The Pharma Innovation Journal 2018; 7(2): 234-241

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.03
TPI 2018; 7(2): 234-241

www.thepharmajournal.com
Received: 02-12-2017
Accepted: 03-01-2018

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Ultrasound treatment: A novel processing technique for food preservation

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Abstract
Ultrasound is a pressure wave that is oscillating at a frequency above that of human hearing. Ultrasonic waves have any frequency above 20 kHz up to a practical limit of around 10 MHz for various applications. Within this band, the measurement of the speed of propagation, the attenuation, or the reflection of ultrasonic signals can be the basis of instrumentation systems for the food industry.
Using ultrasound, full reproducible food processes can now be completed in seconds or minutes with high reproducibility, reducing the processing cost, simplifying manipulation and work-up, giving higher purity of the final product, eliminating post-treatment of waste water and consuming only a fraction of the time and energy normally needed for conventional processes. Several processes such as freezing, cutting, drying, tempering, bleaching, sterilization, and extraction have been applied efficiently in the food industry. The advantages of using ultrasound for food processing, includes: more effective mixing and micro-mixing, faster energy and mass transfer, reduced thermal and concentration gradients, reduced temperature, selective extraction, reduced equipment size, faster response to process extraction control, increased production, and elimination of process steps.

Keywords: Attenuation, cavitation, non-thermal, ultrasonic waves

Introduction
Ultrasonic techniques are finding increasing use in the food industry for both the analysis and processing of foods. Normal human hearing will detect sound frequencies ranging from 0.016 kHz to 18.0 kHz and the power intensity of normal quiet conversation is of the order of 1 Wcm^{-2}. Low intensity ultrasound uses very high frequencies, typically 2-20 MHz with low power levels from 100 $mWcm^{-2}$ to less than 1 Wcm^{-2}. This type of ultrasound is readily used for non-invasive imaging, sensing and analysis and is fairly well established in certain industrial and analytical sectors for measuring factors such as composition, ripeness, the efficiency of emulsification and the concentration or dispersion of particulate matter within a fluid (Powey and McClements, 1988) [12].
Power ultrasound, in contrast, uses lower frequencies, normally in the range of 20-100 kHz (generally less than 1 MHz), and can produce much higher power levels, in the order of 10-1000 Wcm^{-2}. Low frequency high power ultrasound has sufficient energy to break intermolecular bonds, and energy intensities greater than 10 Wcm^{-2} will generate cavitation effects, which are known to alter some physical properties as well as enhance or modify many chemical reactions (Mc Clements, 1995; Mason, *et al*., 1996; Roberts and Wiltshire, 1990) [10, 9, 18].
Ultrasound is considered as one such non-thermal processing alternative, which can be used in many food processing operations. It travels through a medium like any sound wave, resulting in a series of compression and rarefaction. At sufficiently high power, the rarefaction exceeds the attractive forces between molecules in a liquid phase, which subsequently leads to the formation of cavitation bubbles. Each bubble affects the localized field experienced by neighboring bubbles, which causes the cavitation bubble to become unstable and collapse, thereby releasing energy for many chemical and mechanical effects. The collapse of each cavitation bubble acts as a hotspot, which generates energy to increase the temperature and pressure up to 4000 K and 1000 atm, respectively. Depending on the frequency used and the sound wave amplitude applied a number of physical, chemical and biochemical effects can be observed which enables a variety of applications.

Important formulae
1. Ultrasonic Velocity (V) is determined by density (ρ) and elasticity (E) of the medium, according to the Newton-Laplace equation

$V = (E / \rho)^{1/2}$;
Where, $v = \lambda f$ or d/t

2. Attenuation (A) and Acoustic Impedance (z) are expressed as:
$A = A_o e^{-ax}$
$R = A_T/A_t = (z_1 - z_2) / (z_1 + z_2)$
(where, $z = \rho c$)
A_o = Initial (unattenuated) amplitude of the wave
x = Distance travelled
a = Amplitude attenuation factor, cm^{-1}
R = Ratio of the amplitude of reflected wave (A_T) to the incident wave (A_t) reflection coefficient
Z_1 and Z_2 = Acoustic impedances of two materials

Ultrasound generation
Ultrasonic wave producing system consists of three basic parts (Mason, 1998) [8]:

1. **Generator:** This is an electronic or mechanical oscillator that needs to be rugged, robust, reliable and able to operate with and without load.
2. **Transducer:** This is a device for converting mechanical or electrical energy into sound energy at ultrasonic frequencies.
3. **Coupler:** The working end of the system that helps transfer the ultrasonic vibrations to the substance being treated (usually liquid).

