ACTA Acta Sci. Pol., Technol. Aliment. 6(3) 2007, 89-99

APPLICATIONS OF ULTRASOUND IN FOOD TECHNOLOGY

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Abstract. Ultrasonic is a rapidly growing field of research, which is finding increasing use in the food industry for both the analysis and modification of food products. The sound ranges employed can be divided into high frequency, low energy diagnostic ultrasound and low frequency, high energy power ultrasound. The former is usually used as a non-destructive analytical technique for quality assurance and process control with particular reference to physicochemical properties such as composition, structure and physical state of foods. Nowadays, power ultrasound is considered to be an emerging and promising technology for industrial food processing. The use of ultrasound in processing creates novel and interesting methodologies which are often complementary to classical techniques. Various areas have been identified with great potential for future development: crystallisation, degassing, drying, extraction, filtration, freezing, homogenisation, meat tenderization, sterilization, etc. There is a wide scope for further research into the use of ultrasound in food processing both from an industrial and academic viewpoint.

Key words: ultrasound, food processing, meat, microorganisms

GENERAL INFORMATION

Ultrasound is a form of energy generated by sound (really pressure) waves of frequencies that are too high to be detected by human ear, i.e. above 16 kHz [Jayasooriya et al. 2004].

Ultrasound when propagated through a biological structure, induces compressions and depressions of the medium particles and a high amount of energy can be imparted. In dependence of 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 [Got et al. 1999, Knorr et al. 2004, Ultrasound... 1998]. Ultrasound has been used for a variety of purposes that includes areas as diverse as communication with animals (dog whistles), the detection of flaws in concrete buildings, the synthesis of fine chemicals and the treatment of disease. Despite its wide-ranging uses and exciting de-

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velopments the study of ultrasound is a young science. The oldest application, the exploitation of diagnostic ultrasound only dates back to the beginning of the 20th century and ultrasound in processing is even more recent in origin [Mason 2003].

In nature bats and dolphins use low-intensity ultrasound pulses to locate prey; while certain marine animals use high-intensity pulses of ultrasound to stun their victims before capture. In the food industry, a similar division into two distinct categories of ultrasound applications is made [Fellows 2000, McClements 1995]. For the classification of ultrasound applications the energy amount of the generated sound field, characterised by sound power (W), sound intensity ($W \cdot m^{-2}$) or sound energy density ($Ws \cdot m^{-3}$), is the most important criterion [Knorr et al. 2004]. The uses of ultrasound are broadly classified into two groups. Low energy (low power, low-intensity) ultrasound applications involve the use of frequencies higher than 100 kHz at intensities below 1 $W \cdot cm^{-2}$. Low--intensity ultrasound uses a so small power level that the ultrasonic waves cause no physical or chemical alterations in the properties of the material through which the wave passes, that is it is generally non-destructive. They are successfully used for non--invasive monitoring of food processes. The most widespread application of low--intensity ultrasound in the food industry is as an analytical technique for providing information about the physicochemical properties of foods, such as composition, structure and physical state [Fellows 2000, Jayasooriya et al. 2004, Knorr et al. 2004, McClements 1995]. Ultrasound has advantages over other traditional analytical techniques because measurements are rapid, non-destructive, precise, fully automated and might be performed either in a laboratory or on line. One of the most widespread and most promising ultrasonic applications is the utilization of ultrasound for composition measurement. Ultrasonic velocity in fish tissues, chicken and raw meat mixtures can be related to its composition using semi-empirical equations [Simal et al. 2003].

