Possibilities of applying high power ultrasound in meat industry

Režek Jambrak[1], A., Z Herceg[*], J. Grbavac[2]

Scientific paper

Summary

Preserving food by increased temperature in a short period of time is still the most frequent form of food preserving process. Process variables were derived from an empirical research on the effects of temperature and exposure time to microbial survival kinetics, with some attention paid to food quality connected to thermal effects on food composition and structure. The possibilities of applying high power ultrasound in meat processing are found in the following operations: extraction (ultrasound helps the process of extraction by disturbing meat myofibrils which release a sticky content by connecting meat and it leads to a higher strength of a reformed product); emulsification and homogenization (includes mixing of little pieces of meat with aqueous liquid which contains salt), curing (accelerating the process), freezing (the process of nucleation and the growth of ice crystals is accelerated; creating a larger share of smaller crystals), drying (ultrasound pretreatment prior to drying process consequently shortens drying time), changes in structure, and the most important application is in preserving a finished product. Applying high power ultrasound has shown itself in many examples to be a very good method in achieving a desired effect.

Keywords: *meat processing, high power ultrasound, preserving*

Introduction

Scientific researches nowadays are increasingly directed toward the development of different new techniques and combinations of food processing which enable obtaining products of high quality. One of those techniques is also a low-frequency high-power ultrasound whose application leads to physical changes in biological material and to acceleration of certain chemical reactions. The consequence of that is the inactivation of microorganisms and enzymes, facilitated emulsification and homogenization, better extraction, better effects of drying and alike.

High power ultrasound means the application of the intensity higher than 1 W/cm^2 (usually in the range from 10-1000 W/cm^2) and frequency between 18 and 100 kHz (McClements, 1995; Povey and Mason, 1998; Villamiel and de Jong, 2000b). The ultrasound of higher power and low frequencies (20 to 100 kHz) is considered to be the high power ultrasound because its application causes cavitation and has an application in food industry. It is applied for degassing of liquid food, induction of oxidation/reduction reactions, extractions of enzymes and proteins, inactivation of enzymes and induction of nucleation for crystallization (Roberts, 1993; Thakur and Nelson, 1997; Villamiel and de Jong, 2000a).

Pasteurization and sterilization are the most frequent and very widespread thermal treatments used for the inactivation of microorganisms and enzymes in food industry (Chemat et al., 2011). Consumer demands for products of high quality have encouraged food industry to research new techniques of processing to replace traditional processing methods (Awad et al., 2012). Ultrasound application is on the rise due to many advantages in comparison to conventional processes and some of those advantages are: short usage time, high productivity, simplified handling with the machines in comparison with the conventional processes, lower power consumption and products' price reduction (Chemat et al., 2011). The most favorable frequencies for the application in food industry are those above 20 kHz (Režek Jambrak et al., 2010a; 2010b).

The combination of ultrasound with heat and pressure (manothermosonication) has shown itself to be efficient in inactivation of enzymes resistant to heat (O'Donnell et al., 2010; Vercet et al., 1997). High power ultrasound is proved to be useful in the appearance of ice crystals during freezing of water (Li and Sun, 2002). Furthermore, other researches (Ashokkumar and Kentish, 2011; Lima and Sastry, 1990; Sastry et al., 1989) showed that high power ultrasound improves heat transfer. It is used in emulsification, sterilization, extraction, degassing, filtrating, drying and induction of oxidation (Mason, 1998). High power ultrasound induces protein extraction by increasing solubility (Moulton and Wang, 1982), but it also leads to a decrease in protein molecular mass (Režek Jambrak et al., 2014). High power ultrasound is also applied in isolation of starch from rice with promising results in short processing time (Wang and Wang, 2004).

Basic characteristics and activity of high power ultrasound

Zvučni valovi mogu se podijeliti s obzirom na frekvenciju u više područja koja određuju njihovu potencijalnu primjenu (slika 1).

