MHz, and different effects of the acoustic waves attributed at certain frequencies, the technology gives rise to a plethora of promising applications. In the food industry, ultrasonics has been mainly applied in diagnostics, e.g., non-destructive testing for flaw detection in material science, and processes such as cutting (e.g., frozen or soft foods through ultrasonic vibration on the edge of a cutting tool), homogenisation (e.g., sauces and mayonnaise through turbulent mixing induced by cavitation), extraction (e.g., enhanced yields of flavourings and nutraceuticals from plants caused by the breakdown of cell walls), degassing (e.g., beverages before canning or bottling), anti-fouling (of e.g., heat exchangers and membranes) among others (Tiwari and Mason, 2012). Ultrasonic applications have widened as a result of fairly recent developments of systems able to generate ultrasound in air at reasonable power levels as well as systems able to generate ultrasound at higher frequencies (> 400 kHz) various power levels (in the order of > 100 W). Latest developments include the use of airborne ultrasound for defoaming and drying applications (e.g., Rodriguez, Riera, Gallego-Juarez, Acosta, Pinto, Martinez, Blanco, 2010; Sabarez, Gallego-Juarez, Riera, 2012), ultrasound at low frequencies to alter the casein micelles in dairy products (e.g., Liu, Juliano, Williams, Niere, Augustin, 2012) ultrasound at higher frequencies for texture modifi-

*Corresponding author e-mail: kai.knoerzer@csiro.au
cation of processed vegetables (by inducing biochemical stress responses; e.g., Day, Xu, Oiseth, Mawson, 2012), megasonics for enhanced palm oil separation (e.g., Juliano, Swiergon, Mawson, Knoerzer, Augustin, 2013) and megasonics for enhanced milk fat separation (e.g., Juliano, Temmel, Rout, Swiergon, Mawson, Knoerzer, 2013).

I. Fundamentals of Ultrasonic and Megasonic Processing

In general, ultrasound refers to acoustic pressure waves with frequencies of 20 kHz or higher (Rastogi, 2011). Most effects of ultrasound at low and high frequencies are directly related to the cavitation occurring in the treated liquid, i.e., the growth of vapour bubbles, which violently collapse in low frequency applications (20 to 100 kHz), generating locally high pressures (in excess of 500 bar) and temperatures (up to 5000 K) (Tiwari and Mason, 2012), resulting in high shear forces (Figure 1), which can enhance cleaning, homogenisation or reduce fouling, among other effects. Cavitation also is more stable (less violent collapse of smaller bubbles) when applying high frequency ultrasound, while inducing more microstreaming.

![Figure 1] Visual representation of the growth and collapse of an ultrasound induced cavitation bubble (Mason, 2009).

Other effects in high frequency ultrasound applications include inducing biochemical stress responses in living tissue (e.g., fruits and vegetables), which can promote the synthesis of lignin reinforcing intercellular adhesion and the modification of the pectin structure enabling greater calcium ion bonding and cell wall stiffening (Day, Xu, Oiseth, Mawson, 2012). High frequency plate transducers also enable the formation of standing waves in purpose fit reactor designs (Juliano, Temmel, Rout, Swiergon, Mawson, Knoerzer, 2013). These standing waves can form between an ultrasound source and a reflector placed at a distance multiple of a half-wavelength in parallel orientation to the source. Particles or droplets suspended in a continuous phase experience an acoustic force, which, depending on the material properties, move either towards the nodes of the antinodes of the standing wave field (Figure 2).

![Figure 2] Visual representation of the formation of standing waves in a reflecting ultrasound system and collection of particles in the pressure nodes (Laurell, 2010).

II. Review of Recent Advances of Ultrasonic and Megasonic Processing at CSIRO

2.1. Low frequency ultrasound

Over the last few decades, researchers around the world have investigated the use of ultrasound at low frequencies and high powers for various food processing aspects, including the aforementioned applications such as emulsification, dispersion, anti fouling, but also the application for other purposes such as microbial and enzyme inactivation. Yet there are a few applications of low frequency ultrasound that have not been investigated in great detail, such as airborne ultrasound for defoaming and utilisation of the technology for altering casein micelle properties in dairy products. The following section will give a brief overview on the studies performed at CSIRO for these purposes.

