
Pulsed Electric Field Processing in Food Technology

Yashwant Kumar*, Krishna Kumar Patel** and Vivek Kumar***

*Assistant Professor, Dept. of FPT, Bilaspur University, Bilaspur-495001, Chhattisgarh, India

**Scientist (AS&PE), AICRP on PHT, Dept of PHE&T, AMU, Aligarh, UP, India

***Research Scholar, Dept AFE, Indian Institute of Technology, Kharagpur WB, India

ABSTRACT:

Pulsed electric field (PEF) processing is a emerging method of food preservation that uses short bursts of electricity for microbial inactivation (cell-lysis) and causes minimal or no detrimental effect on food quality attributes. PEF can be used for processing liquid and semi-liquid food products.

Keywords: *Pulse effect processing, emerging technology, non-thermal technique, minimal processing and pulse effect field processing.*

INTRODUCTION

Pulsed electric field (PEF) processing is a novel, non-thermal preservation method that has the potential to produce foods with excellent sensory and nutritional quality and shelf-life. High intensity pulsed electric field (HIPEF) processing involves the application of pulses of high voltage (typically 20 - 80 kV/cm) to foods placed between 2 electrodes. PEF treatment is conducted at ambient, sub-ambient, or slightly above ambient temperature for less than 1 s, achieved by multiple short duration pulses typically less than 5 μ s and energy loss due to heating of foods as well as undesirable changes in the sensory properties of the food is minimized. For food quality attributes, PEF technology is considered superior to traditional heat treatment of foods because it avoids or greatly reduces the detrimental changes of the sensory and physical properties of foods (Quass, 1997). Although some studies have concluded that PEF preserves the nutritional components of the food, effects of PEF on the chemical and nutritional aspects of foods must be better understood before it is used in food processing (Qin *et al.*, 1995b).

Some important aspects in pulsed electric field technology are the generation of high electric field intensities, the design of chambers that impart uniform treatment to foods with minimum increase in temperature, and the design of electrodes that minimize the effect of electrolysis. The large field intensities are achieved through storing a large amount of energy in a capacitor bank (a series of capacitors) from a DC power supply, which is then discharged in the form of high voltage pulses. Studies on energy requirements have concluded that PEF is an energy efficient process compared to thermal pasteurization, particularly when a continuous system is used (Qin *et al.*, 1995a).

Consumer demand has increasingly required processed food to have a more 'natural' flavour and colour, with a shelf life that is sufficient for distribution and a reasonable period of home

storage before consumption (Fellow, P. J., 2000). This can be achieved by *minimal processing methods* that preserve foods but also remain to a greater extent their nutritional quality and sensory characteristics by reducing the reliance on heat as the main preservative action. This minimal processing destroys microorganisms, and in some cases enzymes, and there are no substantial increases in product temperature. There is therefore little damage to pigments, flavour compounds and vitamins and, in contrast to heat processing, the sensory characteristics and nutritional value of foods are not degraded to a significant extent. The resulting products have higher quality and consumer appeal in markets where the retention of natural sensory characteristics can command premium prices.

The use of an external electrical field for a few microseconds induces local structural changes and a rapid breakdown of the cell membrane. Based on this phenomenon, called electroporation, many applications of high intensity pulsed electric fields (HIPEF) have been studied in the last decades. In the area of plant and microbial genetics pulsed electric fields are applied to cause an electroporation of cell membranes to infuse foreign material such as DNA into the cell (Neumann, 1996; Zimmermann, 1996). This process of reversible pore formation has to be controlled to maintain viability of the organisms during the application of the PEF. Due to the reversible permeabilization, the cells repair their membranes through resealing the electropores immediately after the PEF treatment. At higher treatment intensity PEF can be utilized for the inactivation of microorganisms by an irreversible breakdown of the cell membrane.

HIPEF consists of a number of components including a power source, capacitor tank, a switch, treatment chamber, voltage current and temperature sensors and aseptic packaging equipment. Generation of different voltage waveforms in PEF: exponential pulses, square pulses, bipolar pulses and oscillatory pulses.