[1] Anet Jambrak Režek, PhD, Associate Professor; Zoran Herceg, PhD, Full Professor; Faculty of Food Technology and Biotechnology, University of Zagreb, Pierottijeva 6, Zagreb
[*] Corresponding author: zherceg@pbf.hr

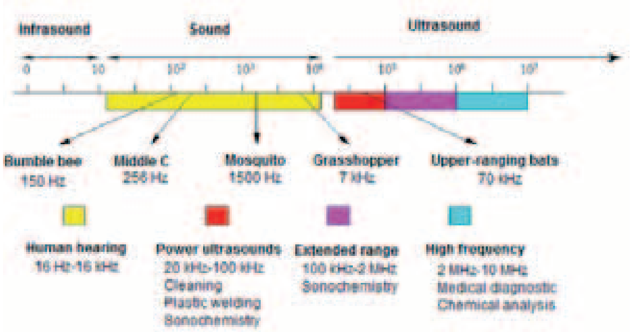

Figure 1. Areas of dividing sound according to frequencies (Mason, 1998)

Thereby the most significant frequencies of ultrasound for the application in food industry are those higher than 20 kHz.

Sound wave is determined by its amplitude [A] and frequency [f] (it can be chosen), then wavelength [λ] and attenuation coefficient [α]. Changes in amplitude of ultrasound at fixed positions in material and time are presented in Figure 2. At fixed positions in material, the distance between the successive maxima of wave varies sinusoidally with time. Amplitude [A] decreases with the increase in distance due to attenuation, and attenuation coefficient [α] is a measure of decrease of ultrasound amplitude after its transit through the material. Attenuation coefficient [α] of the material can be defined by the following expression (1) (Režek Jambrak, 2008):

$$(1)\quad A = A_0 \cdot e^{-\alpha x}$$

where A_0 is the initial amplitude of sound wave and *x* is distance travelled. The main causes for attenuation are absorption and scattering. Absorption is caused by a physical mechanism which transforms ultrasound energy into heat. Dispersion appears in heterogeneous materials like emulsions, suspensions and foams. As opposed to absorption, due to dispersion energy is still stored in the form of ultrasound energy, but it can't be registered because its direction and transmission phase are changed (McClements, 1995).

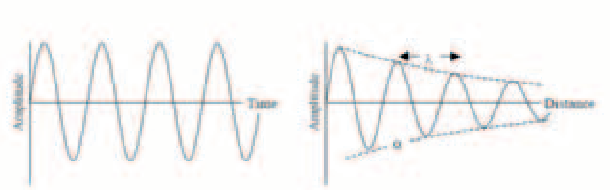

Figure 2. Changes in ultrasound amplitude with certain positions in material (left), and with certain time (right). T is the distance between the neighboring maxima of waves, λ is wavelength and α is attenuation coefficient (McClements, 1995)

High power ultrasound is generated by periodical mechanical probe movements; it transforms ultrasound energy to the medium and causes great changes in pressure, which then lead to the creation of the small, fast-growing bubbles (recesses) (Soria and Villamiel, 2010; Mason, 1998). The bubble expands during negative pressure and implodes during positive pressure by creating high temperatures and pressures. During the process of sonication, when the sound wave gets to the liquid medium, longitudinal waves are created as well as the areas of variable compressions and pressure expansions (Sala et al., 1995) which cause the appearance of cavitation and creating of gas bubbles. These bubbles have a larger surface during the cycle of expansion, so gas diffusion is increased. Maximum is reached where provided energy is insufficient in order to maintain the gas phase in a bubble, so in that way, a fast condensation appears (Režek Jambrak, 2008). Condensed molecules collide, thus creating shock waves. Those shock waves create the areas of very high temperature and pressure, reaching up to 5500 K and 50 MPa. Hot zones can have a bactericidal effect but, they are very limited and do not affect sufficiently a large surface, so bactericidal effect is based on changes in pressure. Cavitation caused by changes in pressure (created by ultrasound waves) shows bactericidal activity. Bactericidal effect is mostly based on thinning of cell membranes, localized heat and the production of free radicals (Butz and Tauscher, 2002; Fellows, 2000).