2.1.1. Airborne ultrasound for defoaming

Foam generation in tanks (e.g., in biotechnology applications such as fermenters, and tank applications in other processing indus-
tries) and on beverage bottling lines, through aeration and agitation of liquids, can lead to significant losses of product. Current methods to reduce foaming include cooling the product or using antifoaming agents. Both methods are not convenient because liquid cooling demands high energy input and the antifoaming agents contaminate the product (Rodriguez et al., 2010), can have a negative effect on the product quality, and impact on the environment. Reducing the product losses by defoaming through low energy airborne ultrasound application has a positive impact on water and energy consumption and, therefore, environmental sustainability. While the concept of the technology has been proven (Rodriguez et al., 2010), the underlying mechanism remains unclear. It was hypothesised that high frequency vibration of the bubble, and potentially induced cavitation in the bubble matrix, overcoming the surface tension of the liquid film, causes the bubble collapse. Research at CSIRO has evolved around the development of sonotrodes, capable of transmitting the mechanical energy generated in the transducer at relatively high powers into the air, where the sound waves lead to efficient defoaming capacity on soft drink bottling lines (Collings and Gwan, 2007).

2.1.2. Airborne ultrasound for enhanced drying

Drying is a very important process in the food and other manufacturing industries, but also high in energy consumption. In fact, drying is probably the largest energy consuming unit operation in the food industry. Furthermore, the use of air at relatively high temperatures negatively affects the quality and structure of the dried product. Recent studies on airborne ultrasound in drying applications have shown that product drying time can be reduced by over 50%

2.1.3. Low frequency ultrasound for altering casein micelle properties

Low frequency ultrasound induced cavitation can also offer opportunities to restructure milk proteins to further impact on milk processability. Liu, Juliano, Williams, Niere, Augustin (2012) have investigated the effects of ultrasound processing on the physicochemical properties of casein micelles in reconstituted skim milks and have shown that ultrasound at 20 kHz can disrupt casein micelles and reform micelle-like particles with smaller size and comparable ξ-potential to native casein micelles. In addition, the volume of the casein micelles that are soluble in the serum increased significantly after ultrasound treatment. As a result, the sonicated milk was able to shorten the cheese renneting time compared to untreated milks. Other ultrasound interventions integrated in dairy processing lines can potentially provide modified physicochemical properties of milk proteins and achieve desired functional properties that impact in food processes. For example, ultrasound can reduce viscosity of concentrates enabling drying at higher total solids content, subsequently increasing throughput and saving energy input into the dryer.

2.2. High frequency ultrasound (megasonics)

Megasonics, operating at frequencies at or above 400 kHz, has been commercially applied only for cleaning of fine structures, e.g., in the semiconductor industry. This is where the development of these systems at larger scale and relatively high powers was pushed over the last decade. Only with the availability of larger scale systems was it seen feasible to conduct studies related to food processing. The researchers at CSIRO have since spent considerable effort into developing a basic understanding of the mechanisms involved in utilising high frequency ultrasound for various applications, such as enhanced separation, texture modification of processed foods among others.

2.2.1 Megasonic milk fat separation

Recent research has shown that high frequency ultrasound (400 kHz to 3 MHz), can enhance milk fat separation in small scale systems able to treat only a few milliliters of sample (e.g., Grenvall, Augustsson, Folkenberg, Laurell, 2009). Juliano, Temmel, Rout, Swergon, Mawson, Knoerzer (2013) have investigated the effect of ultrasonic standing waves on milk fat creaming in a 6 L reactor and the influence of
different frequencies and transducer configurations in direct contact with the fluid. They selected a recombined coarse milk emulsion with fat globules stained with oil-red-O dye for the separation trials. Runs were performed with one or two transducers placed in vertical (parallel or perpendicular) and horizontal positions (at the reactor base) at 400 kHz, 1 MHz and/or 2 MHz. Creaming behaviour was assessed by measuring the thickness of the separated cream layer. Other methods supporting this assessment included the measurement of fat content, backscattering, particle size distribution, and microscopy of samples taken at the bottom and top of the reactor. They found most efficient creaming after treatment at 400 kHz in single and double vertical transducer configurations. Fat globule size increase was observed when creaming occurred. They concluded that there is potential for enhanced separation of milkfat in larger scale systems from selected transducer configurations in contact with a dairy emulsion, or emulsion splitting in general.