Formation of pores and cell membranes by HIPEFs is not entirely understood. Zimmermann *et al.*, (1974), applying the dielectric rupture theory, concluded that membrane rupture is caused by an induced transmembrane potential approximately 1V larger than the natural potential of the cell membrane. The reversible or irreversible rupture (or electroporation) of a cell membrane depends on factors such as intensity of the electric field, number of pulses, and duration of pulses. The plasma membranes of cell become permeable to small molecules after being exposed to an electric field; permeation then causes swelling and the eventual rupture of the cell membrane.

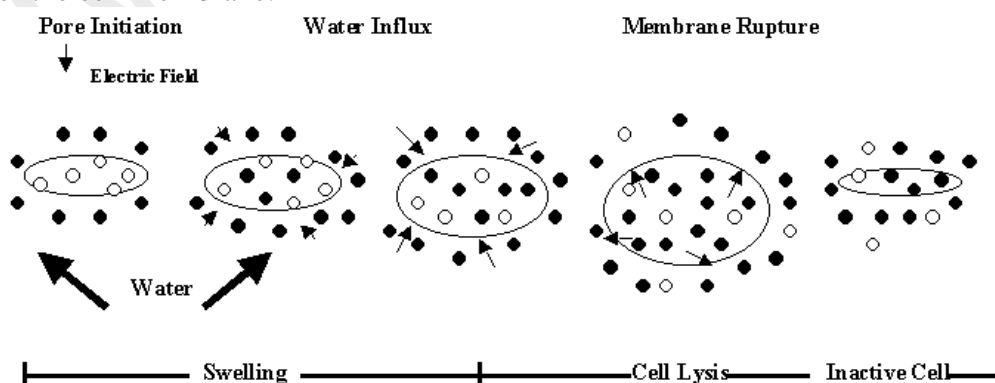


Fig. 1.1: Electroporation of a cell membrane

HIPEF processing system is associated with minimum energy utilization and greater energy efficiency than thermal processing. In apple juice treatment, energy utilized in PEF is 90% less than the amount of energy used in high temperature and short time processing methods (HTST). Recent studies have confirmed that PEF-treated orange juice retains all the physical properties, along with a 97.5% of vitamin C. In September 1996, the U.S. food and Drug Administration (FDA), based in Washington, DC, released a “letter of no objection” for the use of Pulsed electric field processing to treat liquid eggs.

HISTORY AND ENGINEERING APECTS OF PEF PROCESSING

Historical background of PEF processing

The bactericidal effect of an electric current had already been tested at the end of the nineteenth century (Prochownick and Spaeth, 1890; Krüger, 1893; Thiele and Wolf, 1899), but the lethal effects found by applying direct or low-frequency alternating current resulted from thermal or electrochemical effects. In the 1920s a process called ‘Electropure’ was introduced in Europe and the USA (Moses, 1938). Being one of the first attempts to use electricity for milk pasteurization, it was performed by the application of a (not pulsed) 220 V alternating current within a carbon electrode treatment chamber. About 50 plants were in operation until the 1950th, but due to rising energy costs and competition with mild novel thermal preservation technologies such as UHT, these (ohmic heating) plants have been replaced (Reitler, 1990). Apart from thermal effects based on the mechanism of ohmic heating, lethal effects of electrochemical reactions such as the hydrolysis of chlorine were found when subjecting food to discharges with a voltage of 3–4 kV (Pareilleux and Sicard, 1970). Pulsed discharges of high voltage electricity across two electrodes for microbial inactivation were first investigated in the 1950th (Allen and Soike, 1966; Edebo and Selin, 1968), resulting in a process called electrohydraulic treatment. The electrodes were submerged in the liquid medium within a pressure vessel, electric arcs were generated by high voltage pulses forming transient pressure shock waves up to 250MPa and ultraviolet light pulses.

Experiments conducted by Doevenspeck (1984) revealed that pulsed electric fields can be applied for disruption of cells in food material and were further developed and expanded to the inactivation of microorganisms and wastewater treatment. Based on this work, the ‘Elcrack’ process for the disinter-gration of animal material such as fish or meat and the ‘Elsteril’ process for liquid media decontamination were developed by Krupp Maschinentechnik GmbH, Germany (Sitzmann and Münch, 1988). The application of electric fields for electroplasmolysis of apple mash was first reported by Flaumenbaum (1968), in which an increase in juice yield of 10–12 per cent was found and the products were described to be lighter in colour and less oxidized than after a heat or enzymatic pre-treatment (McLellan *et al.*, 1991).

