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Chapter 11

Pulsed Electric Fields for Food Processing Technology

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Additional information is available at the end of the chapter

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1. Introduction

Pulsed electric fields PEF is a non-thermal method of food preservation that uses short pulses of electricity for microbial inactivation and causes minimal detrimental effect on food quality attributes. PEF technology aims to offer consumers high-quality foods. For food quality attributes, PEF technology is considered superior to traditional thermal processing methods because it avoids or greatly reduces detrimental changes in the sensory and physical properties of foods. PEF technology aims to offer consumers high-quality foods. For food quality attributes, PEF technology is considered superior to traditional thermal processing methods because it avoids or greatly reduces detrimental changes in the sensory and physical properties of foods (Quass, 1997).

PEF technology has been presented as advantageous in comparison to, for instance, heat treatments, because it kills microorganisms while better maintaining the original color, flavor, texture, and nutritional value of the unprocessed food . PEF technology involves the application of pulses of high voltage to liquid or semi-solid foods placed between two electrodes. Most PEF studies have focused on PEF treatments effects on the microbial inactivation in milk, milk products, egg products, juice and other liquid foods (Qin et al., 1995). However, whereas a considerable amount of research papers have been published on the microbial aspects of food preservation by PEF, a lesser amount of information is available about the effect of this technology on food constituents and overall quality and acceptability. Recently, the interest in application of pulsed electric fields (PEF) for food processing has revived. The PEF treatment was shown to be very effective for inactivation of microorganisms, increasing the pressing efficiency and enhancing the juice extraction from food plants, and for intensification of the food dehydration and drying (Gulyi *et aI.,* 1994; Barbosa-Cánovas *et aI.,* 1998; Barsotti and Cheftel, 1998, 1999; Estiaghi and Knorr, 1999; Vorobiev *et aI.,* 2000, 2004; Bajgai and Hashinaga, 2001; Bazhal *et aI.,* 2001; Taiwo *et aI.,* 2002).

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(Wouters *et al.*, 2001) mentioned that, Pulsed electric field technology (PEF) is viewed as one of the most promising nonthermal methods for inactivating microorganisms in foods. Electric fields in the range of 5-50 kV/cm generated by the application of short high voltage pulses (μs) between two electrodes cause microbial inactivation at temperatures below those used in thermal processing. The precise mechanisms by which microorganisms are inactivated by pulsed electric fields are not well understood; however, it is generally accepted that PEF leads to the penneabilization of microbial membranes.

Non-thermal processes have gained importance in recent years due to the increasing demand for foods with a high nutritional value and fresh-like characteristics, representing an alternative to conventional thermal treatments. Pulsed electric fields (PEF) is an emerging technology that has been extensively studied for non-thermal food processing. PEF processing has been studied by a number of researchers across a wide range of liquid foods. Apple and orange juices are among the foods most often treated in PEF studies. The sensory attributes of juices are reported to be well preserved, and the shelf life is extended. Yogurt drinks, apple sauce, and salad dressing have also been shown to retain a fresh-like quality with extended shelf life after processing. Other PEF-processed foods include milk, tomato juice (Min et al., 2003), carrot juice, pea soup (Vega-Mercado et al., 1996), liquid whole egg (Martı´n-Belloso et al., 1997), and liquid egg products.

Food preservation technologies are based on the prevention of microbial growth or on the microbial inactivation. In many cases, foods are preserved by inhibiting microbial activity through those factors that most effectively influence the growth and survival of microorganisms such as temperature, water activity, addition of preservatives, pH, and modified atmosphere. In this case, the microorganisms will not be destroyed and will still be metabolically active and viable if transferred to favorable conditions. As estimates of the infection dose of some pathogenic microorganisms are very low, growth of these microorganisms in foods is not necessary to cause infection (Blackburn and McClure, 2002).

To qualify as an alternative method, a new technology should have significant impact on quality while at the same time maintain the cost of technology within feasibility limits. In recent years, several technologies have been investigated that have the capability of inactivating microorganisms at lower temperatures than typically used in conventional heat treatments (Lado and Yousef, 2002).

Application of pulsed electric fields of high intensity and duration from microseconds to milliseconds may cause temporary or permanent permeabilization of cell membranes. The effects of PEF on biomembranes have been thoroughly studied since the use of PEF has attracted great interest in several scientific areas such as cell biology, biotechnology, medicine, or food technology (Zimmermann, 1986; Palaniappan and Sastry, 1990; Ho and Mittal, 1996; Prassanna and Panda, 1997).

Recently published research results will be reviewed and compared with those obtained for other thermal and non-thermal processing technologies, with a special stress on the effect of PEF-processing variables on the bioactive composition of foods throughout their whole shelf-life. Furthermore, different examples will be presented to illustrate not only the

potential but also the limitations of PEF technology when aiming at preserving the health-promoting features of plant-based foods. With the use of electric fields, PEF technology enables inactivation of vegetative cells of bacteria and yeasts in various foods. As bacterial spores are resistant to pulsed electric fields, applications of this technology mainly focus on food-borne pathogens and spoilage microorganisms, especially for acidic food products. In addition to the volumetric effect of PEF technology in controlling the microbiological safety of foods in a fast and homogenous manner, successful application provides extended shelf life without the use of heat to preserve the sensory and nutritional value of foods. PEF technology has the potential to economically and efficiently improve energy usage, besides the advantage of providing microbiologically safe and minimally processed foods. Successful application of PEF technology suggests an alternative substitute for conventional thermal processing of liquid food products such as fruit juices, milk, and liquid egg (Mertens and Knorr, 1992; Bendicho et al., 2002; Hodgins et al., 2002).

The objective of this chapter is to provide some basic information about the pulsed electric field technology for preservation of food.

2. Nonthermal technologies for food processing

Nonthermal technologies represent a novel area of food processing and are currently being explored on a global scale; research has grown rapidly in the last few years in particular. The main purpose of thermal processing is the inactivation of pathogenic microorganisms and spores (depending on the treatment) to provide consumers with a microbiologically safe product. However, despite the benefits of thermal treatment, a number of changes take place in the product that alter its final quality, for example, flavor, color, texture, and general appearance. Now, consumers are looking for fresh-like characteristics in their food, along with high sensorial quality and nutrient content. Consumers are more aware of food content and the technologies used to process their food, showing a higher preference for natural products (Evans and Cox, 2006) free of chemicals and/or additives. Thus, the need for processing alternatives that can achieve microbial inactivation, preserve food's fresh like characteristics, and provide environment friendly products, all at a reasonable cost, has become the present challenge of numerous food scientists/technologists around the world.

Nonthermal processing technologies were designed to eliminate the use of elevated temperatures during processing and so avoid the adverse effects of heat on the flavour, appearance and nutritive value of foods (Barbosa-Canovas et al., 1999).

Novel nonthermal processes, such as high hydrostatic pressure (HHP), pulsed electric fields (PEFs), ionizing radiation and ultrasonication, are able to inactivate microorganisms at ambient or sublethal temperatures. Many of these processes require very high treatment intensities, however, to achieve adequate microbial destruction in low-acid foods. Combining nonthermal processes with conventional preservation methods enhances their antimicrobial effect so that lower process intensities can be used. Combining two or more nonthermal processes can also enhance microbial inactivation and allow the use of lower individual treatment intensities. For conventional preservation treatments, optimal

microbial control is achieved through the hurdle concept, with synergistic effects resulting from different components of the microbial cell being targeted simultaneously. The mechanisms of inactivation by nonthermal processes are still unclear; thus, the bases of synergistic combinations remain speculative (Ross et al.,2003).

Nonthermal technologies encompass all preservation treatments that are effective at ambient or sub lethal temperatures including antimicrobial additives, pH adjustment and modified atmospheres. The term 'nonthermal processing' is more apt for novel nonthermal technologies, such as high hydrostatic pressure, pulsed electric fields (PEFs), high-intensity ultrasound, ultraviolet light, pulsed light, ionizing radiation and oscillating magnetic fields, which are intended for application as microbe-inactivating processes during food manufacture. Such novel technologies have the ability to inactivate microorganisms to varying degrees (Butz and Tauscher, 2002).