Expansion of acoustic wave through a medium causes different changes, out of which only some can be explained by individual mechanisms. The most significant effects of ultrasound are: heating, cavitation, structural effects, compression and expansion, turbulence, cleaning and others.

Generally, cavitation in fluids can cause a fast and complete venting; to initiate different chemical reactions by creating free chemical ions (radicals); to accelerate chemical reactions by improving the mixing of reactants; to encourage reactions of polymerization/depolymerization by temporary dispersion of aggregate or irreversible termination of chemical bonds in polymer chains; to increase the degree of emulsion generation; to improve the diffusion rate; to create highly concentrated emulsions or uniform particle dispersion; to aid the extraction of substances such as the enzymes from animal, plant or bacterial cells; to remove viruses from infected tissue; then, in the end, erode and break sensitive particles, including microorganisms (Režek Jambrak, 2008). Chemical reactions also take place around a reactive or a collapsing bubble in a stable and transient cavitation (growth and collapse of bubbles). Sonochemistry deals with those reactions of synthesis and other reactions. Bubble collapse results in intensive strong waves that can change significantly physical-chemical characteristics of the surrounding material. The effect of ultrasound treatment increases when ultrasound is used in a combination with conventional heating (e.g. homogenization of milk). The beginning of medium cavitation (that is, minimum of pressure oscillation needed to cause cavitation) is determined by a large number of factors (Rahman, 1999). Among them there are: dissolved gas, hydrostatic pressure, specific heat of liquid and gas in a bubble and surface liquid tension. The other, very important value is the temperature, which is inversely proportional to the beginning of cavitation. Still, ultrasound frequency is a determining factor of cavitation. It is hard to achieve cavitation at very high frequencies (above 1 MHz) and there is no cavitation above 2.5 MHz (Sala et al., 1995).

Possibilities of applying ultrasound in meat industry

1. Applying high power ultrasound in homogenization

Homogenization is a very important process of meat industry in which the product is chopped so that its particles are as equal in size as possible, as small as they can be and that the mixture of such particles is stabile (Mason, 1998). Different boiled sausages and salami are an example of homogenization.

2. High power ultrasound application in curing

Curing is a process in which meat is treated by table salt (NaCl) or curing salts in the goal of maintaining product's sustainability in the way to lower the values of water activity below microbiological border level. Ultrasound can greatly help in the process of curing a product because during the ultrasound treatment, by the activity of cavitation microchannels appear in meat tissue and it softens which leads to a faster, better and more equal distribution of cure within muscle tissue (Carcel et al., 2007; Jayasooriya et al., 2004; 2007).

3. High power ultrasound application in freezing

The application is also possible during freezing of meat because under the influence of a high power ultrasound the time shortens between crystallization initialization and a complete formation of ice, so the damage in cells is reduced that way (Li and Sun, 2002). In the research by Dolatowski and associates (2000) it was shown that during the activity of ultrasound on meat after the slaughter and prior to freezing, a larger number of small ice crystals appear which enables equal and proper freezing, as well as proper thawing without disrupting the meat structure.

4. High power ultrasound application in extractions

Ultrasound supports the process of extraction by disrupting meat myofibrils, which release a sticky content by connecting meat and leading to a higher strength of a reformed product (Povey and Mason, 1998). Binding strength, water holding capacity, color of a product and yield were researched after the treatment of mixing with salt, sonication or both (Jayasooriya et al., 2004, 2007). Samples which were subjected to both treatments (salt and sonication) were more superior in their relevant quality (McDonnell et al., 2014). A research on the effect of sonication on rolled ham has shown similar results. The traditional method of tenderization (softening) of meat by mechanical pounding, which gives weaker meat quality, is more palatable (tastier). Sonication of steaks has shown itself to be useful in meat softening (Dolatowski et al., 2000).