The other group is high energy (high power, high-intensity) ultrasound which uses intensities higher than 1 $W \cdot cm^{-2}$ (typically in the range 10-1000 $W \cdot cm^{-2}$) at frequencies between 18 and 100 kHz [McClements 1995, Ultrasound... 1998]. Physical, mechanical or chemical effects of ultrasonic waves at this range are capable of altering material properties (e.g. physical disruption, acceleration of certain chemical reactions) [Jayasooriya et al. 2004]. High-intensity ultrasound has been used for many years to generate emulsions, disrupt cells and disperse aggregated materials. More recently various areas have been identified with greater potential for future development, e.g. modification and control of crystallization processes, degassing of liquid foods, enzymes inactivation, enhanced drying and filtration and the induction of oxidation reactions [Knorr et al. 2004, McClements 1995, Roberts 1993, Zheng and Sun 2006]. The beneficial use of the sound energy is realized through the various effects the ultrasound generates upon the medium where it transmits. Physical, mechanical or chemical effects of ultrasonic waves at this range are capable of altering material properties through generation of immense pressure, shear and temperature gradient in the medium through which they propagate.

During the sonication process, longitudinal waves are created when a sonic wave meets a liquid medium, thereby creating regions of alternating compression and expansion. 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 of gas, 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 5500°C and 50 MPa. Cavitation can result in the occurrence of microstreaming which is able to enhance heat and mass transfer [Jayasooriya et al. 2004, Zheng and Sun 2006]. The ability of ultrasound to cause cavitation depends on ultrasound characteristics (e.g. frequency, intensity), product properties (e.g. viscosity, surface tension) and ambient conditions (e.g. temperature, pressure) The ultrasound intensity required to cause cavitation increases markedly above about 100 kHz [Williams 1983].

APPLICATIONS IN THE FOOD INDUSTRY

Developments in the application of ultrasound in processing began in the years preceding the Second World War when it was being investigated for a range of technologies including emulsification and surface cleaning. By the 1960s the industrial uses of power ultrasound were accepted and being used in cleaning and plastic welding which continue to be major applications [Mason 2003].

The possibility of using low-intensity ultrasound to characterize foods was first realized over 60 years ago; however, it is only recently that the full potential of the technique has been realized [Povey and McClements 1988]. There are a number of reasons for the current interest in ultrasound. The food industry is becoming increasingly aware of the importance of developing new analytical techniques to study complex food materials, and to monitor properties of foods during processing; ultrasonic techniques are ideally suited to both of these applications. Ultrasonic instrumentation can be fully automated and make rapid and precise measurements. Ultrasound is non-destructive and non-invasive, can easily be adapted for on-line applications, and used to analyse systems that are optically opaque [McClements 1995].

Within food technology we can find almost all of the examples of processing to which ultrasound can be applied. Until recently the majority of applications of ultrasound in food technology involved non-invasive analysis with particular reference to quality assessment. Such applications use techniques that are similar to those developed in diagnostic medicine, or non-destructive testing, using high frequency low power ultrasound. Examples of the use of such technologies are found in the location of foreign bodies in food, the analysis of droplet size in emulsions of edible fats and oils and the determination of the extent of crystallization in dispersed emulsion droplets [Mason et al. 1996]. The relationship between measurable ultrasonic properties of foods (velocity, attenuation coefficient and impedance) and their physicochemical properties (composition, structure and physical state) is the basis of the ultrasonic analysis. This relationship can be established either empirically by preparing a calibration curve relating the property of interest to the measured ultrasonic property, or theoretically by using equations describing the propagation of ultrasound through materials [McClements 1995]. By monitoring the attenuation of an ultrasound pulse has proved possible to determine the degree of homogenisation of fat within milk. The measurement of ultrasound velocity in conjunction with attenuation can be used to estimate the degree of emulsification in such materials. It is possible to determine factors such as the degree of "creaming" of a sample, i.e. the movement of solid particles/fat droplets to the surface.

Such information gives details, for example, of the long term stability of fruit juices and the stability of emulsions such as mayonnaise. The combination of velocity and attenuation measurements shows promise as a method for the analysis of edible fats and oil as well as for the determination of the extent of crystallization and melting in dispersed emulsion droplets [Mason et al. 1996].