One nonthermal technology, high hydrostatic pressure (HHP), has shown a negligible effect on the nutrient content of food, for example, in processing of fruits and vegetables, where pressure has minimal effect on the anthocyanin content after processing. Anthocyanins are considered phytonutrients, and they not only are responsible for color but also have an important antioxidant effect on human health. However, anthocyanin content in juices after pulsed electric fields (PEF) treatment has shown contradictory results. Some researchers report a minimum effect on the pigment content after processing, while others show that there is degradation in anthocyanin content after pulsing (Tiwari et al., 2009).

The most extensively researched and promising nonthermal processes appear to be high hydrostatic pressure (HHP), pulsed electric fields (PEF) and high intensity ultrasound combined with pressure. Gamma irradiation has high potential although its development and commercialization has been hampered in the past by unfavourable public perceptions (Resurreccion et al., 1995).

Despite the current gaps in understanding, combining nonthermal processes with other nonthermal technologies has been investigated to improve control over food borne microorganisms, with promising results. A better understanding of the antimicrobial mechanisms of emerging nonthermal technologies as well as their effectiveness when combined with traditional food preservation hurdles is needed so that new food preservation strategies can be developed on a sound scientific basis (Barbosa-Canovas et al., 1998).

High-pressure processing applied at room temperature yields a product with most of food's quality attributes intact; for example, pressurization does not affect covalent bonds, avoiding any development of strange flavors in the food (Knorr et al., 2002).

Ultrasound has also been used in milk pasteurization, with important results; milk shows a higher degree of homogenization, whiter color, and better stability after processing. In this method, pasteurization and homogenization are completed in a one-step process (Bermúdez-Aguirre et al., 2009).

3. The principles of pulsed electric field

The basic principle of the PEF technology is the application of short pulses of high electric fields with duration of microseconds micro- to milliseconds and intensity in the order of 10-80 kV/cm. The processing time is calculated by multiplying the number of pulses times with effective pulse duration. The process is based on pulsed electrical currents delivered to a product placed between a set of electrodes; the distance between electrodes is termed as the treatment gap of the PEF chamber. The applied high voltage results in an electric field that causes microbial inactivation. The electric field may be applied in the form of exponentially decaying, square wave, bipolar, or oscillatory pulses and at ambient, sub-ambient, or slightly above-ambient temperature. After the treatment, the food is packaged aseptically and stored under refrigeration. applied to a food product held between two electrodes inside a chamber, usually at room temperature. Food is capable of transferring electricity because of the presence of several ions, giving the product in question a certain degree of electrical conductivity. So, when an electrical field is applied, electrical current flows into the liquid food and is transferred to each point in the liquid because of the charged molecules present (Zhang et al., 1995).

Several nonthermal processing technologies were proposed on the basis of the same basic principle of keeping food below temperatures normally used in thermal processing. This would retain the nutritional quality of food including vitamins, minerals, and essential flavors while consuming less energy than thermal processing. High hydrostatic pressure, oscillating magnetic fields, intense light pulses, irradiation, the use of chemicals and biochemicals, high intensity pulse electric fields, and the hurdle concept were all recognized as emerging nonthermal technologies in recent years (Barbosa-Cánovas et al., 1999).

As a result of this permanent membrane damage, microorganisms are inactivated. Some applications of PEF technology are in biotechnology and genetic engineering for electroporation in cell hybridization (Chang et al., 1992).

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The basis for this prediction is because of PEF ability to inactivate microorganisms in the food, reduce enzymatic activity, and extend shelf-life with negligible changes in the quality of the final product as compared to the original one. According to the intensity of the field strength, electroporation can be either reversible (cell membrane discharge) or irreversible (cell membrane breakdown or lysis), but this effect can be controlled depending on the application (Ho and Mittal, 1996).

(Zimmermann and Benz, 1980) mentioned that, PEF technology is based on a pulsing power delivered to the product placed between a set of electrodes confining the treatment gap of

the PEF chamber. The equipment consists of a high voltage pulse generator and a treatment chamber with a suitable fluid handling system and necessary monitoring and controlling devices (Fig. 1.). Food product is placed in the treatment chamber, either in a static or continuous design, where two electrodes are connected together with a nonconductive material to avoid electrical flow from one to the other. Generated high voltage electrical pulses are applied to the electrodes, which then conduct the high intensity electrical pulse to the product placed between the two electrodes. The food product experiences a force per unit charge, the so-called electric field, which is responsible for the irreversible cell membrane breakdown in microorganisms.

This leads to dielectric breakdown of the microbial cell membranes and to interaction with the charged molecules of food (Fernandez-Díaz et al., 2000; Zimmermann, 1986). Hence, PEF technology has been suggested for the pasteurization of foods such as juices, milk, yogurt, soups, and liquid eggs (Vega-Mercado et al.,1997; Bendicho., 2003; Puértolas et al., 2004).

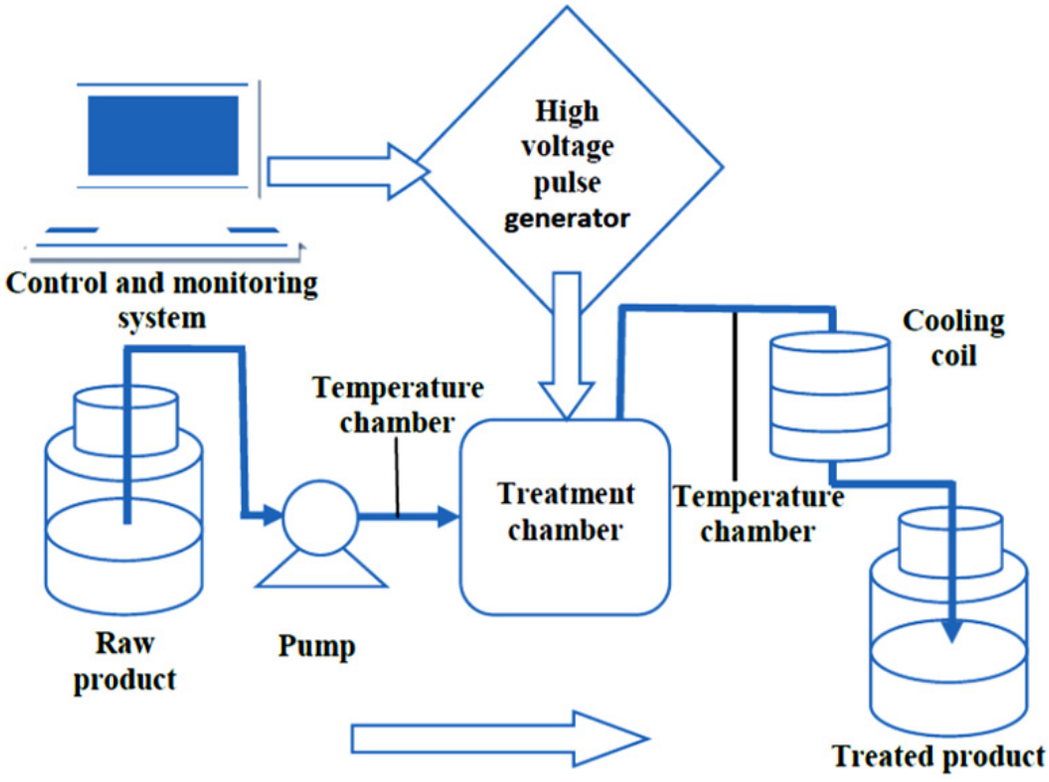


Figure 1. Flow chart of a PEF food processing system with basic component.

4. System components

A pulsed Electric Field processing system consists of a high-voltage power source, an energy storage capacitor bank, a charging current limiting resistor, a switch to discharge energy from the capacitor across the food and a treatment chamber. An oscilloscope is used to observe the pulse waveform. The power source, a high voltage DC generator, converts voltage from an utility line (110 V) into high voltage AC, then rectifies to a high voltage DC.