Important early patents in the application of PEF for treatment were applied by Krupp in Germany, developing the ‘Elcrack’ and ‘Elsteril’ processes, for inactivation of vegetative microorganisms in milk and fruit juices with an electric field strength up to 30 kV/cm, but heating due to high energy dissipation and consequently high costs of operation inhibited a successful industrial application. Later patents were applied by PurePulse Technologies, San Diego, USA with electric fields in the range from 10 to 25 kV/cm and the microbial

inactivation and effect on fruit juice quality was investigated by Dunn and Pearlman (1987) showing an increase of shelf-life of about one week.

Today about 20 research groups are working in this area worldwide, but still there is no commercial, industrial system available. For liquid food preservation four pilot scale systems are available at present, at Ohio State University (USA), at Stork Food and Dairy Systems (The Netherlands), at SIK (Sweden) and at the Berlin University of Technology (Germany).

Engineering Aspects of PEF processing:

(a). bench-Top Unit; (b). lab- Scale Pulser and (c).treatment Chamber.

MECHANISM OF ACTIONS IN PEF PROCESSING

It is generally accepted that the primary effect of PEF on biological cells is related to local structural changes and the breakdown of the cell membrane, which is a highly important component of the biological cell as it acts as a semi-permeable barrier responsible for mass transfer and plays an important role in the synthesis of RNA and DNA, protein and cell wall components as well as many other complex metabolic activities (Rogers *et al.*, 1980). Disruption of intracellular organelles and other structural changes have also been described (Harrison *et al.*, 1997).

When the overall potential exceeds a critical value of about 1V, depending upon the compressibility, the permittivity and the initial thickness of the membrane (Crowley, 1973; Zimmermann, 1996), the electrocompressive force causes a local dielectric rupture of the membrane inducing the formation of a pore, acting as a conductive channel (Schoenbach *et al.*, 1997). Taking into account a membrane thickness of 5 nm, this translates to a dielectric strength of 2000 V/cm. A drastic increase in permeability re-establishes the equilibrium of the electrochemical and electric potential differences of the cell plasma and the extracellular medium.

Alternative concepts are based on molecular reorientation and localized defects within the cell membrane which are expanded and destabilized by exposure to an electric field. The presence of small fluctuating hydrophobic pores in the lipid matrix was suggested to be the initial structural basis of electroporation (Chernomordik, 1992).

PULSED ELECTRIC FIELD PROCESSING

Present status of pulsed electric field technology

The extent of improvement in a food processing company achieved by an emerging technology generally reflects the interest in that technology by the food industry. The method of high intensity pulse electric field used to inactivate microorganisms has been under research for nearly 45 years, initiated with the first patent received by Doevenspeck (Doevenspeck, 1960). During this time span the technology has proved to be most effective in the activation of vegetative bacteria, yeasts, and molds, while bacterial spores are much more tolerant (Qin *et al.*, 1996). Additionally, the synergistic effect to PEF technology in combination with other mild preservation methods is one of the interests popular in recent years. The use of antimicrobials as nisin or other bacteriosins has been proposed as having lethal effects on electroporation.

Among all liquid products, PEF technology has been most widely applied to apple juice, orange, juice, milk, liquid egg, and brine solutions (Qin *et al.*, 1995).

A significant inactivation of staphylococcus aureus inoculated skim milk treated by PEF was also reported (Evrendilek *et al.*, 2004). The ability of PEF to increase permeabilization means it can be successfully used to enhance mass and heat transfer to assist drying of plant tissues. As started before, PEF technology commonly focused on processing pumpable and homogenous liquid foods free of particles and air. In the case of solid foods the mixture is mixed with air, contributing to the low electric conductivity of the product, hence, not limiting the maximum applicable electric field intensity. Some studies conducted on model foods, viscous foods such as yoghurt and rice pudding or particulate foods such as pea soup with plastic beads, reported successful result for PEF application on solid or semi-solid foods.