5. High power ultrasound application in inactivation of microorganisms

One of the roles of ultrasound is also an assisted process of preservation, i.e., pasteurization of products at lower temperatures and a shorter time of treating than in usual preservation methods. The effect of inactivation of microorganisms by ultrasound is assigned to creating intracellular cavitation so exactly these mechanical strokes can disrupt structural and functional components of cells until the point of breaking down (lysis) of the cell (Figure 3.). The effect of ultrasound is not equally efficient for microorganisms if it is applied at room temperatures (Butz and Tauscher, 2002).

The applications that use combinations of ultrasound with other preservation procedures are:

Manosonication (MS): combination of ultrasound and pressure

Thermosonication (TS): combination of ultrasound and heat

Manothermosonication (MTS): combination of ultrasound, heat and pressure

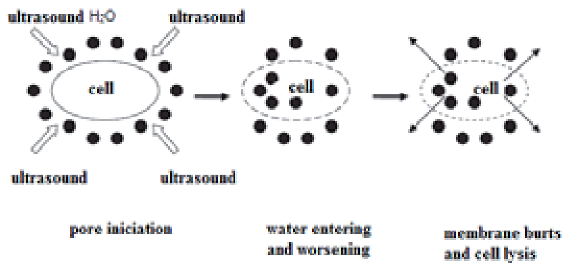

Figure 3. Mechanism of cell damage caused by ultrasound (Chemat et al., 2011)

Applying ultrasound in the goal of inactivating microorganisms started in the 1960s, after it had been discovered that sound waves used in submarine war cause fish kill (Earnshaw et al., 1995). Passing of acoustic energy of high intensity through a solid medium, sound wave causes series of fast and successive compressions and relaxations, with speeds that depend on its frequency. Due to that material is exposed to fast series of changeable shrinkages and expansions, similar to constant shrinkage and relaxation of a sponge (Režek Jambrak, 2008).

The used frequency of ultrasound treatment was studied by a large number of groups. Even though there are patents on systems of ultrasound inactivation of bacteria, Sala et al. (1995) determined that the usage of ultrasound in food processing is a very interesting assignment. Efficacy of ultrasound treatment is dependent on the type of treated bacteria. Microorganisms (especially spores) are relatively resistant to effects. Therefore, prolonged periods of ultrasonication would be needed in order to provide a safe product. If ultrasound were used in practice, it is most likely that it should be used in a combination with pressure treatment (manosonication) or heat treatment (manothermosonication). An improved mechanical breaking down of cells is a reason for better destroying of bacteria, when ultrasound is combined with pressure or heat.

The first paper in this area was made by Ordonez et al. (1984) using a 20 kHz and 160 W ultrasound in a combination with temperatures ranging from 5 to 62°C. The combination of heat and ultrasound was more efficient considering the time of treatment and energy consumed in comparison to any other individual treatment (Ordonez et al., 1984). McClements (1995) suggested that inactivation of microbes by using an ultrasound is efficient when used in a combination with other methods of decontamination such as heating, extreme pH or chlorination. Processes of sonication, thermosonication and manothermosonication were used by many researchers (Manas et al., 2000; Miles et al., 1995; Raso et al., 1998; Ordonez et al., 1984; Herceg et al., 2012a; Herceg et al., 2012b). Inactivation of microorganisms is defined by the decimal reduction time (D) (duration of treatment in minutes by which the count of surviving microorganisms decreases to 1/10 of the initial count) and it follows the first-order reaction kinetics. By analogy, inactivation of microorganisms during a thermal treatment was shown by the equation (2), after the ultrasound treatment (3) and the combination of thermal treatment and ultrasound treatment (4):