There are three main types of transducer: *liquid driven*, *magnetostrictive* and *piezoelectric*. Liquid driven transducers are effectively a liquid whistle where a liquid is forced across a thin metal blade causing it to vibrate at ultrasonic frequencies: rapidly alternating pressure and cavitation effects in the liquid generate a high degree of mixing. This is a simple and robust device but, because it involves pumping a liquid through an orifice and across a blade, processing applications are restricted to mixing and homogenisation.
Magnetostrictive transducers are electromechanical devices that use magnetostriction, an effect found in some ferromagnetic materials which change dimension in response to the application of a magnetic field. The dimensions of the transducer must be accurately designed so that the whole unit resonates at the correct frequency. The frequency range is normally restricted to below 100 kHz and the system is not the most efficient (60% transfer from electrical to acoustic energy, with losses mainly due to heat). The main advantages are that these transducers are rugged and able to withstand long exposure to high temperatures.
Piezoelectric transducers are electrostrictive devices that utilise ceramic materials such as Lead Zirconate Titanate (PZT) or Barium Titanate and Lead Metaniobate. This piezoceramic element is the most common of the transducers and is more efficient (80-95% transfer to acoustic energy) but less rugged than magnetostrictive devices; piezoelectric transducers are not able to withstand long exposure to high temperatures (normally not > 85 °C).

Sonication process
During the sonication process, longitudinal waves are created when a sonic wave meets a medium, regions of alternating compression and expansion are created. Ultrasound on propagation through a medium, induces compressions and depressions of the medium particles. These regions of pressure change cause cavitation to occur, and gas bubbles are formed in the medium. These bubbles have a larger surface area during the expansion cycle, which increases the diffusion, causing the bubble to expand. A point is reached where the ultrasonic energy provided is not sufficient to retain the vapour phase in the bubble; therefore, rapid condensation occurs.
The condensed molecules collide violently, creating shock waves. These shock waves create regions of very high temperature and pressure, reaching up to 4000K and 1000 atm and finally collapse. Cavitation can result in the occurrence of microstreaming which is able to enhance heat and mass transfer. Cavitation depends on ultrasound characteristics (e.g. frequency, intensity), product properties (e.g. viscosity, surface tension) and ambient conditions (e.g. temperature, pressure).

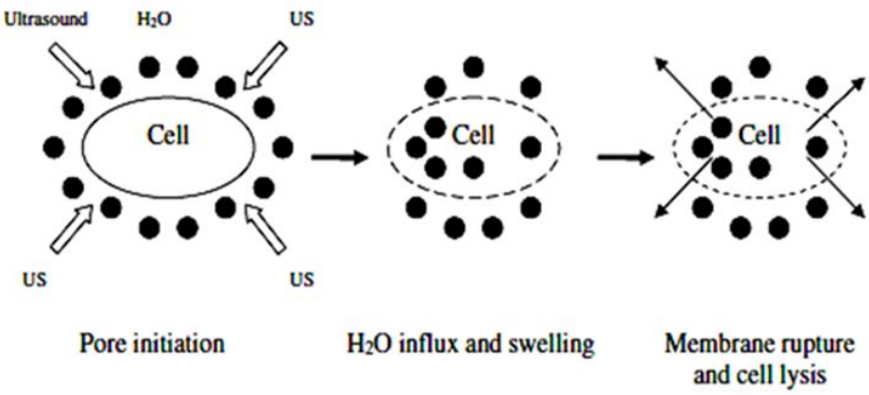


Fig. Mechanism of ultrasound-induced cell damage.

Factors affecting cavitation
The frequency of ultrasound is an important parameter and influences the bubble size (Suslick, 1989) [21]. At lower frequencies such as 20 kHz, the bubbles produced are larger in size and when they collapse higher energies are produced. At higher frequencies, bubble formation becomes more difficult and, at frequencies above 2.5 MHz, cavitation does not occur (Alliger, 1975) [2]. The amplitude of the ultrasound also influences the intensity of cavitation. If a high intensity is required then a high amplitude is necessary.
The intensity of bubble collapse also depends on factors such as temperature of the treatment medium, viscosity and frequency of ultrasound. As temperature increases, cavitation bubbles develop more rapidly, but the intensity of collapse is reduced. This is thought to be due to an increase in the vapour pressure, which is offset by a decrease in the tensile strength.