Energy from the power source is stored in the capacitor and is discharged through the treatment chamber to generate an electric field in the food material. The maximum voltage across the capacitor is equal to the voltage across the generator . The bank of capacitors is charged by a direct current power source obtained from amplified and rectified regular alternative current main source. An electrical switch is used to discharge energy (instantaneously in millionth of a second) stored in the capacitor storage bank across the food held in the treatment chamber. Apart from those major components, some adjunct parts are also necessary. In case of continuous systems, a pump is used to convey the food through the treatment chamber. A chamber cooling system may be used to diminish the ohmic heating effect and control food temperature during treatment. High-voltage and high-current probes are used to measure the voltage and current delivered to the chamber. (Ho et al., 1995; Barbosa-Cánovas et al. 1999; Floury et al. 2005; Amiali et al. 2006). Fig. 2 shows a basic PEF treatment unit (Ortega-Rivas et al. 1998)

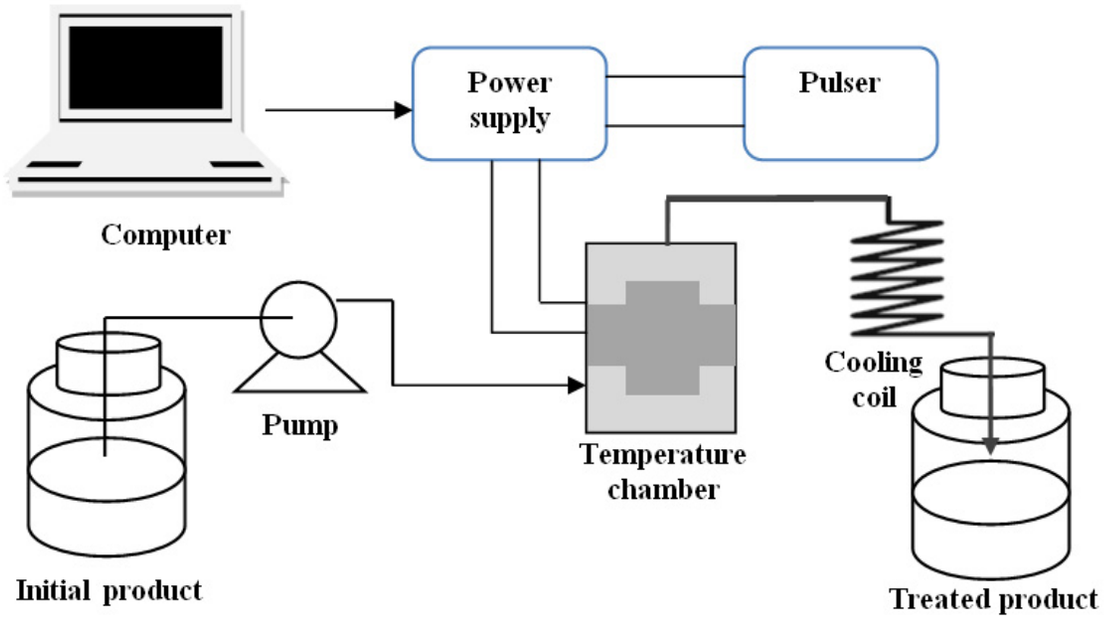


Figure 2. Schematic diagram of a pulsed electric fields operation.

A PEF system for food processing in general consists of three basic components (Fig.3): a high voltage pulse generator, a treatment chamber and a control system for monitoring the process parameters (Loeffler, 2006).

Many successful steps have been taken in the design of system components and inactivation mechanism for different species, however, there are still many points that have not been fully explained. Inactivation kinetics and the effect of PEF on spores are some of the most discussed issues in recent studies. Methods applied to thermal processing technologies by plotting logs of the numbers of survivors against log or treatment time, or number of pulses, have been used to explain inactivation kinetics neglecting the deviations from linearity for these plots (Zhang *et al.*, 1995).

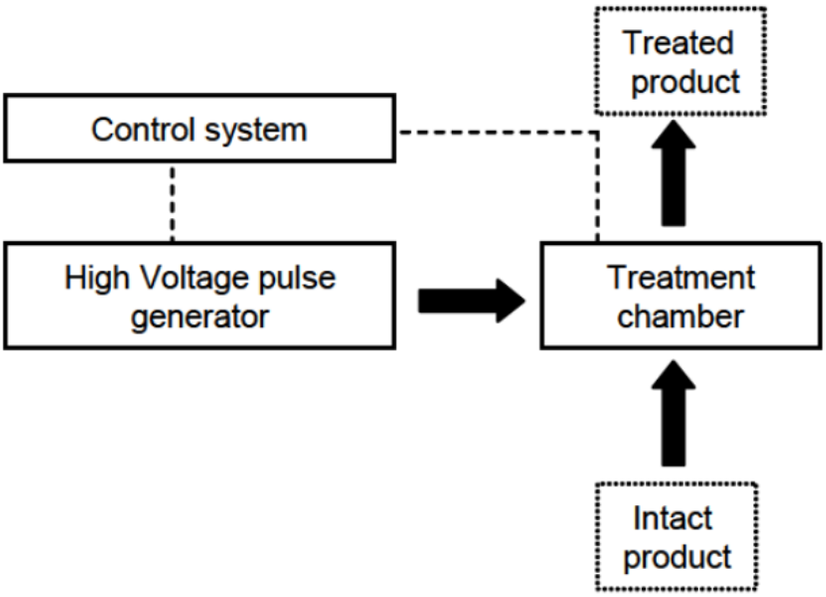


Figure 3. Scheme of a pulsed electric field system for food processing.

The high intensity pulsed electric field processing system is a simple electrical system consisting of a high voltage source, capacitor bank, switch, and treatment chamber. Generation of pulsed electric fields requires a fast discharge of electrical energy within a short period of time. This is accomplished by the pulse-forming network (PFN), an electrical circuit consisting of one or more power supplies with the ability to charge voltages (up to 60 kV), switches (ignitron, thyratron , tetrode, spark gap, semiconductors), capacitors (0.1-10 μF), resistors (2Ω-1O MΩ), and treatment chambers (Gongora-Nieto et al., 2002).

The PEF processing system is composed of a high voltage repetitive pulser, a treatment chamber(s), a cooling system(s), voltage- and current measuring devices, a control unit, and a data acquisition system. A pulsed power supply is used to obtain high voltage from low utility level voltage, and the former is used to charge a capacitor bank and switch to discharge energy from the capacitor across the food in the treatment chamber. Treatment chambers are designed to hold the food during PEF processing and house the discharging electrodes. After processing the product is cooled, if necessary, packed aseptically, and then stored at refrigerated or ambient temperatures depending on the type of food (Qin et al., 1995a; Zhang et al., 1997).

4.1. Power supply

High voltage pulses are supplied to the system via a high voltage pulse generator at required intensity, shape, and duration. The high voltage power supply for the system can either be an ordinary source of direct current (D) or a capacitor charging power supply with high frequency AC inputs that provide a command charge with higher repetitive rates than the DC power supply (Zhang et al., 1996).

High voltage pulses are supplied to the PEF system via a high voltage generator at required electric field intensity, pulse waveform and pulse width. In general, the high voltage power supply is used to charge the capacitor bank and store the energy to the capacitor bank. Liquid food may be processed in a static treatment chamber or in a continuous treatment chamber through a pump. For preliminary laboratory-scale studies, the static treatment chamber is used, but a continuous treatment chamber (s) is desirable for the pilot plant or industrial-scale operations. In order to avoid undesirable thermal effects, cold water of the cooling system is recirculated through the electrodes to dissipate the heat generated by the electric current passing through the food (Barbosa-Cánovas et al., 1999).

Total power of the system is limited by the number of times a capacitor can be charged and discharged in a given time. The electrical resistance of the charging resistor and the number and size of the capacitors determine the power required to charge the capacitor, wherein a smaller capacitor will require less time and power to be charged than a larger one. The capacitance C_o (F) of the energy storage capacitor is given by Eq. (1):

$$C_o = \frac{\tau}{R} = \frac{\tau \sigma A}{d} \tag{1}$$

where τ (s) is the pulse duration, R (Ω) is the resistance, σ (S/m) is the conductivity of the food, d (m) is the treatment gap between electrodes, and A (mm^2) is the area of the electrode surface. The energy stored in a capacitor is defined by the mathematical expression:

$$Q = 0.5 C_o V^2 \tag{2}$$

where Q is the stored energy, C_o is the capacitance, and V is the charge voltage.