In recent years food technologists have turned their attention to employment of power ultrasound in processing. Its history can be traced back to 1927 when a paper entitled "The chemical effects of high frequency sound waves I. A preliminary survey" was published [Richards and Loomis 1927]. Physical, mechanical, or chemical effects of ultrasonic waves at this range are capable of altering material properties (e.g., disrupting the physical integrity, acceleration of certain chemical reactions) through generation of immense pressure, shear, and temperature gradient in the medium through which they propagate [Ultrasound... 1998]. High power ultrasonic applications generally depend on complex vibration induced effects in the propagating media, which produces cavitation in liquids or biological tissue. In addition to cavitation, ultrasound is able to weaken the physical structure of the material or medium, provided the dimensions of the media are similar to those of the ultrasonic wavelength used [Got et al. 1999].

One of the major long-established industrial applications of power ultrasound is for cleaning and it has proved to be an extremely efficient technology [Mason et al. 1996]. Surface cleaning is applicable to a wide range of disciplines and applications (e.g. sensors, filters, substrates, reactors, catalysers and heat exchangers). Ultrasound has been shown to be particularly effective for in situ cleaning in conjunction with chemical treatment and offers such advantages as: reduced chemical consumption, reduction of direct worker contact with hazardous cleaning chemicals/substances, enhanced cleaning speed, cleaning consistency – the ultrasonic activity is micro in nature and reaches all areas of complex configurations for uniform cleaning, automatic operation and control savings in energy costs, labour and floor space [Mason 2003].

Possible applications of power ultrasound in the food industry are very wide ranging. One of the earliest uses of power ultrasound in processing was in emulsification. Emulsions generated with ultrasound are often more stable than those produced conventionally and often require little, if any, surfactant [Mason et al. 1996].

Investigations have shown that the use of ultrasound as a processing aid can reduce the production time of yoghurt of up to 40%. Moreover, sonication reduced the normal dependence of the process on the origin of milk as well as improved both the consistency and the texture of the product. It was also found that fish egg exposure to ultrasound of frequency 1 MHz for 35 min, three times a day resulted in the reduction in hatch time for loach from 72 to 60 hours. Several reports in the literature suggest that ultrasonic treatment of seeds before sowing is an effective method of improving crop yield [Mason et al. 1996].

One of the original uses of power ultrasound in biochemistry was to break down biological cell walls to liberate the contents. Subsequently it has been shown that power ultrasound can be used to activate immobilized enzymes by increasing the transport of substrate to the enzyme. As far as enzymes are concerned, ultrasound can also be employed as a method of their inhibition [Mason et al. 1996]. Chambers [1937] reported that pure pepsin was inactivated by sonication probably as a result of cavitation. By applying ultrasound for over three hours, the original activity of peroxidase, responsible for the development of off-flavours and brown pigments, was progressively reduced by 90% [Mason et al. 1996].

The use of power ultrasound significantly improves the extraction of organic compounds contained within the body of plants and seeds. The mechanical effects of ultrasound provide a greater penetration of solvent into cellular materials and improve mass transfer [Mason et al. 1996]. Additional benefit results from the disruption of biological cell walls to facilitate the release of contents. Combined with this effect is enhanced mass transfer, due to the effects of microstreaming which results in a more efficient method for sugar extraction [Chendke and Fogler 1975]. The sonication accelerated sugar diffusion and gave the higher level of dry matter content and sugar content in juice [Stasiak 2005]. In some cases sonication increased the efficiency of extraction at lower temperatures producing a purer product in a shorter time [Mason et al. 1996]. By using of ultrasound extraction of tea solids from leaves was improved by nearly 20%. Authors noticed that the majority of material was extracted in the first 10 minutes of sonication [Mason and Zhao 1994]. Zayas [1986] reported that an increased yield of the enzyme rennin from calf stomachs has been achieved by using ultrasound. Moreover, the activity of ultrasonic extract was found to be slightly increased in comparison with normal technology.