This results in cavitation becoming less intense and therefore less effective as temperature increases. This effect can be overcome if required, by the application of an overpressure (200-600 kPa) to the treatment system. Combining pressure with ultrasound and heat increases the amplitude of the ultrasonic wave and it has been shown that this can increase the effectiveness of microbial inactivation. Pressures of 200 kPa (2 bar) combined with ultrasound of frequency 20 kHz and a temperature of 30 °C produced a decrease in the decimal reduction time (*D* value: the time taken to achieve a 1 log reduction in cell levels) by up to 90% for a range of microorganisms (Raso *et al*., 1994) [15].

Methods of ultrasound

Ultrasound can be used for food preservation in combination with other treatments by improving its inactivation efficacy:

1. Ultrasonication (US): application of ultrasound at low temperature

- for heat sensible products
- it requires longer treatment time

2. Thermosonication (TS): combined method of ultrasound and heat

- produces a greater effect on inactivation of microorganisms than alone

3. Manosonication (MS): combined method of ultrasound and pressure

- Inactivates enzymes and/or microorganisms by combining ultrasound with moderate pressures at low temperatures.
- Inactivation efficiency is higher

4. Manothermosonication (MTS): MS is combined method of heat, ultrasound and pressure.

- It inactivates several enzymes at lower temperatures and/or in a shorter time than thermal treatments at the same temperatures
- Thermoresistant enzymes/ thermotolerant/ microorganisms can be destroyed using manothermosonication

Applications in food processing

1. On-line measurements

Ultrasonic transducer is set into the wall of a pipe through which the sample flows. The time taken for a pulse to travel across the sample (t) is measured using a digital timing device, and the ultrasonic velocity is calculated from a knowledge of the inside diameter of the pipe (d):

$c = 2d/t$

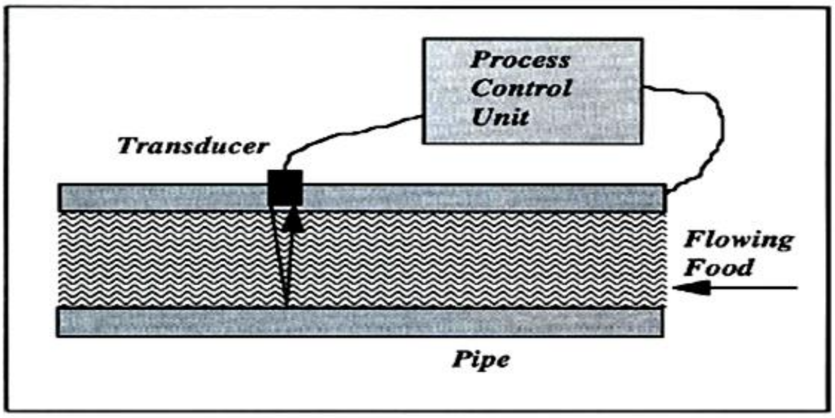


Figure – On-line sensor for measuring the ultrasonic properties of foods flowing through pipes.

2. Foreign body detection

If an ultrasonic pulse is propagated into a sample it will be reflected from any boundaries it encounters, providing there is a large enough difference in acoustic impedance between the food and the foreign body, which is usually the case. The distance of the foreign body from the surface of the can is determined by measuring the time of-flight of ultrasonic pulses reflected from the foreign body and from the can wall:

$d_2 = d_2\ (t_2/t_1)$

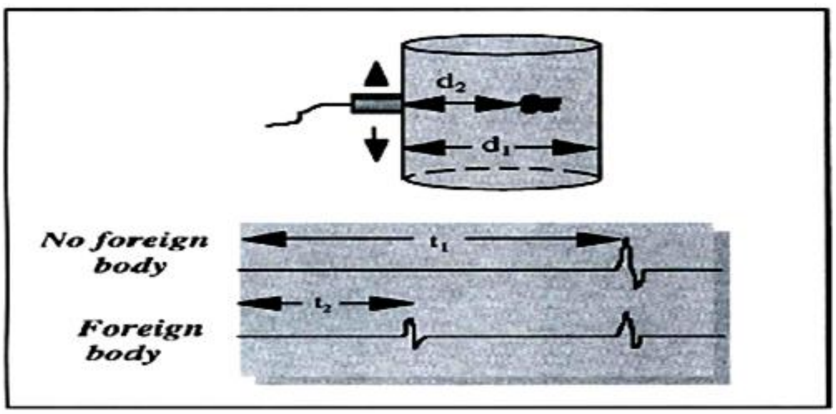


Figure – Detection of a foreign body in a can using the ultrasonic pulse-echo experiment: $d_1=ct_1$, $d_2=ct_2$.