More complex PFN systems can provide square pulses, bipolar pulses, and instantaneously reversal pulses, as illustrated in Fig. 4.

4.2. High-power capacitors

The main components of high-power sources are storage capacitors and on- and off-switches. Because of their relatively high ohmic power consumption, inductors in comparison to capacitors play a minor role. The energy stored in capacitors is used to generate electric or magnetic fields. Electric fields are used to accelerate charged particles, leading to thermal, chemical, mechanical, electromagnetic wave, or breakdown effects. Electromagnetic fields transfer energy as electromagnetic waves. xray, microwaves, and laser beam generation are typical examples. Magnetic fields facilitate the generation of extremely high pressures ranging from 0.1 GPa to many GPa. These effects are applied to modify molecules to remodell, compress, weld, segment, fragment, or destroy materials; and t o modify the surface of organic and inorganic parts and particles (Weise and Loeffler, 2001).

4.3. Switches

The discharging switch also plays a critical role in the efficiency of the PEF system. The type of switch used will determine how fast it can perform and how much current and voltage it

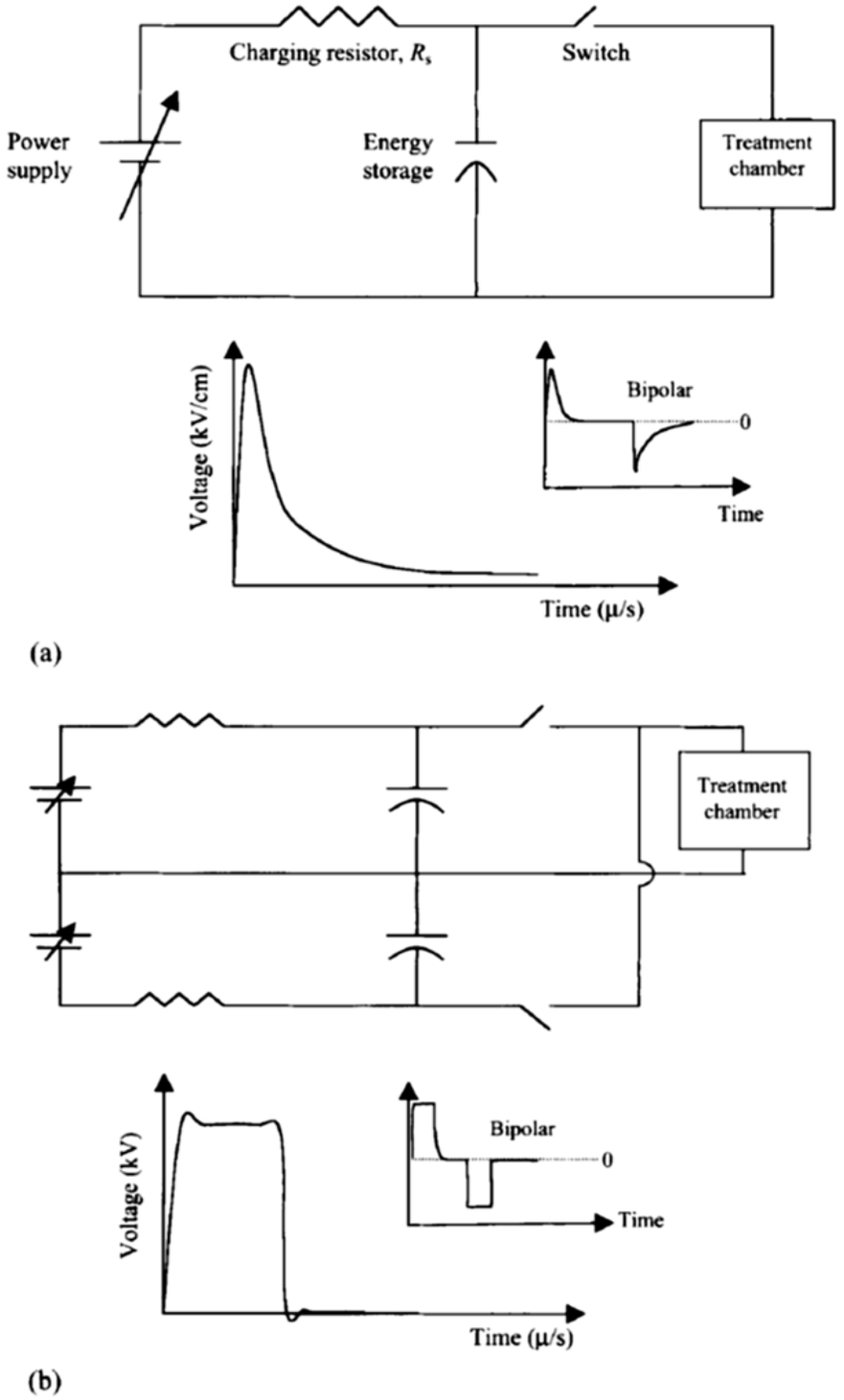


Figure 4. Commonly used pulse wave shapes and the generic electrical circuits: () Monopolar exponential decaying circuits and possible waveform; () Monopolar square circuit and possible waveform.

can withstand. In increasing order of service life, suitable switches for PEF systems include: ignitrons, spark gaps, trigatrons, thyratrons, and semiconductors. Solid-state semiconductor switches are considered by the experts as the future of high power switching (Bartos, 2000).

After the energy storage device, the switch is the most important element of a high-power pulse generator. High-power switching systems are the connecting elements between the storage device and the load. The rise time, shape, and amplitude of the generator output pulse depends strongly on the properties of the switches in the pulse forming elements. Generators with capacitive storage devices need closing switches, while generators with inductive storage devices require opening switches (Bluhm 2006).

There are two main groups of switches currently available: ON switches and ON/OFF switches. ON switches provide full discharging of the capacitor but can only be turned off when discharging is completed. ON switches can handle high voltages with relatively lower cost compared to ON/OFF switches, however, the short life and low repetition rate are some disadvantages to be considered for selection. The Ignitron, Gas Spark Gap, Trigatron, and Thyratron are some of the examples from this group. ON/OFF type switches have been developed in recent years that provide control over the pulse generation process with partial or complete discharge of the capacitors. Improvements on switches, mainly on semiconductor solid-states witches, have resulted in longer life spans and better performance. The gate turn off (GTO) thyristor, the insulated gate bipolar transistor (IGBT), and the symmetrical gate commutated thyristor (SGCT) are some examples from this group (EPRI and Army, 1997; Barbosa-Cánovas *et al.*, 1999; Barsotti *et al.*, 1999; Gongora-Nieto *et al.*, 2002; Sepulveda and Barbosa-Cánovas, 2005).

4.4. High voltage pulse generator

The high voltage pulse generator provides electrical pulses of the desired voltage, shape and duration by using a more or less complex pulse forming network (PFN). More in detail, a PFN is an electrical circuit consisting of several components: one or more DC power supplies, a charging resistor, a capacitor bank formed by two or more units connected in parallel, one or more switches, and pulse-shaping inductors and resistors. The DC power supply charges the capacitors bank to the desired voltage. Using this device, the ac power from the utility line (50-60Hz) is converted in high voltage alternating current (A) power and then rectified to high voltage dc power (Zhang et al., 1995).

A low-energy PEF system, which consists of a high voltage pulse generator (Fig. 5) is used to treat the spoiled grape juice samples. The details are given by Ho and Mittal (2000). The system consists of a 30 kV d.c. high-voltage pulse generator, a circular treatment chamber, and devices for pumping and recording. The 110V a.c. was raised in voltage through a high-voltage transformer, and then rectified. The d.c. high-voltage supply then charges up the 0.12 uF capacitor through a series of 6 MΩ resistors (the time constant =0.72 s). The pulse generator emits a train of 5V pulses, and the trigger circuit serves to convert that to 500V pulses using a silicon control rectifier (SCR). The generation of high voltage pulses relies on the discharge of the 0.12 uF capacitor through the thyratron. The batch unit can generate short duration pulses (2 ms width, 0.5Hz frequency) with a peak-to-peak electric field strength up to 100 kV/cm. The uniqueness of this pulser is that the pulses of low energy (<25 J/pulse) and of instant charge reversal shape are generated.