Industrialization and Production Costs

The major concern of industrialization in the application of PEF is the initial investment. Cost estimates of a commercial-scale PEF pulse generator with a production scale of 1000 to 10,000 liter/hr indicate a range between \$500,000 and \$1,000,000 U. S. dollars. However these expenses are estimate for a custom design, so the initial cost of future equipment may be less expensive. The pilot plant size pulser commercially available at the PurePulse Company in San Diego, California, can process 100-300 liter/hr and apply square pulses of 2-3 μ sec at a repetition rate of 1000 Hz. It is design to process orange juice at a flow rate of 100-300 liter/hr. PurePulse also has estimated costs for a 10 liter/hr, 50-kV/cm, 100-J/ml, and 2- μ sec square-wave laboratory-scale system available upon request. Also important to note is that these systems have estimated operating costs of \$0.2/liter (EPRI, 1998).

The expected lifetime of a high-pulse voltage generator is around 4-5 years with 20 hr/day of operation. Researchers have estimated that 42% of the operating costs are those related to electricity. Energy consumption for the pasteurization step has been reported as low as 1.3 J/ml, which is particularly appealing compared with almost 100 J/ml used in heat pasteurization.

Advantages: Kills vegetative cells; colors, flavors and nutrients are preserved; no evidence of toxicity; relatively short treatment time; accelerated thawing; decontamination of heat sensitive foods; best suitable for liquid foods; pasteurization of fruit juices, soups, liquid egg and milk; no environmental hazard.

Limitations: Some of the most important current technical drawbacks or limitations of the PEF technology are: - High initial cost; no effect on enzymes and spores, PEF alone; only suitable for liquids particles in liquids; products of electrolysis may adversely affect foods; energy efficiency not yet certain; the availability of commercial units, which is limited to one by PurePulse Technologies, Inc., and one by Thomson-CSF; The presence of bubbles, which may lead to non-uniform treatment as well as operational and safety problems; Limited application, which is restricted to food products that can withstand high electric fields; The particle size of the liquid food in both static and flow treatment modes. The maximum particle size in the liquid must be smaller than the gap of the treatment region in the chamber in order to maintain a proper processing operation.

APPLICATIONS OF PEF TECHNOLOGY IN FOOD PROCESSING

Rahman (1999) reported the applications of PEF as a food processing tool is gaining popularity, since it represents a nonthermal alternative to conventional pasteurization methods. The PEF treatment, being a nonthermal process, may also have no significant detrimental effect on heat-labile components present in foods such as vitamins. The major disadvantage of PEF operation is the initial investment. A pilot-size pulser may cost around \$250,000. Other units for industrial use are available at prices that range from \$450,000 to 2,000,000.

Microorganism inactivation

PEF has been mainly applied to preserve the quality of foods, such as to improve the shelf-life of bread, milk, orange juice, liquid eggs, and apple juice, and the fermentation properties of brewer's yeast.

1. Processing of apple juice: Simpson *et al.* (1995) reported that apple juice from concentrate treated with PEF at 50 kV/cm, 10 pulses, and pulse width of 2 μ s and maximum processing temperature of 45 °C had a shelf-life of 28 day compared to a shelf-life of 21 day of fresh-squeezed apple juice. There were no physical or chemical changes in ascorbic acid or sugars in the PEF-treated apple juice and a sensory panel found no significant differences between untreated and electric field treated juices.

2. Processing of orange juice: Zhang *et al.* (1997) evaluated the shelf-life of reconstituted orange juice treated with an integrated PEF pilot plant system. The PEF system consisted of a series of co-field chambers. Temperatures were maintained near ambient with cooling devices between chambers. Three waveshape pulses were used to compare the effectiveness of the processing conditions. Their results confirmed that the square wave is the most effective pulse shape.

3. Processing of milk: Fernandez-Molina *et al.* (1999) studied the shelf-life of raw skim milk (0.2% milk fat), treated with PEF at 40 kV/cm, 30 pulses, and treatment time of 2 μ s using exponential decaying pulses. The shelf-life of the milk was 2 wk stored at 4 °C; however, treatment of raw skim milk with 80 °C for 6 s followed by PEF treatment at 30 kV/cm, 30 pulses, and pulse width of 2 μ s increased the shelf-life up to 22 d, with a total aerobic plate count of 3.6-log cfu/ml and no coliform. The processing temperature did not exceed 28 °C during PEF treatment of the raw skim milk.