3. Thickness and Level Detection
An ultrasonic transducer is pressed against the side of a material and the time taken for a pulse to travel across the material and back is measured. If the velocity of ultrasound in the material is known then the distance can be calculated:

$2d = ct$

4. Defoaming
High intensity ultrasound (20 kHz) has been described as an effective procedure to remove foam and dissolved oxygen (80% of foam reduction) with very low energy consumption (40 kJ/l) in milk (Villamiel *et al*., 2000) [22]. Ultrasound defoamer has been developed and commercially applied to control the excess foam produced during the filling operation of bottles and cans on high-speed canning lines and in fermenting vessels and other reactors of great dimensions (Gallego-Juárez *et al*., 2010) [5].

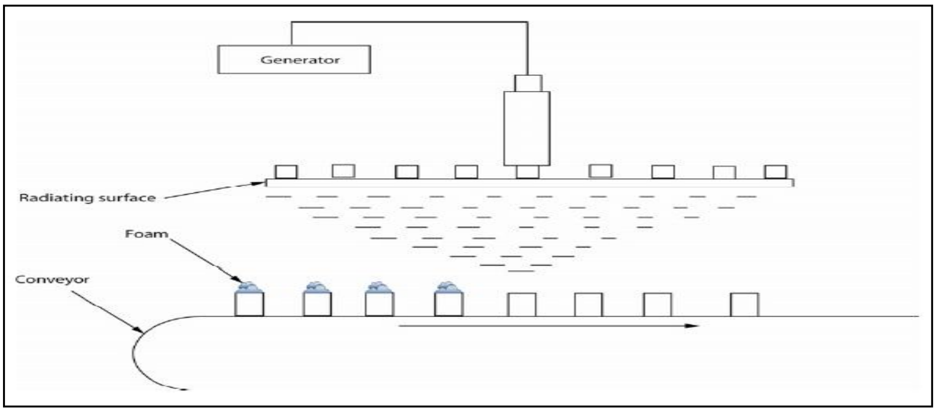
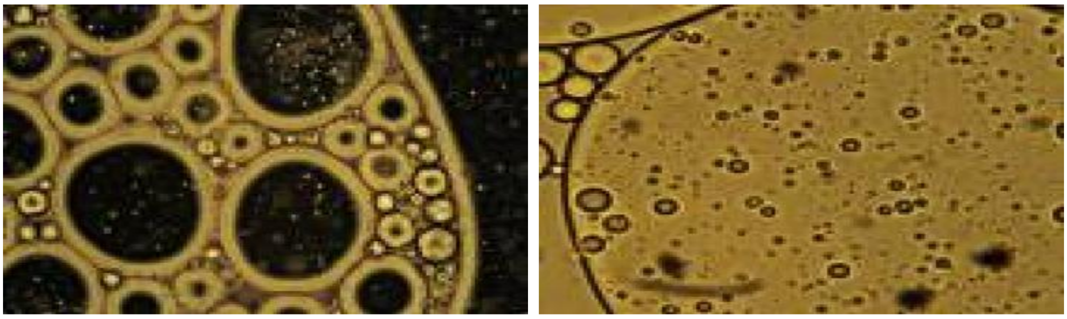


Fig: Ultrasonic transducer for defoaming.

5. Degassing/Deaeration
Common used methods for degassing liquids are boiling or reducing pressure. However, in ultrasound small temperature change is brought about in the product. So, it does not deteriorate the quality of product. Rapid vibration of gas bubbles brings them together by acoustic waves and bubbles grow to a size sufficiently large to allow them to rise up through the liquid against gravity, until they reach the surface. Compared with mechanical agitation, the ultrasonic method decreases the number of broken bottles and overflow of the beverage. Ultrasonically assisted degassing is rapid in aqueous systems, but more difficult in very viscous liquids such as melted chocolate.

6. Emulsification
Emulsification is the process of mixing two immiscible phases (e.g., oil and water) with the aid of a surface active agent (emulsifier) into homogeneous dispersion or emulsion. The process requires an energy input by means of mechanical agitation or ultrasonication to facilitate the formation of small droplets. With ultrasonication, cavitation releases high energy micro-jets near interfaces and facilitate emulsification. Compared to mechanical agitation, the use of ultrasound requires less amounts of surfactants and produces smaller and more stable droplets.



Classical double emulsion　　Ultrasonic double emulsion

Fig. Phase dispersion of two immiscible solvent and drop size distribution by Power Ultrasound Mechanical Agitation.