4.5. Treatment chamber

One of the most important and complicated components in the processing system is the treatment chamber. The basic idea of the treatment chamber is to keep the treated product inside during pulsing, although the uniformity of the process is highly dependent on the characteristic design of the treatment chamber. When the strength of applied electric fields exceeds the electric field strength of the food product treated in the chamber, breakdown of food occurs as a spark. Treatment chambers are mainly grouped together to operate in either a batch or continuous manner; batch systems are generally found in early designs for handling of static volumes of solid or semi-solid foods. Several treatment chambers have been designed. they can be categorized within two types: parallel plate and coaxial. (Fig. 6). parallel plate chambers have been typically used in batch modes while coaxial designs have been used in continuous modes where the medium is pumped through at a known flow rate and pulses are applied at a known pulse frequency. coaxial chambers used in continuous operation have been found to result in higher inactivation rates compared to batch systems sins there is a more uniform diatribution of the electric field in continuously flowing media (Qin et al., 1998). (Fig.7) presents different chamber designs

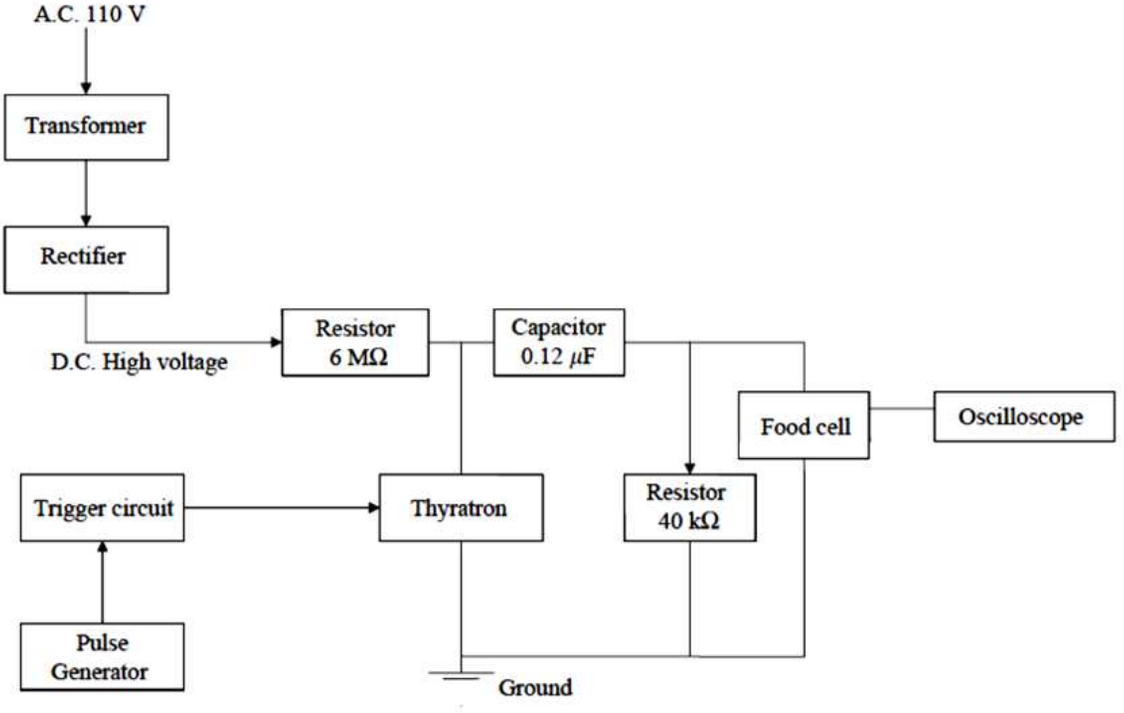


Figure 5. Generalized scheme of pulsed electric field equipment.

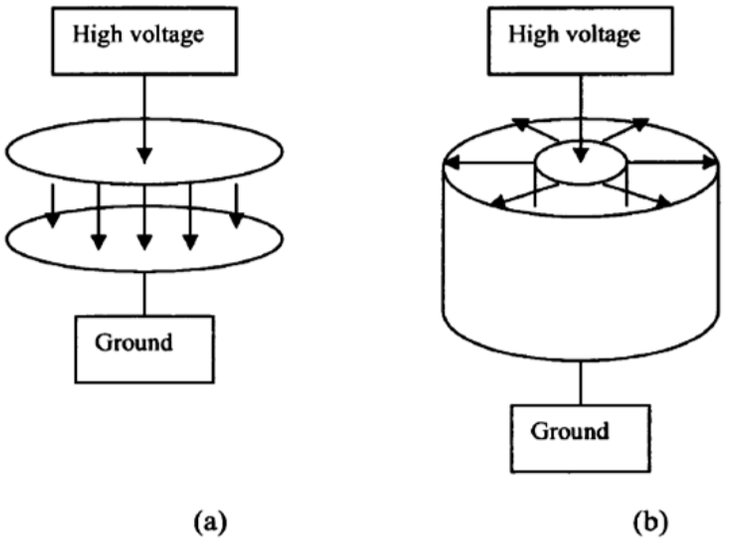


Figure 6. Common electrode configurations in pulsed electric field treatment chambers () parallel-plate () coaxial

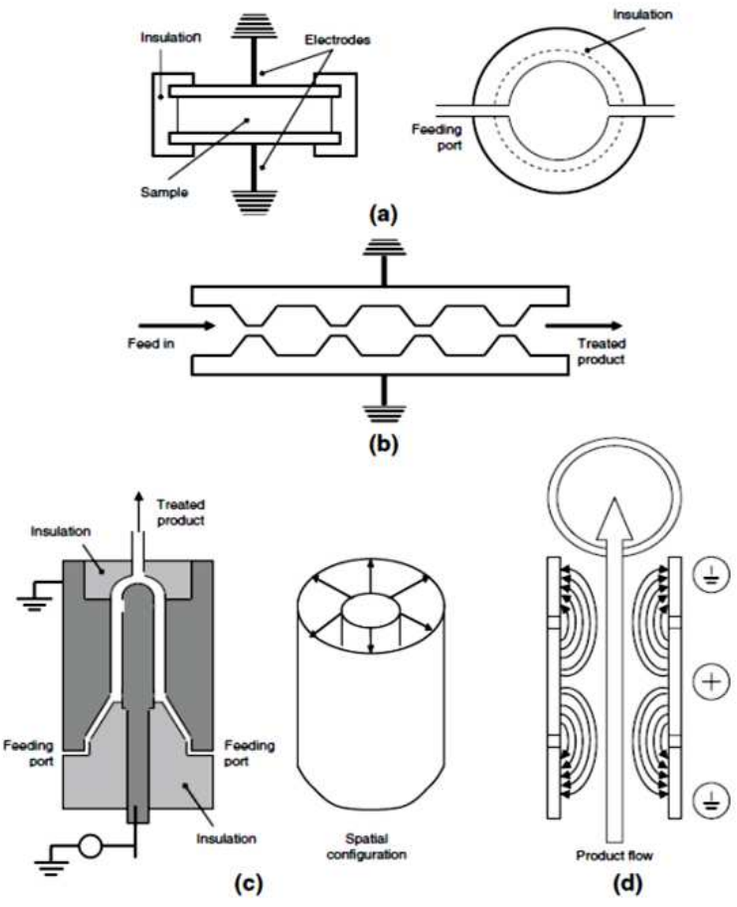


Figure 7. Schematic diagram of a pulsed electric fields operation design of treatment chambers for pulsed electric fields equipment: a static chamber, b side view of a basic continuous design, c coaxial chamber, and d co-linear chamber.