Power ultrasound has proved to be extremely useful in crystallization processes. It serves a number of roles in the initiation of seeding and subsequent crystal formation and growth [Mason et al. 1996, Stasiak and Dolatowski 2007]. Ultrasound has also been applied to filtration. As a result, the moisture content of slurry containing 50% water was rapidly reduced to 25%; whereas conventional filtration achieves a limit of only 40% [Mason et al. 1996].

Another example of ultrasound application of potentially great commercial importance is acoustic drying. Ultrasonically enhanced drying can be carried out at lower temperatures than the conventional methodology which reduces the probability of oxidation or degradation in the material. By employing ultrasound the heat transfer between a solid heated surface and a liquid is increased by approximately 30-60% [Ensminger 1988].

Power ultrasound has proved itself an effective method in assisting food freezing and its benefits are wide-ranged. In addition to its traditional application in accelerating ice nucleation process, it can also be applied to freeze concentration and freeze drying processes in order to control crystal size distribution in the frozen products. If it is applied to the process of freezing fresh foodstuffs, ultrasound can not only increase the freezing rate, but also improve the quality of the frozen products. Application of power ultrasound can also benefit ice cream manufacture by reducing crystal size, preventing incrustation on freezing surface, etc. [Zheng and Sun 2006].

Among other applications are improvements in the extraction of flavourings, filtration, mixing and homogenization and the precipitation of airborne powders, destruction of foams which cause general difficulties in process control e.g. in fermentation [Ultrasound... 1998]. As a result of continued research interest and development in instrumentation, novel applications such as oxidation of unsaturated oils, aging of alcoholic beverages, hydration of acetylene, decalcification of bone, hydrolysis of esters have been developed [Mason 1999, McClements 1995].

ULTRASONIC INACTIVATION OF MICROORGANISMS

The most common techniques currently used to inactivate microorganisms in food products are conventional thermal pasteurization and sterilization. Thermal processing does kill vegetative microorganisms and some spores; however, its effectiveness is dependent on the treatment temperature and time. However, the magnitude of treatment, time and process temperature is also proportional to the amount of nutrient loss, development of undesirable flavours and deterioration of functional properties of food products. High power ultrasound is known to damage or disrupt biological cell walls which will result in the destruction of living cells. Unfortunately very high intensities are needed if ultrasound alone is to be used for permanent sterilization. However, the use of ultrasound coupled with other decontamination techniques, such as pressure, heat or extremes of pH is promising. Thermosonic (heat plus sonication), manosonic (pressure plus sonication), and manothermosonic (heat plus pressure plus sonication) treatments are likely the best methods to inactivate microbes, as they are more energy – efficient and effective in killing microorganisms. The advantages of ultrasound over heat pasteurization include: the minimizing of flavour loss, greater homogeneity and significant energy savings [Mason et al. 1996, Piyasena et al. 2003]. A considerable amount of data exists regarding the impact of ultrasound on the inactivation of microorganisms [Piyasena et al. 2003]. The effectiveness of an ultrasound treatment is dependent on the type of bacteria being tested. Other factors are amplitude of the ultrasonic waves, exposure time, volume of food being processed, the composition of food and the treatment temperature. Bactericidal effects of ultrasound were observed while suspended in culture medium [Davies 1959]. According to Lillard [1993] Salmonellae attached to broiler skin were reduced upon sonication in peptone at 20 kHz for 30 min. Results of research carried out by Dolatowski and Stasiak [2002] proved that ultrasound processing was having a significant influence on microbiological contamination of meat.

There are a large number of potential applications of high intensity ultrasound in the food industry. Applications of both high- and low-frequency ultrasound in the food industry have already been shown to have considerable potential for either modifying or characterising the properties of foods. In many instances, techniques based on ultrasound have considerable advantages over existing technologies.