7. Cooking
In a conventional cooking method outer surface of the food may be overcooked while the interior insufficiently cooked. Ultrasound improves heat transfer characteristics. Ultrasound cooking results in greater cooking speed, moisture retention and energy efficiency and may also improve the textural attributes of cooked meat.

8. Cutting
Ultrasonic cutting uses a knife-type blade attached through a shaft to an ultrasonic source. The most widespread application of ultrasound is in the cutting of fragile and heterogeneous products (cakes, pastry and bakery products) and fatty (cheese) or sticky products. The vibration prevents the adherence of the product on the blade and thus reduces the development of micro-organisms on the surface, i.e. ultrasonic vibrations provide ‘auto-cleaning’ of the blade. The accuracy and repetitiveness of the cut produce a reduction in losses relative to the cutting (due to cracks, crumbs, etc.) and a better standardization of the weight and dimensions of portions.

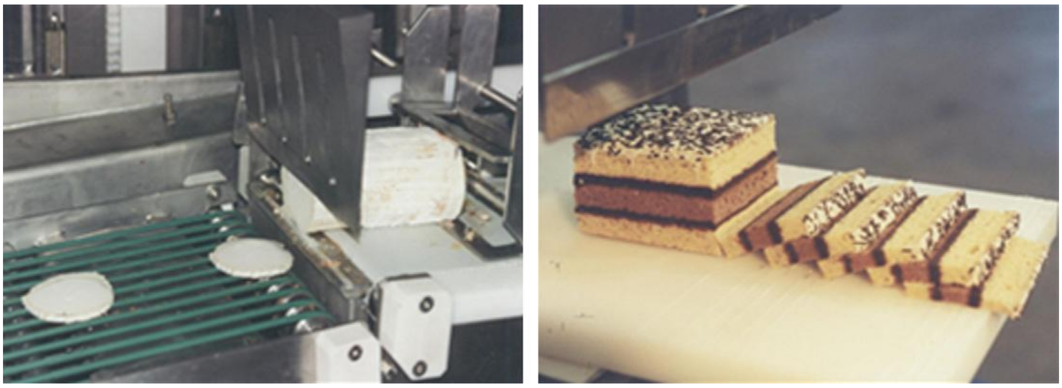


Fig: Difference in cutting slices of a bakery product cut with and without ultrasound

9. Enzyme inactivation

Enzyme inactivation is an important process for enhancing the stability, shelf life and quality of many food products. Power ultrasound is used to increase or inactivate enzymatic activities depending on ultrasound intensity. Ultrasound combined with low pressure and heat (manothermosonication) can be used for inactivation tomato pectic enzyme, soybean lipoxygenase, horseradish peroxidase, orange PME, lipase, protease, etc.

10. Microbial Inactivation

Commonly used techniques for microbial inactivation are thermal pasteurization and sterilization. However, the effectiveness of these methods requires long time exposure to high treatment temperatures, which leads to deterioration of functional properties, sensory characteristics (e.g., off-flavor) and nutritional value of food products. Less energy-intensive preservation methods including high-pressure processing, ionizing radiation, pulsed electric field, microfiltration, ultraviolet radiation and HPU are cost-efficient and environment friendly.

In combination with heat, these methods can accelerate the rate of food sterilization, thereby reducing the duration and intensity of thermal treatment and the resultant damage. In particular, the use of HPU has shown several advantages compared to heat pasteurization such as minimization of flavor loss in sweet juices, greater homogeneity and significant energy savings.

11. Freezing

HPU has gained considerable interest in food processing and preservation due to its ability to control/modify nucleation and crystal growth (Acton and Morris, 1993; Mason, Paniwnyk, and Lorimer, 1996) [1, 9]. In addition, HPU is chemically non-invasive, operates in a non-contact mode and does not present legislative difficulties (Delgado, Zheng, and Sun, 2009) [3]. Several studies have indicated the potential of using HPU in accelerating the freezing rate and improving the quality of frozen food plants such as potatoes and apples (Delgado, Zheng, and Sun, 2009) [3].

HPU treated frozen potatoes exhibited a better cellular structure as less extracellular void and cell disruption/breakage appeared than those without acoustic treatment. The most important effect of power ultrasound in food freezing is due to the acoustic cavitation, which not only promotes ice nucleation by micro-bubbles but also enhances the heat and mass transfer due to the violent agitation created by the acoustic microstreaming (Zheng and Sun, 2006) [25]. Power ultrasound has also been applied during the production of molded frozen products such as sorbets and ice lollipops to provide product with much smaller ice crystals and uniform crystal size distributions (Price, 1992) [13].