4. Processing of eggs: Earliest studies in egg products were conducted by Dunn and Pearlman (1987) in a static parallel electrode treatment chamber with 2-cm gap using 25 exponentially decaying pulses with peak voltages of around 36 kV. Tests were carried out on liquid eggs, on heat-pasteurized liquid egg products, and on egg products with potassium sorbate and citric acid added as preservatives. Comparisons were made with regular heat-pasteurized egg products with and without the addition of food preservatives when the eggs were stored at low (4 °C) and high (10 °C) refrigeration temperatures. The study showed the importance of the hurdle approach in shelf-life extension.

5. Processing of green pea soup: Vega-Mercado *et al.* (1996a) exposed pea soup to 2 steps of 16 pulses at 35 kV/cm to prevent an increase in temperature beyond 55 °C during treatment. The shelf-life of the PEF-treated pea soup stored at refrigeration temperature exceeded 4 wk. There were no apparent changes in the physical and chemical properties or sensory attributes of the pea soup directly after PEF processing or during the 4 wk of storage at refrigeration temperatures.

6. Processing of beer: Inactivation and sub-lethal injury of the beer spoilage organism *Lactobacillus plantarum* in a model system using different pulsed electric field (PEF) strengths (10–19 kV/cm) and total energy inputs (13–42 kJ/kg) were investigated (Ulmer *et al.*, 2002).

Spore inactivation

Compared to vegetative cells, microbial spores are resistant to extreme ambient conditions such as high temperatures and osmotic pressures, high and low pHs, and mechanical shocks. Their resistance is associated not only with their small size (which make them more difficult to destroy than larger cells), but also dehydration and mineralization. Yin *et al.* (1997) reported that inactivation up to 2 log cycles of *B. subtilis* spores with pulse durations of 1, 2, 4, and 6 μsec at frequencies of 3000, 1500, 750, and 500 Hz, respectively, with an applied electric field strength of 30 kV/cm at 36 °C.

Enzyme inactivation

Enzymatic activity is altered by PEF, though, in general, enzyme inactivation by PEF requires stronger electrical condition to achieve significant reductions than microbial inactivation (Ho *et al.*, (1997). This fact is important because some enzymes are useful for the food industry, thus PEF would allow the destruction of microorganisms while maintaining the activity of some enzymes (Martin-Belloso *et al.*, 2004).

PROBLEM AND CHALLENGES IN PEFS PROCESSING

A task still challenging for electro-engineers is the development of equipment with reliable, industrial scale generation of high-strength electric field pulses.

Javier Raso and Volker Heinz (2006) reported important things which are that, from 2000 to the present, great advances have been achieved in the commercialization of PEFs applications. However translating the technical parameters into affordable and effective PEF system within legal regulation is not easy. Currently, commercial PEF systems are available that include both bench-top and industrial systems, as those provided by Pure-pulse Technologies, Inc. and Thomson. CSF, besides many different lab-scale and pilot-scale PEF systems. The present challenge is to increase treatment capacity with the use of feasible high power systems, by optimizing the overall PEF system design in light of critical process parameters.

In the last few years problems due to electrochemical reactions at the electrode/medium interfaces have been discussed (Morren *et al.*, 2003; Roodenburg *et al.*, 2003), indicating that there is a challenge to replace commonly used stainless steel electrodes by other materials or to modify pulse generator systems to reduce the amount of electrochemical reactions. An overview of possible electrochemical reactions at a steel electrode may cause harmful to human being.

Application of carbon electrodes may be one solution to overcome this problem (Toepfl *et al.*, 2004) and application of shorter pulses or switching systems without leak current have also been discussed (Mastwijk, 2004) to avoid electrochemical reactions. Apart from a reduction in electrode life time the release of particles and heavy metals from the electrode may cause toxicity problems. Reyns *et al.* (2004) reported the generation of bactericidal and mutagenic compounds by a PEF treatment, even if they operated with 300 pulses at a pulse

width of 2 s and 26.7 kV/cm, treatment intensity much higher than required for liquid food preservation.

FUTURE ASPECTS

Researchers all over the world still have many possible project development designs that need to be focused on the better understanding of the technology (Barbosa-Canovas et al., 1999). The project must be related to aspects of the PEF product and process that have not been addressed yet and are of relevance to implementation at a commercial level. The result obtained up to now are not enough for a complete generalization of different aspects dealing with the quality, microbiology, and nutritional characteristics of the products as well as their processing conditions.