$$\log \frac{N_t^T}{N_0} = -\frac{t}{D_T} \qquad /2/$$

$$\log \frac{N_t^S}{N_0} = -\frac{t}{D_S} \qquad /3/$$

$$\log \frac{N_t^{TS}}{N_0} = -\frac{t}{D_{TS}} \qquad /4/$$

Since the mechanism of inactivating microorganisms by ultrasound and heat completely differs, Herceg et al. (2013) made a mathematical model for thermosonication (combination of ultrasound and thermal treatment) in order to determine the decimal reduction time during thermal treatment and ultrasound treatment with the presumption that ultrasound and temperature act individually (independently) and that destroying microorganisms by heat and ultrasound follows the first-order reaction kinetics. In that way logarithmic order of microorganism die-off can be expressed by the following equations: (the listed model is developed based on the model developed by Pagán et al. (1999) and Raso et al. (1998) :

$$\frac{N_t^{TS}}{N_0} = \frac{N_t^S}{N_0} \cdot \frac{N_t^T}{N_0} \qquad /5/$$

$$\log \frac{N_t^{TS}}{N_0} = \log\left(\frac{N_t^S}{N_0} \cdot \frac{N_t^T}{N_0}\right) \qquad /6/$$

$$\log \frac{N_t^{TS}}{N_0} = \log \frac{N_t^S}{N_0} + \log \frac{N_t^T}{N_0} \qquad /7/$$

$$-\frac{t}{D_{TS}} = -\frac{t}{D_S} - \frac{t}{D_T} \qquad /8/$$

$$\frac{1}{D_{TS}} = \frac{1}{D_S} + \frac{1}{D_T} \qquad /9/$$

$$\frac{1}{D_{TS}} = \frac{D_T + D_S}{D_S \cdot D_T} \qquad /10/$$

$$D_{TS} = \frac{D_T \cdot D_S}{D_T + D_S} \qquad /11/$$

where N_0 - is microorganism count before the treatment- N_t^T - is microorganism count after the time t and thermal treatment, N_t^S - is microorganism count after the time "t" and ultrasound treatment, N_t^{TS}- is microorganism count after the time "t" and ultrasound and heat treatment (thermosonication) D_T - is decimal time of reduction during thermal treatment (s), D_S - is decimal time of reduction during ultrasound treatment (s), D_{TS}- is decimal time of reduction during ultrasound and heat treatment (thermosonication) (s).

6. High power ultrasound application in emulsifying

One of the earliest uses of ultrasound in processing is emulsifying (Povey and Mason, 1998). If a bubble collapses near the phase boundary of two liquids which are not mixed, the resulting wave can ensure an efficient mixing of the layers. Stabile emulsions created by ultrasound were used in textile, cosmetic, pharmaceutical and food industry. Such emulsions are usually more stable than those produced conventionally and usually require little or no surfactants. There were obtained emulsions with smaller sizes of drops and a narrower distribution of size, in comparison to other methods. The degree of emulsification with such materials can be estimated by measuring the ultrasound speed in connection with attenuation. The combination of measuring speed and attenuation is promising as a method of analysis of edible fats and oils, and for determining the degree of crystallization and melting in dispersed drops of emulsion (Režek Jambrak, 2008).

7. The effect of ultrasound on meat texture

In the research by Ozun et al. (2013) the application of ultrasound consequently leads to an increased salting kinetics, which efficiently increases moisture and NaCl diffusion. The increase in the share of NaCl in meat leads to a change in meat texture, and a high share of NaCl leads to tough meat. Microstructural analysis has shown that the application of high power ultrasound during salting brought appropriate effects in microstructure of meat, as well as it contributed to a more homogenous distribution of NaCl in meat. Therefore, ultrasound can be considered to be potential technology which can be used to accelerate the salting process (Ozuna et al., 2013).

8. Low power ultrasound application in the process of stuffing sausages

The application of low power ultrasound as opposed to the application of high power ultrasound has a different purpose and usage. Low power ultrasound uses higher frequencies and can be used during determining the composition of meat (share of fat, thickness of adipose tissue), during determining the quantity of stuffing while filling the casings in sausage production, during determining the mineral share in meat, for determining the share of water and other purposes. Figure 4. shows an example of using a low power ultrasound during filling the stuffing in sausage production (Knorr et al., 2004).