12. Freeze concentration and freeze drying

HPU can be used to induce the formation of a few nucleation active sites at low supercooling. Therefore, crystal growth will dominate nucleation, and leads to formation of large crystals, which enhances the freeze concentration process. HPU increases the freezing rate and improves the quality of fresh food products such as potatoes by enhancing the heat and mass transfer process.

13. Ultrasound-assisted extraction

A major application of HPU is for facilitating the extraction process of a variety of food components (e.g., herbal, oil, protein, polysaccharides) as well as bioactive ingredients (e.g. antioxidants) from plant and animal resources. The action of HPU is due to cavitation, which generates high shear forces and micro-bubbles that enhances surface erosion, fragmentation and mass transfer resulting in high yield of extracted materials and faster rate of extraction.

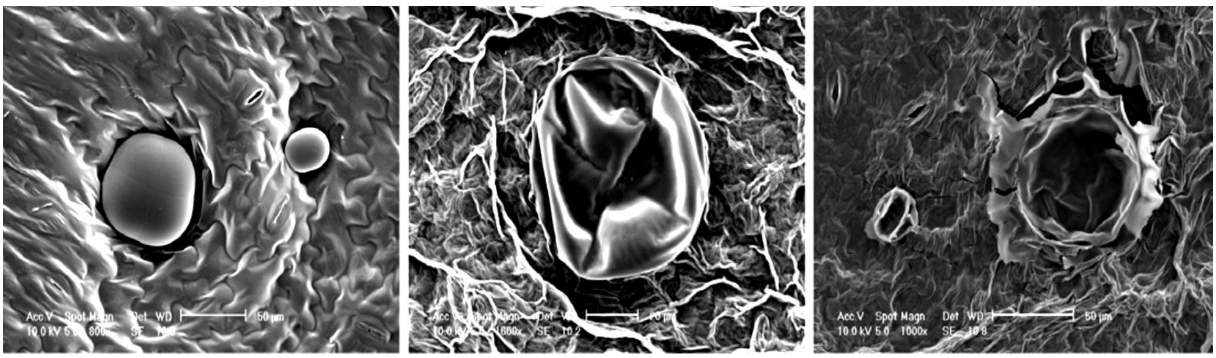


Fig: Cavitation bubble collapse and plant material releasing: example of extraction of essential oil from basil.

14. Decontamination

Seymour *et al*. (2002) [19] described the potential of using HPU for fresh produce decontamination, which is due to the mechanical effect generated by cavitation bubbles. They stated that cavitation enhances the mechanical removal of attached or entrapped bacteria on the surfaces of fresh produce by displacing or loosening particles through a shearing or scrubbing action, achieving an additional log reduction when applying to a chlorinated water wash.

15. Depolymerization

For degradation of polymers there are two possible mechanisms:

- Mechanical degradation of the polymer from collapsed cavitation bubble
- Chemical degradation as a result of the chemical reaction between the polymer and high energy molecules such as hydroxyl radicals produced from cavitation

Sonication can lead to several improvements in various properties like increased solubility and foaming ability. The application of low-power ultrasound causes a temporary changes. However, high powers causes depolymerization and results in a permanent change in their rheology.

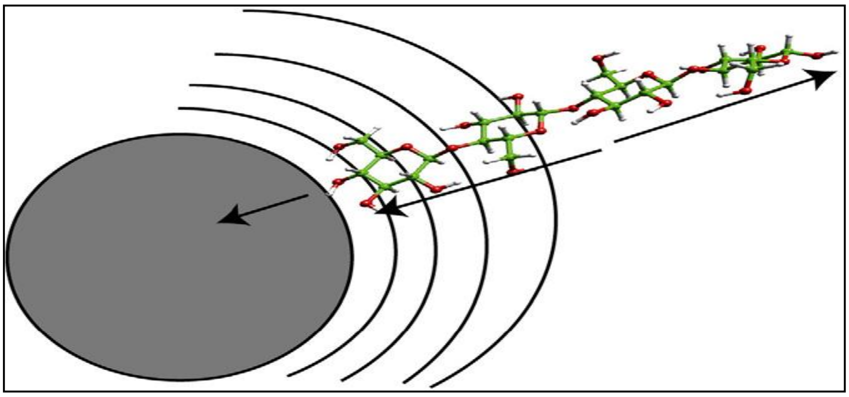


Fig. Representation of depolymerization phenomenon using ultrasound

16. Demoulding and extrusion

The device for demoulding industrial food products couples the mould and the ultrasonic source in order to enhance removal of the product by virtue of the high-frequency relative movement between the contact surfaces of the mould and of the product contained in the latter. This technique allows surface coatings to be eliminated and ensures that any residual material in the mould can be cleaned automatically. Ease of removal makes the cleaning and recycling of the container far easier.