PEF investigators studying inactivation and preservation effects have been highly inventive in treatment chamber design (Fig. 8). Several different designs have been developed through the years for this key component, wherein high voltage delivered by the power supply is applied to the product located between a pair of electrodes. The basic idea of the treatment chamber is to keep the treated product inside during pulsing, although the uniformity of the process is highly dependent on the characteristic design of the treatment chamber. When the strength of applied electric fields exceeds the electric field strength of the food product treated in the chamber, break down of food occurs as a spark. Known as the dielectric breakdown of food, this is one of the most important concepts to be considered in treatment chamber design. Dielectric breakdown of the food is generally characterized as causing damage on the electrode surfaces in the form of pits, a result of arching and increased pressure, leading to treatment chamber explosions and evolution of gas bubbles. Intrinsic electrical resistance, electric field homogeneity, and reduction and generation of enhanced field areas are some other important design criteria for a successful design in terms of energy consumption and low product heating (Barbosa-Cánovas and Sepulveda, 2005).

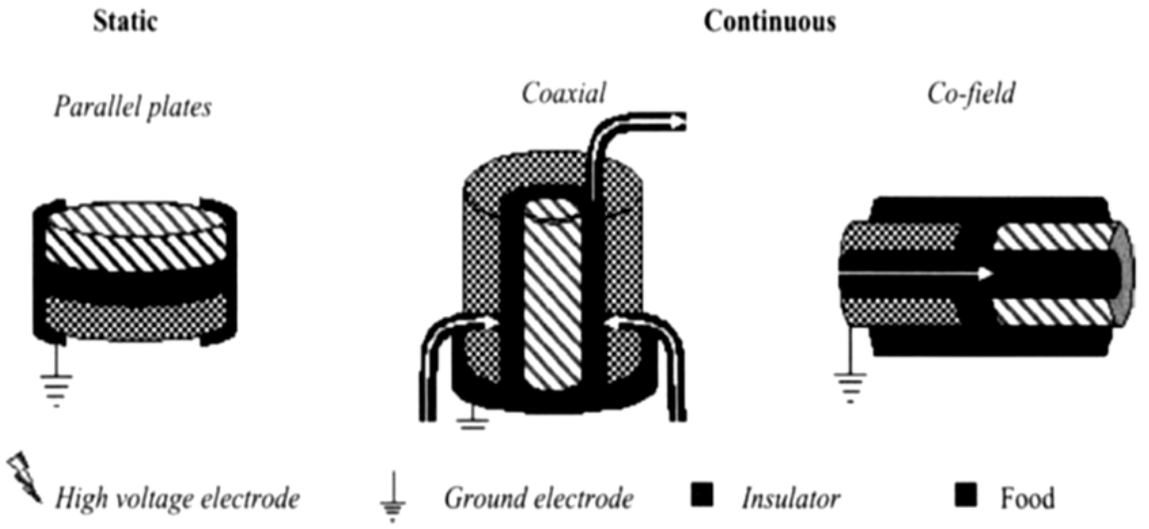


Figure 8. Schematic configurations of the three most used PEF treatment chambers.

Dunn and Pearlman (1987) designed a chamber consisting o f two parallel plate electrodes and a dielectric space insulator (Fig. 9). The electrodes are separated from the food by ion conductive membranes made of sulfonated polystyrene and acrylic acid copolymers, but fluorinated hydrocarbon polymers with pendant groups would also be suitable. An electrolyte is used to facilitate electrical conduction between electrodes and ion permeable membranes. Suitable electrolyte solutions include sodium carbonate, sodium hydroxide, potassium carbonate, and potassium hydroxide. These are circulated continuously to remove the products of electrolysis and replaced in the event of excess concentration or depletion of ionic components.

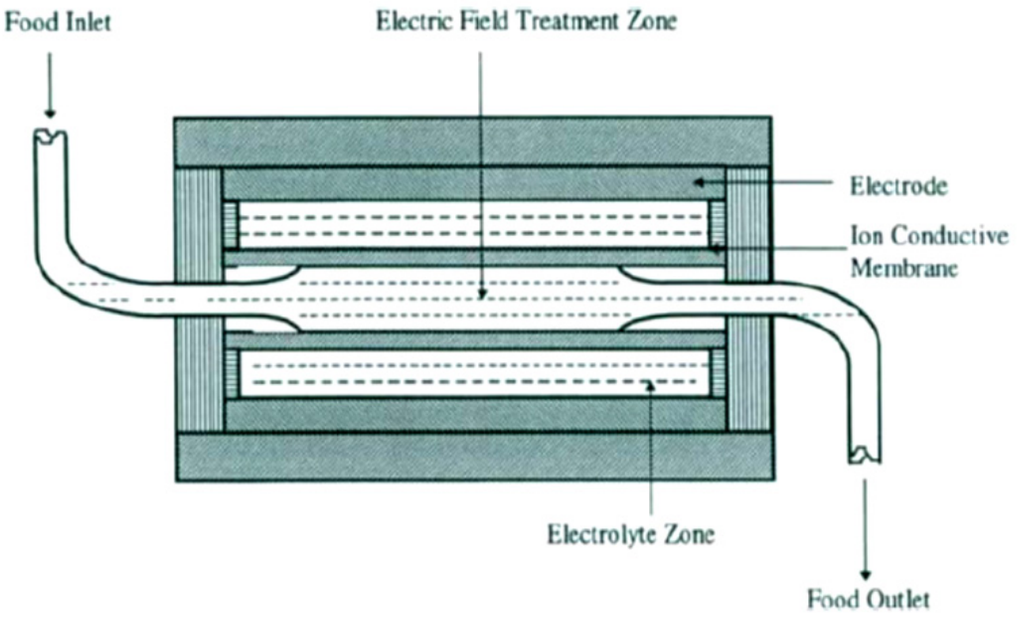


Figure 9. A continuous chamber with ion-conductive memberanes separating the electrodes and food.

From the electrical point of view, the PEF treatment chamber represents the electrical load consisting of two or more electrodes filled with the liquid substance to be treated. The chamber has to be constructed in such a way that the electrical field acting on the liquid is more or less homogeneous across the entire active region. Planar electrode configurations consist of two parallel electrodes fixed by insulators. The insulators and the electrodes form a channel for the streaming liquid. Coaxial electrode configurations consist of two coaxial electrodes. The liquid streams between these electrodes that are fixed by insulators not shown in the Fig.. Axial electrode configurations consist of several electrode rings on alternating potentials separated by insulating rings. Electrode materials also play an essential role. If monopolar voltage waveforms are applied, electrode corrosion can become critical and the substance to be treated can be contaminated. In commercially available electroporation devices with small probes, aluminum, stainless steel, carbon, gold-plated electrodes, and even silver electrodes are used (Barbosa-Cánovas *et al.*, 2000; Puc *et aI.*, 2004).

The static parallel plate electrode chamber was modified by adding baffled flow channels inside to make it operate as a continuous chamber (Fig. 10). Two stainless-steel disk-shaped electrodes separated by a polysulfone spacer form the chamber. The designed operating conditions are: chamber volume, 20 or 8 ml; electrode gap, 0.95 or 0.51 cm; and food flow rate, 1200 or 6 ml/min (Qin et al., 1996).

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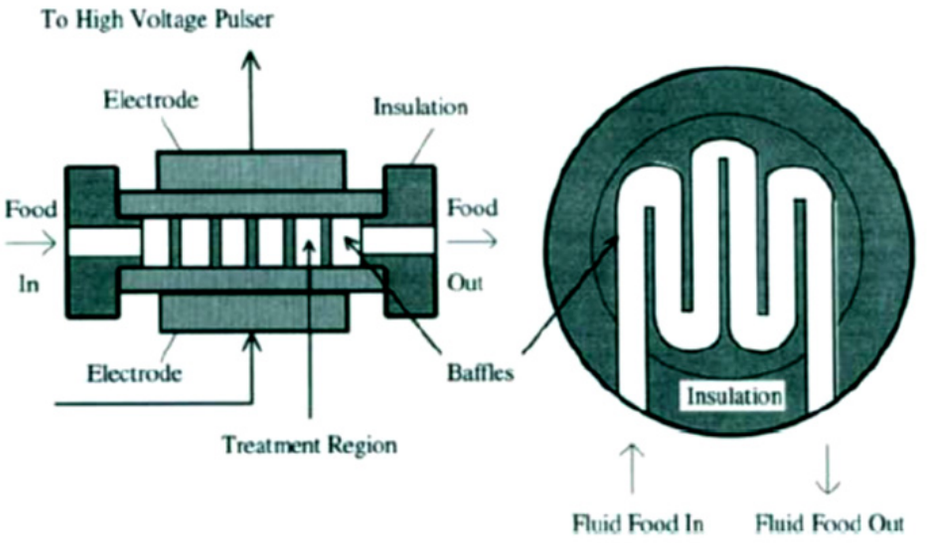


Figure 10. The continuous chamber with baffles

Jemai and Vorobiev, (2007) mentioned that In most runs, one or two chambers were manually filled with grated cossettes (see Fig. 11 for shapes and cross-sections of two types of cossettes). In a few runs, up to six chambers were used at the same time. Each chamber consists of a plate covered by a filter cloth and a flexible electrode (metallic grid) on one side and a rigid electrode on the other. The pressure (compressed air) is applied to the membrane of the plate, which in turn exerts and distributes the pressure over the cossettes placed between the plate and the rigid electrode (Fig. 11). Juice is drained through channels leading to the outlet, where juice accumulation is monitored by a weighing balance connected to a data acquisition system (Bouzrara, 2001).