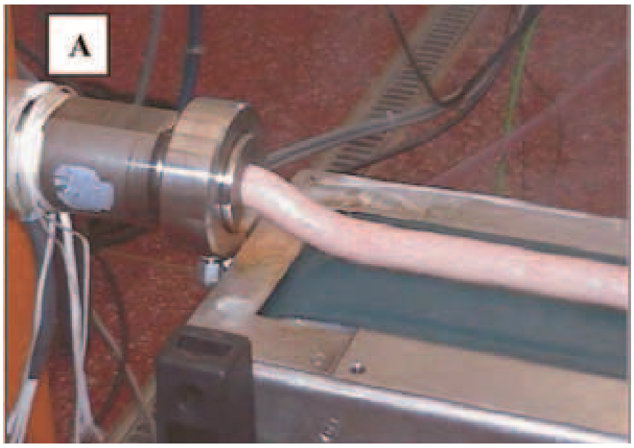

Figure 4. Photo of sausage production assisted by ultrasound which enables a proper filling (e.g. Frankfurter sausage), (Knorr et al., 2004)

9. World producers of equipment for food processing by high and low power ultrasound

QSonica Sonicators

(http://www.sonicator.com); Hielscher (http://www.hielscher.com);

Etrema (http://www.etrema.com);

Lincis

(http://www.lincis.com/index.php?option=com_k2&view=item&id=159:ultratender);

Bandelin (http://www.bandelin.com);

Newtech (http://www.newtech-ltd.co.uk) and others.

Info (http://www.sonochemistry.info);

Conclusions

Ultrasound has shown itself to be a very interesting and important technique in food technology and meat processing due to promising results in food preservation. As one of the more advanced techniques, it is possible to be applied while creating a process that is simple. Also, it is a target process of improving quality and safety of processed food and it provides potential for the improvement of the existing processes as well as for the creation of new ones. The paper presents some of the application possibilities for high power ultrasound in meat processing: emulsification and homogenization, extraction, microorganism inactivation, freezing improvement, drying, changes in meat texture, assisted (accelerated) curing, etc. Ultrasound cavitation, micro flows and localized heating enable creating a high-quality product and extended shelf life. Ultrasound also enables a quicker maturing of meat.

A loss of quality is connected to deformation of plant and animal structures, modification of macromolecules and creating of new ones from reactions catalyzed by heat. As one of the methods of non-heat treatment of food products, ultrasound gives the possibility of decreasing these effects. A possible application of high power ultrasound enables applying ultrasound in order to use the ability of cell damage in preserving systems –destroying the microorganisms. High power ultrasound can be used with the goal of inactivating microorganisms or in other case to activate an individual process which is catalyzed by some enzymes depending on the frequency applied, power and the duration of ultrasound treatment.

References

Ashokkumar, M., S. Kentish (2011): The physical and chemical effects of ultrasound. U: Ultrasound technologies for food and bioprocessing, (Feng, H., Barobosa-Cànovas, G., Weiss, J., ured.), Springer, New York, USA, str. 1-105.

Awad, T.S., H.A. Moharram, O.E. Shaltout, D. Asker, M.M. Youssef (2102): Applications of ultrasound in analysis, processing and quality control of food: A review. Food Research International 48 (2), 410---427.

Butz, P., B.Tauscher. (2002): Emerging technologies: chemical aspects. Food Research International 35 (2/3), 279– 284.

Carcel, J., J. Benedito, J. Bon, A. Mulet (2007): High intensity ultrasound effects on meat brining. Meat Science 76, 611–619.

Chemat, F., F. Zill-e-Huma, M.K. Khan (2011): Applications of ultrasound in food technology: processing, preservation and extraction. Ultrasonic Sonochemistry 18, 813-835.

Dolatowski, Z. J., Stadnik, D. Stasiak (2007): Applications of ultrasound in food technology. ACTA Scientiarum Polonorum Technologia Alimentaria Journal 6 (3), 89-99.