17. Drying

HPU improves heat and mass transfer phenomena in drying processes. Acoustic dehydration relies on cavitation and also on the effects of compressions and expansions induced by soundwaves passing through the food medium. The dehydration of vegetables using forced-air drying assisted by air-borne ultrasound and ultrasonic dehydration have been carefully studied by the power ultrasonic group of the institute of acoustics in Spain. They designed a multi-sample ultrasonic dehydration prototype system with a high-power rectangular plate transducer (20 khz, 100 W) and a series of sensors to study mechanical and thermal effects on vegetable samples, and to evaluate the feasibility at the industrial level.

Direct increase of the drying effect with the acoustic intensity when the other thermomechanical parameters (temperature, flow rate, suction, etc.) are kept constant.

18. Brining, pickling and marinating

Most current salt-brining or pickling-fermentation processes are subject to three main drawbacks:

a) In brining very high sodium chloride content is required, which may require a ‘desalting’ process prior to shipping to reduce the sodium chloride content of the product
b) There is a potential lack of control in fermentation
c) Any soaking process can lead to enzymatic softening, structural damage and bloating.

All three of these side-effects are detrimental to rapid and efficient food preservation and so alternative technologies are of interest to food producers. Ultrasound allows the pickling time of products to be reduced considerably, particularly those foods with a crunchy texture. It also provides a method for manufacturing a pickle having a low level of sodium chloride compared with the pickles currently on the market. Hence, there is no need to ‘desalt’, repack to reach the desired finished product salt level.

19. Ultrasound and Meat Processing

Power ultrasound has been used as an alternative to pounding, tumbling or massaging. There is evidence that enhanced myofibrillar protein extraction occurs and that binding in reformed and cured meats is improved following ultrasound application. The binding strength, water holding capacity, product colour and yields of processed meats were evaluated after treating with either salt tumbling, sonication in an aqueous liquor or both. The samples that received both treatments were judged superior in all qualities (Vimini, *et al*., 1983) [23]. Pilot studies in the early 1990s showed that sirloin steak connective tissue could be reduced when subjected to sonication at 40 kHz (2 Wcm^{-2}) for 2 h (Roberts, 1991) [17].

20. Sonocrystallisation

Cavitation induces formation of nucleation active sites and create smaller crystals with modified properties. Power ultrasound in the range of 20 kHz and upto the MHz range has contributed as an effective tool for influencing the crystallization of liquids and melts (i.e., sonocrystallization). This is used in fat fractionation such as separating stearin (high melting) and olein (low melting) from a triglyceride oil.

21. Agricultural Applications

Ultrasonic waves, in high frequency range, are used for detection of internal bruises in fruits and vegetables. However, this process may be difficult in certain products like apple, due to presence of high percentage of air, which contriubutes to acoutic impedance, causing most incident energy to be reflected. Ultrasonic waves can also be used for determining surface cracks in agricultural produce.

22. Ultrasonically Enhanced Oxidation

Ageing of fermented products and inducing rapid oxidation in alcoholic drinks for flavour development and early maturation has been developed, using higher frequency lower energy power ultrasound. In 1981, in Japan, the use of 1 MHz ultrasound was shown to alter the alcohol/ester balance (Ishimori *et al*., 1981) [14] with possible applications for accelerating whisky maturation through the barrel wall being tested (Rosenfeld and Schmidt, 1984) [16].