ULTRASOUND IN MEAT TECHNOLOGY

The use of ultrasound for predicting fat and muscle content in live cattle has been around since the early 1950s [Wild 1950]. Today, ultrasound technology is routinely used by the beef industry for: evaluating seed stock [Wilson 1992], identifying dates to slaughter cattle [Hamlin et al. 1995], predicting quality, palatability, and cut-ability in carcasses [Houghton and Turlington 1992].

One of the most important quality attributes affecting consumer satisfaction and positive perception of beef is its tenderness. Inconsistency in beef tenderness has been rated as one of the major problems faced by the meat industry [Koohmaraie 1996]. Despite long term research interest in achieving consistent eating quality of meat, it still remains as an elusive goal in meat science. Tenderness is influenced by composition, structural organization and the integrity of skeletal muscle [Jayasooriya et al. 2004].

Tenderness of meat is determined by two major components of the skeletal muscle: contractile tissue, which is largely the myofibrillar fraction, and connective tissue fraction [Jayasooriya et al. 2007]. Traditional ageing relies on endogenous proteases [Koohmaraie 1994], however it is time consuming and its effectiveness varies between animals. Meat tenderness can be controlled by manipulating pre- and post-slaughter conditions through the use of physical methods, such as electrical stimulation [Hwang and Thompson 2001] and tenderstretch (pelvic suspension) of the prerigor carcass [Fisher et al. 2000]. Postrigor meat tenderness can also be improved by mechanical methods such as blade tenderization [Hayward et al. 1980], high pressure technology [Cheftel and Culioli 1997] or Hydrodyne process [Solomon et al. 1997]. Chemical and biochemical methods are also being used for tenderization. The importance of tenderness in determining meat acceptability, and the need for processes giving consistent and rapid improvements in tenderness, mean that other processes must be evaluated.

One possibility is the use of ultrasound which can cause physical disruption of materials through cavitation related mechanisms such as high shear, pressure and temperature and formation of free radicals [Jayasooriya et al. 2007]. Applications of ultrasound to provoke changes in physical and chemical properties of meat and meat products have attracted the interest of research workers for the past few decades because it is a pure physical technique, providing an alternative to chemical or thermal means of processing. Ultrasound was tested for its ability to induce membrane cell disruption that could increase meat tenderness either directly, through the physical weakening of muscle structure, or indirectly, by the activation of proteolysis either by release of cathepsins from lysosomes and/or of Ca^{++} ions from intracellular stores so that it may activate the calpains.

Ultrasound treatment of meat has produced inconsistent effects on meat tenderness, with some ultrasound treatments producing no effect on tenderness, while others decreased or increased tenderness [Jayasooriya et al. 2004]. Acoustic parameters (frequency, intensity, duration of treatment, temperature) determine the extent of the desired result achieved from sonication. Some studies show increased tenderness with low frequency ultrasound (22-40 kHz) treatment [Dickens et al. 1991, Dolatowski 1988, 1989]. Zayas and Gorbatow [1978] also reported the improvement of the tenderness of meat immersed in brine, sonifying at frequency of 22 kHz and 1.5-3 $W \cdot cm^{-2}$.

Experiments carried out on Semimembranosus muscle showed that ultrasound treatment (frequency 25 kHz; intensity 2 $W \cdot cm^{-2}$) during rigor mortis period (up to 24 hours post mortem) resulted in improved tenderness of meat during its ageing. The changes of sarcomere structure as well as higher WHC were observed for sonicated samples [Dolatowski 1999, Dolatowski and Twarda 2004]. Alterations in muscle structure, particularly the loss of the typical myofibrillar structure were observed for sonicated horse Semimembranosus muscle pumped with brine. Ultrasound treatment caused fragmentation of myofibrils and disintegration of other cellular components [Dolatowski 1988]. Ultrasound-assisted process of meat tumbling caused the significant improvement of the yield, tenderness and juiciness of the end product [Dolatowski and Stasiak 1995]. Sonication resulted in decreased drip loss and shear force of PSE meat [Dolatowski et al. 2001, Twarda and Dolatowski 2006].