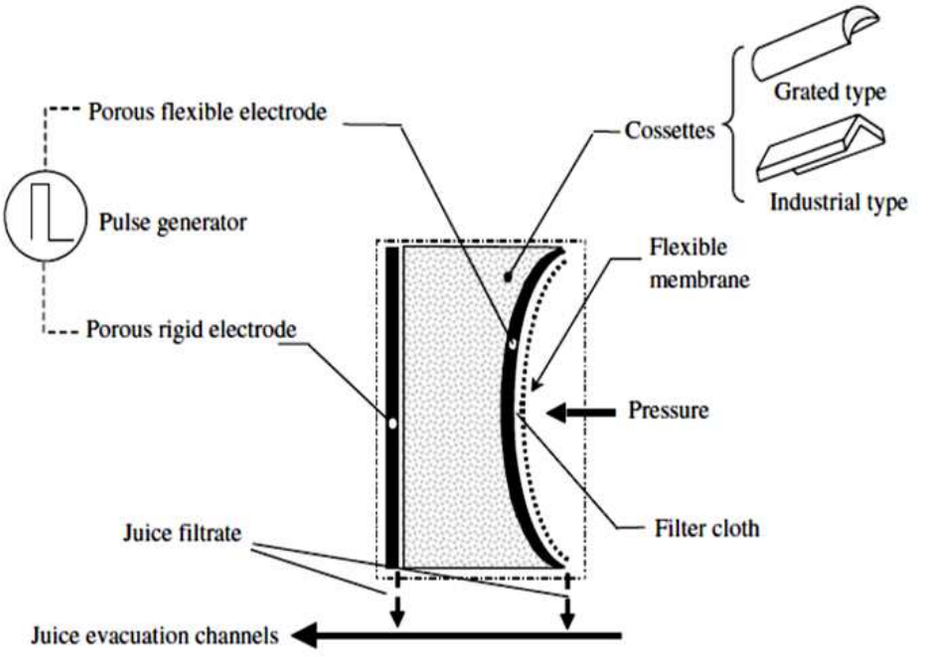


Figure 11. Schematic of a one chamber configuration of plate and frame filter press

5. Applications of pulsed electric fields technology

Application of pulsed electric fields technology has been successfully demonstrated for the pasteurization of foods such as juices, milk, yogurt, soups, and liquid eggs. Application of PEF processing is restricted to food products with no air bubbles and with low electrical conductivity. The maximum particle size in the liquid must be smaller than the gap of the treatment region in the chamber in order to ensure proper treatment. PEF is a continuous processing method, which is not suitable for solid food products that are not pump able. PEF is also applied to enhance extraction of sugars and other cellular content from plant cells, such as sugar beets. PEF also found application in reducing the solid volume (sludge) of wastewater.

PEF processing has been successful in a variety of fruit juices with low viscosity and electrical conductivity such as orange, apple, and cranberry juice. Recent studies reported more than a 3-10g reduction in orange juice (Qin *et al.,* 1998) and apple juice (Evrendilek *et al.,* 2000).

Additionally, the color change in fruit juices (subject to prolonged storage) was reportedly less in juices treated by PEF, as in a recent study of PEF-treated orange juice stored at 4°C for 112 days; there was less browning than thermally pasteurized juice, which was attributed to conversion of ascorbic acid to furfural (Yeom *et al.,* 2000).

Considering the effectiveness of PEF treatment on liquid products, such as milk, fruit juices, liquid egg, and any other pumpable food products, extensive research has been done to implement the process at an industrial level. Flavor freshness, economic feasibility, improvements in functional and textural attributes and extended shelf life are some of the main points of interest besides achievement of microbiological safety of food products (Dunn, 2001). 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).*

Each of the nonthermal technologies has specific applications in terms of the types of foods that can be processed. Among these, pulsed electric fields (PEF) is one of the most promising nonthermal processing methods for inactivation of microorganisms, with the potential of being an alternative for pasteurization of liquid foods. Comparable to pasteurization, yet without the thermal component, PEF has the potential to pasteurize several foods via exposure to high voltage short pulses maintained at temperatures below 30-40°C. The basic definition of PEF technology relies on the use of high intensity pulsed electric fields (l0-80 kV/cm) for cell membrane disruption where induced electric fields perforate microbial membranes by electroporation, a biotechnology process used to promote bacterial DNA interchange. Induction of membrane potentials exceeding a threshold value often result in cell damage and death (Zimmermann,1986).

PEF technology has recently been used in alternative applications including drying enhancement, enzyme activity modification, preservation of solid and semisolid food products, and waste water treatment, besides pretreatment applications for improvement of metabolite extraction. 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. Studies conducted on different plant tissues such as potato tissue (Angersbach and Knorr, 1997), coconut (Ade-Omowaye *et al.,* 2000), carrots (Rastogi *et al.,* 1999), mango (Tedjo *et al.,* 2002), and apple slices (Ade-Omowaye *et al.,* 2002).

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Application of PEF is especially promising for the citrus industry, which is concerned with the spoilage microorganisms and resultant production of off-flavor compounds such as lactic acid bacteria (Hendrix and Red, 1995).

Jemai and Vorobiev (2002) stated the enhancing effect of a PEF treatment on the diffusion coefficients of soluble substances in apple slices. The results available in literature clearly indicate that PEF can be successfully applied to disintegrate biological tissue and to improve the release of intracellular compounds, though an industrial application has not been achieved up to now. At Berlin University of Technology a system with a peak voltage of 20 kV, an average power of 7 kW and a production capacity of 2 ton/h has been developed for the treatment of fruit mashes. The power supply and the treatment chamber are shown in Fig. 12. It is noteworthy that avoiding an enzymatic maceration the pectin fractions will remain in a native, highly esterified structure. This provides a potential to extract high quality pectin from the pomace after juice winning and therefore a step toward a more economic and sustainable processing.

PEF treatments are applied in the form of short pulses to avoid excessive heating or undesirable electrolytic reactions. In general, a continuous PEF treatment system is composed of treatment chambers, a pulse generator, a fluid-handling system, and monitoring systems (Fig. 13.) (Elez-Martínez et al., 2006; Min et al., 2007).

An OSU-4D bench-scale continuous unit manufactured in Ohio State University (US) was used to treat the food sample (Fig. 14). Six co-field chambers with a diameter of $2.\ 3*10^{-3}$m and a gap distance of $2.93 * 10^{-3}$ m between electrodes were connected in series. Two cooling coils were connected before and after each pair of chambers and submerged in a circulating bath (Polystat, Cole Parmer, IL, USA, $\pm 0.05\ ^{0}$) to maintain the selected temperature at 35 or 55 ^{0}C. The temperature was recorded by thermocouples (T type, $\pm 0.1\ ^{0}$) at the entrance of the first treatment chamber (initial temperature) and at the edcxit of the last treatment chamber (final temperature) (Sampedro, 2007).