23. Filtration

In the food industry, the separation of solids from liquids is an important procedure either for the production of solid-free liquid or to produce a solid isolated from its mother liquor. But the deposition of solid materials on the surface of filtration membrane is one of the main problems. The application of ultrasonic energy can increase the flux by breaking the concentration polarization and cake layer at the membrane surface without affecting the intrinsic permeability of membrane. The liquid jet serves as the basis for cleaning, and some other cavitational mechanisms lead to particle release from the blocked membrane (Kyllönen *et al*., 2005) [6]. Ultrasonically assisted filtration (generally referred to as acoustic filtration) has been successfully employed to enhance the filtration of industrial waste-water that is generally considered difficult to process (Kyllönen *et al*., 2006; De-Sarabia, *et al*., 2000; Smythe and Wakeman, 2000) [7, 4, 20]. Moreover, the optimized ultrasound intensity is very important to prevent the damage of filters (Wen *et al*., 2008) [24]. Ultrasound can also be applied to the production of fruit extracts and drinks. In the case of juice extraction from apple pulp, conventional belt vacuum filtration achieves a reduction in moisture content from an initial value of 85% to 50%, whereas electro-acoustic technology achieved 38% (Mason, *et al*., 1996) [9]. The use of ultrasound in combination with membrane filtration has also been investigated, with positive results (Kyllönen *et al*., 2005; Muthukumaran, *et al*., 2005) [6, 11]. Here ultrasonic irradiation at low power levels was employed to aid the filtration of whey solutions. The results indicated a significant enhancement of flow rate, with ultrasound aiding in preventing blockage of the filter and flow through it by lowering the compressibility of both the initial protein deposit and the growing filter cake.

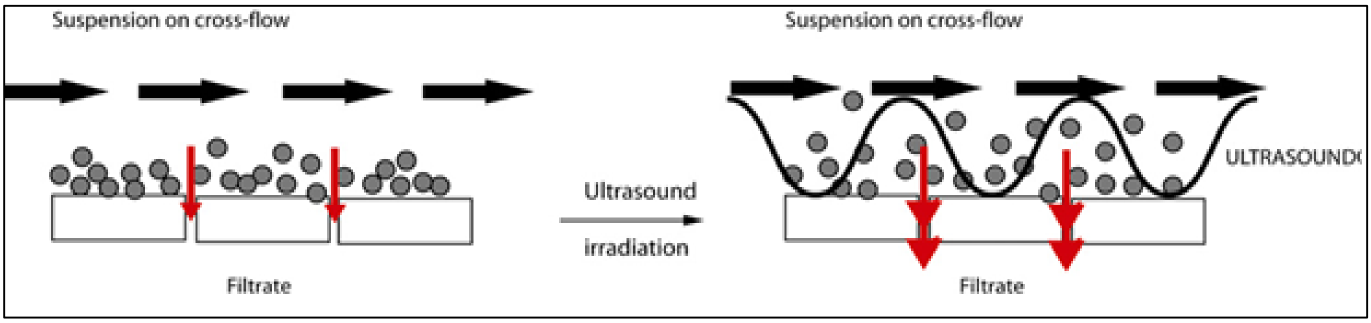


Fig. Enhancement of permeability using ultrasound

The future for power ultrasound

Ultrasound currently finds numerous applications in the food industry, including emulsification of fats and oils, mixing, blending, cutting and accelerating the ageing processes in meats and wines. In the laboratory, it has the potential to be applied to the pasteurisation of a range of low viscosity liquid products as well as enhance the effectiveness of other processing methods. However, the process remains some way from being a viable preservation technology. This is in part due to a lack of knowledge regarding full-scale design and scale-up, but also in part due to a considerable knowledge gap relating to the optimisation of process conditions for food processing. Much more research is required to gain a greater understanding of issues such as:

1. Equipment design to optimise microbial and enzyme inactivation;
2. Ultrasonic enhancement of heat transfer to augment existing thermal processes;
3. Accurate mapping of field intensity variations within a treatment chamber to develop reliable scheduled processes using ultrasound;
4. Inactivation mechanisms for vegetative cells, spores and enzymes, which need to be clearly identified, especially when combination technologies are used;
5. Development of mathematical models for the inactivation of microorganisms and enzymes involving ultrasound;
6. Identifying the influence of food properties such as viscosity and particle size on process lethality as well as the implication of process deviations when using ultrasound.

Conclusion

Ultrasound is an emerging technology in food science and technology. The tunable frequency of ultrasound has diversified its applications in the areas of food analysis, processing and quality control. The application of low power (high frequency) ultrasound provides a non-invasive, cheap and simple technique that can be used for estimating the food composition (fish, eggs, dairy, etc.), monitoring physicochemical and structural properties (emulsions, dairy products and juices) and detecting contamination by metals and other foreign materials (canned food, dairy foods, etc.). The simplicity, portability and low cost of ultrasound devices make them essential elements in research laboratories, pilot plants and large food factories. High power (low frequency) ultrasound, on the other hand, modifies the food properties by inducing mechanical, physical and chemical/ biochemical changes through cavitation, which reduces reaction time and increases reaction yield under mild conditions compared to conventional route.

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