Other studies showed ultrasound did not tenderize meat samples. This may be due to the use of relatively low intensity ultrasound baths (0.29-1.55 $W \cdot cm^{-2}$) [Lyng et al. 1997, Pohlman et al. 1997], or high intensity ultrasound (62 $W \cdot cm^{-2}$) applied to individual regions of the meat sample for short treatment times (15 s) [Lyng et al. 1998 a, b], which may have been insufficient to produce a tenderizing effect. Smith et al. [1991] exposed Semitendinosus muscle to ultrasound source at a frequency of 25.9 kHz in a water bath (filled with degassed saline water). Samples that were treated for 2 or 4 min had significantly lower shear force values than the untreated controls. However, the shear force increased after 8 min of treatment or an increased tenderness with short ultrasound treatments (up to 4 min), but decreased tenderness at longer treatment times (8-16 min). In a study of the effect of high frequency ultrasound on meat texture, pre- and postrigor meat were treated with high frequency, high intensity ultrasound (2.6 MHz, 10 $W \cdot cm^{-2}$) [Got et al. 1999]. Pre- and post-rigor ultrasound treatments had small effects on raw meat texture, with ultrasound treated meat having a slightly softer raw meat texture after three to six days ageing. The difference between control and ultrasound treated sample texture had disappeared after 14 days ageing.

However, the results of different studies may not be comparable because of differences in the type of muscles used, the animal age, the ultrasonic equipment and efficiency, intensities, frequencies, and the durations of ultrasound treatments.

Research in the last decade has shown the potential benefits of ultrasound treatment as an alternative technology for modifying properties of meat and meat products. The meat industry will benefit from further research and development on the applications of ultrasound in modifying physical and/or chemical properties of meat [Jayasooriya et al. 2004].

CONCLUSIONS

Ultrasound has attracted considerable interest in food science and technology due to its promising effects in food processing and preservation. As one of the advanced food technologies it can be applied to develop gentle but targeted processes to improve the quality and safety of processed foods and offers the potential for improving existing processes as well as for developing new process options. There are an increasing number of industrial processes that employ power ultrasound as a processing aid including the mixing materials; foam formation or destruction; agglomeration and precipitation of airborne powders; the improvement in efficiency of filtration, drying and extraction techniques in solid materials and the enhanced extraction of valuable compounds from vegetables and food products. Ultrasonic can be a specialized and versatile technology with numerous applications in food processing. Ultrasonic processing is still in its infancy and requires a great deal of future research in order to develop the technology on an industrial scale, and to more fully elucidate the effect of ultrasound on the properties of foods.

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ZASTOSOWANIE ULTRADŹWIĘKÓW W TECHNOLOGII ŻYWNOŚCI

Streszczenie. Ultradźwięki znajdują coraz powszechniejsze zastosowanie w przemyśle spożywczym. Większość badaczy rozróżnia dwa główne kierunki ich wykorzystania: pomiary ultradźwiękowe oraz bezpośrednie wspomaganie procesów przetwórczych. Ultradźwięki o małej intensywności są wykorzystywane do nieinwazyjnych, w pełni zautomatyzowanych pomiarów składu, struktury i właściwości produktów żywnościowych. Wykorzystanie ultradźwięków do wspomagania procesów technologicznych ma służyć przede wszystkim poprawie ich wydajności, ograniczeniu czasu i kosztów produkcji. Szeroki zakres możliwości stosowania ultradźwięków pozwala sądzić, iż w ciągu najbliższych lat będą one powszechnie wykorzystywane w zakładach przemysłu spożywczego.

Słowa kluczowe: ultradźwięki, przetwórstwo żywności, mięso, mikroorganizmy

Accepted for print – Zaakceptowano do druku: 2.08.2007

For citation – Do cytowania: Dolatowski Z.J., Stadnik J., Stasiak D., 2007. Applications of ultrasound in food technology. Acta Sci. Pol., Technol. Aliment. 6(3), 89-99.