The establishment of unknown destruction kinetics of many microbial pathogens (especially *Clostridium botulinum*) and the identification of the proper indicator organisms for each specific product that consider the handling and storage conditions of raw products and finished products are examples of where microbiological experience will be major contribution. The uniformity of the delivered treatment and the means to assess the process are still challenging food and electrical engineers. The impact of processing conditions such as temperature, pH, moisture, and lipid content on the safety and quality aspects of new products leaves an area that is still open to food chemists. Furthermore, the implementation of the hurdle technology and the use of food additives suggest even more new alternatives.

It is not clear yet if the food industry will fully accept PEF as a processing technology. Nevertheless, its tremendous potential to replace or compliment conventional methods, which provides the basis for ongoing studies on PEF that can be regarded as both meaningful and worthy of consideration to all those in the field of food processing.

CONCLUSION

Some of the possible applications of PEF as a non-thermal cell membrane permeabilization technique have been highlighted in this overview. The low energy consumption (1–2 kJ/kg for stress induction and 5–10 kJ/kg for plant cell permeabilization) and the continuous operability of this short-time, waste free membrane permeabilization technique are key advantages and allow the development of innovative, cost effective and sustainable processing concepts in the food and drink industry as well as in the biotechnology and pharmaceutical industry. An application of PEF for food preservation provides the tremendous potential to preserve high quality products at lower temperatures and short residence times to retain the fresh-like character and nutritional value of the products. Competition with PEF processing will take place in the growth markets of United States, Asia, Europe, and Central and South America. India has great opportunity to develop the novel technology for the food processing.

LIST OF MANUFACTURERS/SUPPLIERS OF PEF SYSTEM

- (a). **Commercial plants:** At Ohio State University (USA) and PurePulse Technologies, San Diego.
- (b). **Pilot plants:** For liquid food preservation four pilot scale systems are available at present- At Ohio State University (USA); at Stork Food and Dairy Systems (*The Netherlands*); at SIK (*Sweden*) and at the Berlin University of Technology (*Germany*).

Table 1: Comparison between HPP and PEF

S. No.	Demonstrated effects	HPP	PEF
1.	Quality and flavour improvements over thermally processed products	YES	YES
2.	Equivalent level of food safety to thermal pasteurization	YES	YES
3.	Improved nutrients retention	YES	YES
4.	Shelf life extension	YES	YES
5.	Can create 'new' product textures	YES	-
6.	Uniform treatment of food, regardless of	YES	-
7.	Can be used as a continuous process	YES	YES
8.	Can be used for in-pack foods	YES	-
9.	Accelerated thawing	-	YES
10.	Suitable for heat sensitive foods	-	YES
11.	Can be used for solid foods	YES	-
12.	Can be used for liquid foods	YES	YES
13.	Has the potential to reduce energy consumption	YES	YES
14.	Suitable for washing systems	-	-
15.	Can be coupled with other processes	YES	YES
16.	Process efficiency improvements	-	-

(Source - Effects of Nonthermal Food Processing Methods on the Functional Properties of Fruit and Vegetables by Handan DĐNÇER BAYSAL & Taner BAYSAL)

REFERENCES

- i Allen M, Soike K (1966) Sterilization by electrohydraulic treatment. *Science*, 154, 155–157.
- ii Barbosa-Cánovas GV, Góngora-Nieto MM, Pothakamury UR, Swanson BG (1999) *Preservation of foods with pulsed electric fields*. San Diego: Academic Press.
- iii Chernomordik LV (1992) Electropores in lipid bilayers and cell membranes. In *Guide to electroporation and electrofusion* (Chang DC, Chassy BM, Saunders JA and Sowers AE, eds). San Diego: Academic Press, pp. 63–67.
- iv Crowley JM (1973) Electrical breakdown of bimolecular lipid membranes as an electromechanical instability. *Biophysical Journal*, 13, 711–724.
- v Doevenspeck H (1960) Verfahren und Vorrichtung zur Gewinnung der einzelnen Phasen aus dispersen Systemen. Patent No. DE 1237541, Germany.