Earnshaw, R. G., J. Appleyard, R.M. Hurst (1995): Understanding physical inactivation processes: combined preservation opportunities using heat, ultrasound and pressure. International Journal of Food Microbiology 28, 197-219.

Fellows, P. (2000): Food Processing Technology - Principles and Practice (2 izdanje), Woodhead Publishing, Cambridge, UK.

Herceg Z., E. Juraga, B. Sobota Šalamon, A. Režek Jambrak (2012a): Inactivation of mesophilic bacteria in milk by means of high intensity ultrasound using response surface methodology, Czech Journal of Food Science 30, 108–117.

Herceg Z., A. Režek Jambrak, V. Lelas, S. Mededovic Thagard (2012b): The effect of high intensity ultrasound treatment on the amount of Staphylococcus aureus and Escherichia coli in milk, Food Technology and Biotechnology 50,46–52.

Herceg Z., K. Markov, B. Sobota Šalamon, A. Režek Jambrak, T. Vukušić, J. Kaliterna (2013): High Intensity Ultrasound against Spoilage Bacteria, Food Technology and Biotechnology, 51, 352–359.

Jayasooriya S.D.,B.R. Bhandari, P. Torley, B.R. D'Arcy (2004): Effect of high power ultrasound waves on properties of meat: a review. International Journal of Food Properties 7, 2, 301-319.

Jayasooriya S.D., P. Torley, B. R. D'Arcy, B.R. Bhandari (2007): Effect of high power ultrasound and ageing on the physical properties of bovine Semitendinosus and Longissimus muscles. Meat Science 75, 628-639.

Knorr, D., M. Zenker, V. Heinz, D.U. Lee (2004): Applications and potential of ultrasonics in food processing. Trends in Food Science & Technology 15, 261–266.

Li, B, D.W. Sun (2002): Effect of power ultrasound on freezing rate during immersion freezing. Journal of Food Engineering 55(3), 277-282.

Lima, M., S.K. Sastry (1990): Influence of fluid rheological properties and particle location on ultrasound-assisted heat transfer between liquid and particles. Journal of Food Science 55, 1112-1115.

Manas, P., R. Pagan, J. Raso, F.J. Sala, S. Condon (2000): Inactivation of Salmonella Typhimurium, and Salmonella Senftenberg by ultrasonic waves under pressure. Journal of Food Protection 63 (4), 451– 456.

Mason, T. J. (1998): Power ultrasound in food processing - the way forward. U: Ultrasound in Food Processing. Povey, M. J. W. i Mason, T. J. (ured.), Blackie Academic & Professional: London.

McClements, D. J. (1995): Advances in the application of ultrasound in food analysis and processing. Trends in Food Science & Technology, 6, 293.

McDonnell, C.K, P. Allen, C. Morin, J.G. Lyng (2014): The effect of ultrasonic salting on protein and water-protein interactions in meat. Food Chemistry 147, 245-251,

Miles, C.A., M.J. Morley, W.R. Hudson, B.M. Mackey (1995): Principles of separating microorganisms from suspensions using ultrasound. Journal of Applied Bacteriology 78, 47– 54.

Moulton, K.J., L.C. Wang (1982): A pilot-plant study of continuous ultrasonic extraction of soybean protein. Journal Food Science 47, 1127.

O'Donnell, C. P., B.K. Tiwari, P. Bourke, P.J. Cullen (2010): Effect of ultrasonic processing on food enzymes of industrial importance. Trends in Food Science and Technology 21, 358-367.

Ordonez, J.A., B. Sanz, P.E. Hernandez, P. Lopez-Lorenzo (1984): A note on the effect of combined ultrasonic and heat treatments on the survival of thermoduric streptococci. Journal of Applied Bacteriology 54, 175– 177.