### 2.2.2. Enhanced palm oil separation

In the palm oil milling operation, depending on the efficiency of the mill, a substantial part of the contained oil can be lost in the effluent stream. Therefore, an intervention at any processing stage that increases recoverable oil and reduces oil in the discharged palm oil mill effluent is expected to improve palm milling performance. Juliano, Swiergon, Mawson, Knoerzer, Augustin (2013) have examined the effects of applying ultrasound on the oil recovery from the ex-screw press feed and the underflow sludge from a palm oil vertical clarification tank to determine the usefulness of an intervention based on ultrasound. Megasonics was applied at frequencies of 400 kHz to 1.6 MHz in a standing wave field and the effects on two process streams (containing oil, non-oil solids and water) in palm oil milling were examined. Ultrasonication of the ex-screw press feed obtained upon crushing of the sterilised palm fruit and of the underflow sludge from the vertical clarification tank enhanced oil separation on gravity settling. Megasonics also enhanced the total oil recoverable, which consists of the sum of the oil separated under gravity and the decantable oil separated upon centrifugation of the remaining fraction. It was concluded that ultrasound-assisted separation of oil from process streams was attributed to the acoustic forces exerted on the suspended particles in the feed, similar to the effects in milkfat separation, which causes the oil to migrate to the antinodes and non-oil solids (comprising vegetal matter and residual oil) to the nodes. This work demonstrated the potential of applying high frequency ultrasound to improve the separation of oil in the clarification tanks and reduce oil that is lost in the non-oil fraction from the separators (i.e., sludge underflow). This application represents a step-change innovation in palm oil milling operations to reduce oil loss during milling.

### 2.2.3. Texture modification in processed vegetables

Recent studies (Curulli, Klingler, Mawson, Suwanchewakorn, 2007) have shown that ultrasound at a selected frequency, energy and time profile can be used to modify the surface structure of plant tissue which has a cellular structure with substantial starch content (e.g. potatoes). Day, Xu, Osseth, Mawson (2012) took this as a baseline to investigate the use of ultrasound pre-processing treatment, compared to blanching, to enhance mechanical properties of non-starchy cell wall materials using carrot as an example. They measured the mechanical properties of carrot tissue by compression and tensile testing after the pre-processing treatment prior to and after retorting and found that ultrasound treated samples at 400 kHz provided a higher mechanical strength to the cell wall structure than blanching for the same time period. They hypothesised that the mechanism involved appears to be related to the stress responses present in all living plant matter and concluded that the ultrasound treatment has great potential to improve the textural properties, i.e., firmness and crunchiness, in canned vegetables.
III. Conclusions

Ultrasound technology has proven to be a versatile technology for a number of different applications, with the potential to increase process speed with minimum energy requirements or allow for effects that are not accessible by any other means. Applications can have benefits from a quality perspective (e.g., better flavour, texture and nutrient retention of the processed food material) but also from an environmental and economical sustainability perspective (e.g., increased throughput, higher extraction yields, lower energy consumption).

While low frequency ultrasound has been investigated extensively in food processing applications, there are still new opportunities that are at earlier stages of research and development (e.g., airborne ultrasound). However, particularly in the high frequency spectrum, the use of ultrasound for enhancing food processes is still in its infancy and many of the theories that would explain the observed effects have not been proven yet. Furthermore, with the development of higher performance systems and extension of the frequency range to frequencies in excess of 3 MHz, will give rise to new applications not investigated to date.

IV. References