-
- vi Doevenspeck H (1984) Elektroimpulsverfahren und Vorrichtung zur Behandlung von Stoffen. Patent No. DE 0 148 380 A3, Germany.
- vii Dunn JE, Pearlman JS (1987) Methods and apparatus for extending the shelf life of fluid food products. Patent No. US 4695472, USA.
- viii Edebo L, Selin I (1968) The effect of the pressure shock wave and some electrical quantities in the microbicidal effect of transient electric arcs in aqueous systems. *Journal of General Microbiology*, 50, 253–259.
- ix EPRI (1998). Pulsed electric field processing in the food industry: A status report on PEF.
- x Evrendilek, G. A., Zhang, Q. H., and Richer, E. R., 2004, Application of pulsed electric field to skim milk inoculated with *Staphylococcus aureus*, *Biosystems Eng.* 87(2): 137-144.
- xi Fellow, P. J. (2000), *Processing using electric fields, high hydrostatic pressure, light or ultrasound*, Food Processing Technology: Principles and Practice, 210 (210-216).
- xii Fernandez-Molina, J. J., Barkstrom, E., Torstensson, P., Barbosa-Cánovas, G. V. and Swanson, B. G. 1999. Shelf-life extension of raw skim milk by combining heat and pulsed electric fields. *Food Res Int.*
- xiii Flaumenbaum BL (1968) Anwendung der Elektroplasmolyse bei der Herstellung von Fruchtsäften. *Flüssiges Obst*, 35, 19–22.
- xiv Harrison SL, Barbosa-Cánovas GV, Swanson BG (1997) *Saccharomyces cerevisiae* structural changes induced by pulsed electric field treatment. *Lebensmittel-Wissenschaft und Technologie*, 30, 236–240.
- xv Ho, S. Y., Mittal, G. S., and Cross, J. D. (1997). Effects of high field electric pulses on the activity of selected enzymes. *J. Food Engineering*, 31, 69-85.
- xvi Javier Raso and Volker Heinz (2006), *Pulsed electric fields technology for the food industry: fundamental and applications*, Springer Science, pp. 7.
- xvii Krüger S (1893) Über den Einfluss des constanten elektrischen Stromes auf Wachstum und Virulenz der Bakterien. *Zeitschrift klinische Medizin*, 22, 191–207.
- xviii Martín-Belloso O, Bendicho S, Elez-Martínez P, Barbosa-Cánovas GV (2004) Do high intensity pulsed electric fields induce changes in enzymatic activity, protein conformation, and vitamins and flavors stability? In *Novel Food Processing Technologies* (Barbosa-Cánovas GV, Tapia MS, Cano P, Martín O, Martínez A, eds). New York: Marcel Dekker, pp. 87–104.
- xix Mastwijk H (2004) Recent developments in pulsed electrical field treatment in relation to food safety. In *Proceedings of the Safe Consortium Seminar: Novel Preservation Technologies in Relation to Food Safety*, Brussels, Belgium.
- xx McLellan MR, Kime RL, Lind KR (1991) Electroporation and other treatments to improve apple juice yield. *Journal of Science of Food and Agriculture*, 57 (2), 303–306.
- xxi Morren J, Roodenburg B, de Haan SWH (2003) Electrochemical reactions and electrode corrosion in pulsed electric field (PEF) treatment chambers. *Innovative Food Science and Emerging Technologies*, 4 (3), 285–295.
- xxii Moses BD (1938) Electric pasteurization of milk. *Agricultural Engineering*, 19 (12), 525–526.
- xxiii Neumann E (1996) Gene delivery by membrane electroporation. In *Electrical Manipulation of Cells* (Lynch PT, Davey MR, eds). New York: Chapman & Hall, pp. 157–184.
- xxiv Pareilleux A, Sicard N (1970) Lethal effects of electric current on *Escherichia coli*. *Applied Microbiology*, 19 (3), 421–424.
-