Ozuna C., A.Puig, J.V- Garcia-Perez, A. Mulet, J.A. Carcel (2013): Influence of high intensity ultrasound application on mass transport, microstructure and textural properties of pork meat (Longissimus dorsi) brined at different NaCl concentrations. Journal of Food Engineering 119, 84–93.

Págan R., P. Maòas, J. Raso, S. Condon (1999): Bacterial resistance to ultrasonic waves under pressure at nonlethal (manosonication) and lethal (manothermosonication) temperatures, Appiled and Environmental Microbiology, 65, 297–300.

Povey, M. J. W., T.J. Mason (1998): Ultrasound in Food Processing, Blackie Academic & Professional, London.

Rahman, M.S. (1999): Light and sound in food preservation. U: Handbook of Food Preservation. Rahman, M.S. (ured.), Marcel Dekker: New York, 673–686.

Raso, J., P. Pagan, S. Condon, F.J. Sala (1998): Influence of temperature and pressure on the lethality of ultrasound. Appiled and Environmetal Microbiology 64, 465.

Režek Jambrak A. (2008): Utjecaj ultrazvuka na fizikalna i funkcionalna svojstva proteina sirutke. Doktorska disertacija, Prehrambeno-biotehnološki fakultet, Zagreb.

Režek Jambrak, A.,V. Lelas, Z. Herceg, M. Badanjak, Z. Werner (2010a): Primjena ultrazvuka visoke snage u sušenju voća i povrća. Kemija u industriji 59 (4), 169-177.

Režek Jambrak, A., Z. Herceg, D. Šubarić, J. Babić, M. Brnčić, S. Rimac Brnčić, T. Bosiljkov, D. Čvek, B.Tripalo, J. Gelo (2010b): Ultrasound effect on physical properties of corn starch. Carbohydrate Polymers 79 (1), 91-100.

Režek Jambrak, A., T.J. Mason, V. Lelas, L. Paniwnyk, Z. Herceg (2014): Effect of ultrasound treatment on particle size and molecular weight of whey proteins. Jorunal of food engineering 121, 15–23.

Roberts, R. T. (1993): High intensity ultrasonics in food processing. Chemistry and Industry, FEB, 15(4), 119–121.

Sala, F. J., J. Burgos, S. Condon, P. Lopez, P., J. Raso (1995): Effect of heat and ultrasound on microorganisms and enzymes. U: New Methods of Food Preservation. Gould, G. W. (ured.), Blackie Academic & Professional: London.

Sastry, S. K., G. Q. Shen, J.L. Blaisdell (1989): Effect of ultrasonic vibration on fluid-to particle convective heat transfer coefficients. Journal of Food Science 54, 229.

Soria, A. C., M. Villamiel (2010): Effect of ultrasound on the technological properties and bioactivity of foods: a review. Trends in Food Science and Technology 21, 323-331.

Suslick, K. S. (1988): Ultrasounds: its Chemical, Physical and Biological Effects. VHC

Publishers, New York.

Thakur, B. R., P.E. Nelson (1997): Inactivation of lipoxygenase in whole soy flour suspension by ultrasonic cavitation. Die Nahrung 41, 299.

Vercet, A., P. Lopez, J. Burgos (1997): Inactivation of heat-resistant lipase and protease from Pseudomonas fluorescens by manothermosonication. Journal of Dairy Science 80, 29.

Villamiel, M., P. de Jong (2000a): Inactivation of Pseudomonas fluorescens and Streptococcus thermophilus in Tryptocase Soy Broth and total bacteria in milk by continuous-flow ultrasonic treatment and conventional heating. Journal of Food Engineering 45, 171-179.

Villamiel, M., P. de Jong (2000b): Influence of high-intensity ultrasound and heat treatment in continuous flow on fat, proteins, and native enzymes of milk. Journal of Agricultural Food Chemistry 48, 472-478.

Wang, L., Ya-Jane Wang (2004): Rice starch isolation by neutral protease and high-intensity ultrasound. Journal of Cereal Science 39 (2), 291-296.

Delivered: 13.6.2014. Accepted: 21.7.2014.