- xxv** Prochownick L, Spaeth F (1890) Über die keimtötende Wirkung des galvanischen Stroms. *Deutsche Medizinische Wochenschrift*, 26, 564–565.
- xxvi** Qin . B. L., Pothakamury, U.R. Barbosa–Canovas, G V., and Swanson, B., 1996, Nonthermal pasteurization of liquid foods using high intensity pulsed electric field fields, *crit. Rev. Food Sci. Nutr.* 36(6): 603-627.
- xxvii** Qin B. L., Zhang, Q., Barbosa – Canovas, G., Swanson, B., and pedrow, P. D., 1995, Pulsed electric field treatment chamber design for liquid food pasteurization using finite element method, *Trans. ASAE* 38(2):557-565.
- xxviii** Qin, B., Pothakamury, U. R., Vega, H., Martin, O., Barbosa-Cánovas, G. V. and Swanson, B. G. 1995b. Food pasteurization using high intensity pulsed electric fields. *J Food Technol.* 49(12):55-60.
- xxix** Qin, B.-L., Chang, F.-J., Barbosa-Cánovas, G. V. and Swanson, B. G. 1995a. Nonthermal inactivation of *S. cerevisiae* in apple juice using pulsed electric fields. *Lebensm Wiss Technol.* 28(6):564-568.
- xxx** Quass, D. W. 1997. Pulsed electric field processing in the food industry. A status report on PEF. Palo Alto, CA. Electric Power Research Institute. CR-109742.
- xxxi** Rahman Shafiur, (1999), *Pulsed Electric Fields in Food Preservation*, Handbook of food preservation, Technology & Engineering, pp. 792.
- xxxii** Reitler W (1990) Conductive heating of foods. Munich, PhD Thesis, TU Munich, Germany.
- xxxiii** Reyns KM, Diels AM, Michiels CW (2004) Generation of bactericidal and mutagenic components by pulsed electric field treatment. *International Journal of Food Microbiology*, 93, 165–173.
- xxxiv** Rogers HJ, Perkins HR, Ward JB (1980) *Microbial cell walls and membranes*. London: Chapman & Hall.
- xxxv** Roodenburg B, Morren J, de Haan SWH, Berg HE (2003) Corrosion experiments in a PEF treatment chamber with stainless steel electrodes. In *Proceedings of Workshop Nonthermal Food Preservation*, Wageningen, The Netherlands.
- xxxvi** Schoenbach KH, Peterkin FE, Alden RWI, Beebe SJ (1997) The effect of pulsed electric on biological cells: experiments and applications. *IEEE Transactions on Plasma Science*, 25 (2), 284–292.
- xxxvii** Simpson, M. V., Barbosa-Cánovas, G. V. and Swanson, B. G. 1995. The Combined inhibitory effect of lysozyme and high voltage pulsed electric fields on the growth of *Bacillus subtilis* spores. IFT Annual Meeting: Book of Abstracts. 267.
- xxxviii** Sitzmann W, Münch EW (1988) Das ELCRACK Verfahren: Ein neues Verfahren zur Verarbeitung tierischer Rohstoffe. *Die Fleischmehlindustrie*, 40 (2), 22–28.
- xxxix** Thiele H, Wolf K (1899) Über die Einwirkung des elektrischen Stroms auf Bakterien. *Centralblatt Bakterien und Parasitenkunde*, 25, 650–655.
- xl** Toepfl S, Heinz V, Knorr D (2004) Optimization of pulsed electric field treatment for liquid food pasteurization. In *Proceedings of the 2nd European Pulsed Power Symposium (EPPS) 2004*. Aachen: Shaker, pp. 68–72.
- xli** Ulmer HM, Heinz V, Gaenzle MG, Knorr D, Vogel RF (2002) Effects of pulsed electric fields on inactivation and metabolic activity of *Lactobacillus plantarum* in model beer. *Journal of Applied Microbiology*, 93, 326–335.
- xlii** Vega-Mercado, H., Martin-Belloso, O., Chang, F.-J., Barbosa-Cánovas, G. V. and Swanson, B. G. 1996a. Inactivation of *Escherichia coli* and *Bacillus subtilis* suspended in pea soup using pulsed electric fields. *J Food Process Preserv.* 20(6):501-510.

-
- xliii** Yin, Y., Zhang, Q. H., and Sastry, S. H. (1997). High voltage pulsed electric field treatment chamber for the preservation of liquid food products. U. S. Patent 5,690,978.
- xliv** Zhang, Q. H., Qiu, X. and Sharma, S. K. 1997. Recent development in pulsed electric field processing. Washington, DC. National Food Processors Association. New Technologies Yearbook. 31-42.
- xlv** Zimmermann U (1996) The effect of high intensity electric field pulses on eukaryotic cell membranes: fundamentals and applications. *Electromanipulation of cells* (Zimmermann U, Neil GA, eds). Boca Raton: CRC Press, pp. 1–106.
- xlvi** Zimmermann U, Pilwat G, Riemann F (1974) Dielectric breakdown in cell membranes. *Biophysical Journal*, 14, 881–899.

www.ijesta.com