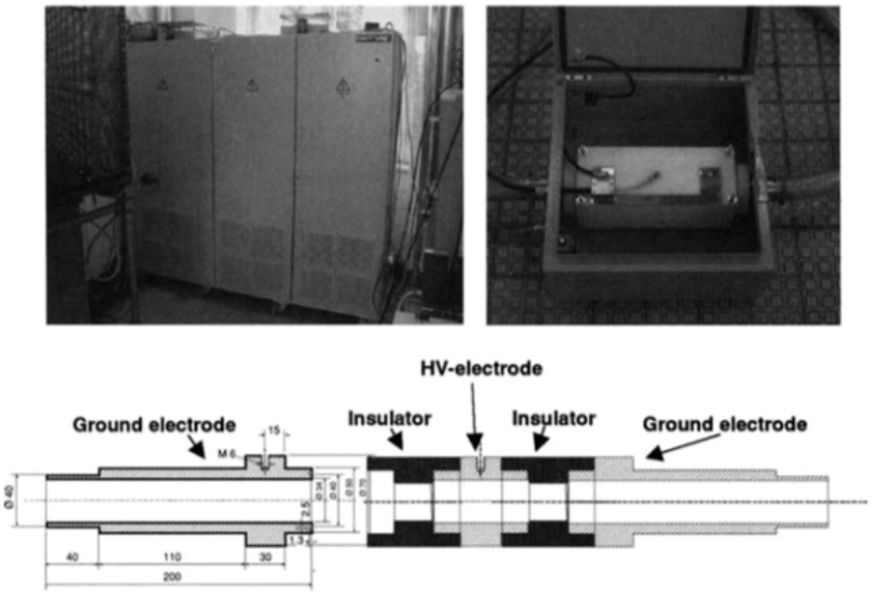


Figure 12. Power supply and treatment chamber of a pilot scale system for fruit mashes. The treatment chamber is a co-linear configuration of 3 cylindrical electrodes separated by insulators.

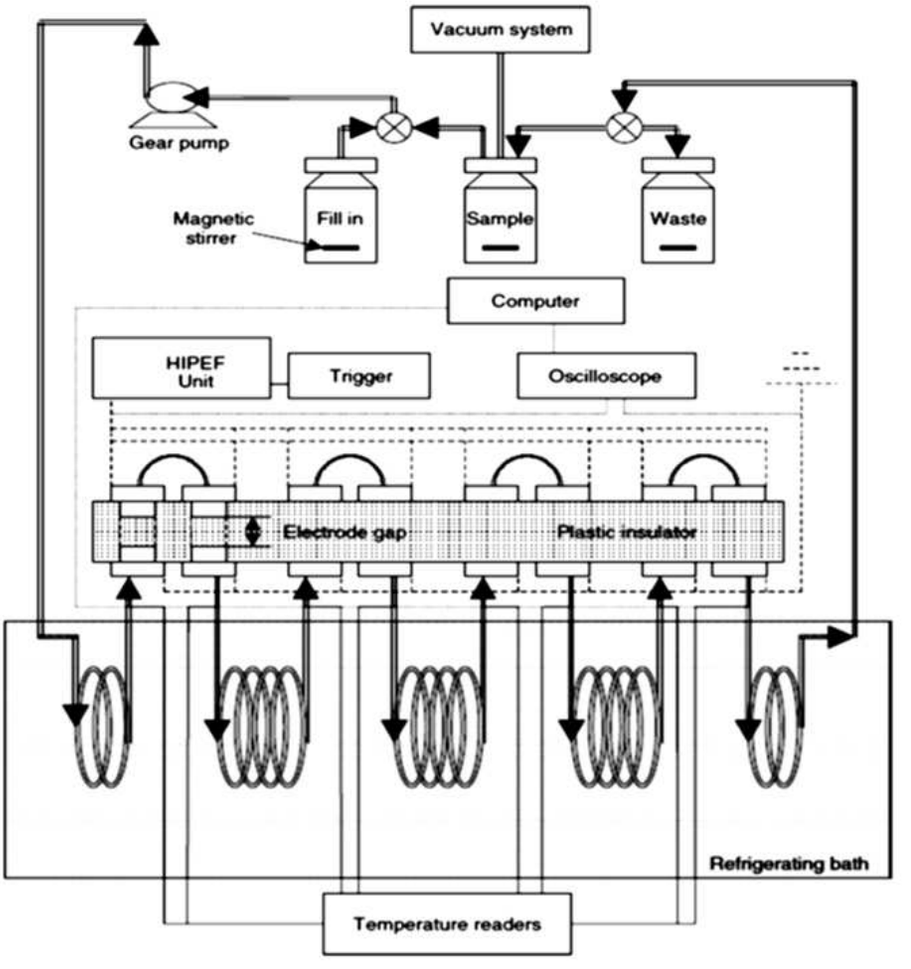


Figure 13. Diagram of the high-intensity pulsed electric field bench-scale processing unit.

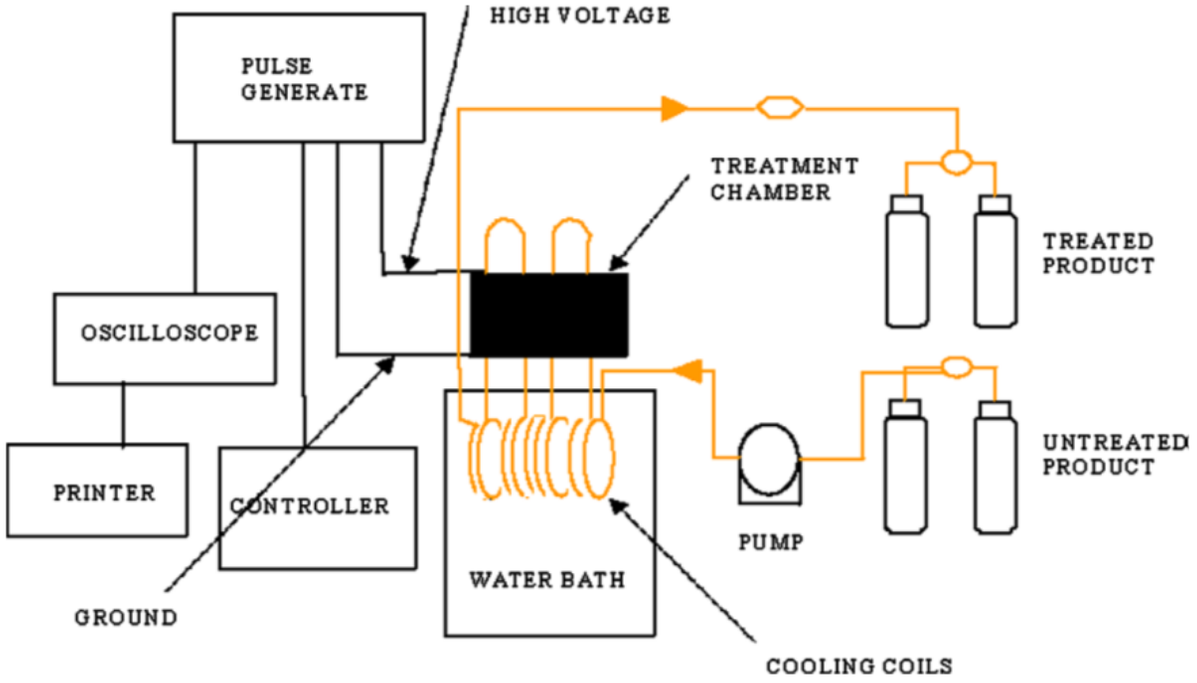


Figure 14. Scheme of the pulsed electric field equipment.

Vorobiev (2008), developed a laboratory device in the University of Technology of Compiegne (UT) (Fig. 15) permits both pretreatment and intermediate treatment by PEF. The treatment cell has a polypropylene frame with a cylindrical cavity compartment (20 mm thick, 56 mm in diameter), which should be initially filled with gratings and then closed from both sides by steel covers. A mobile electrode is attached to the elastic rubber diaphragm. A stationary wire gauze electrode is installed between the filter cloth and the layer of gratings. Both electrodes are connected to the PEF generator, which can provide the monopolar or bipolar pulses of near-rectangular shape.

Studies conducted on the effects of PEF on dairy products such as skim milk, whole milk, and yogurt compromise a major section of PEF applications (Alvarez and Ji, 2003). Milk is very susceptible to both spoilage and pathogenic microorganisms requiring the application of thermal pasteurization under current regulations, which ensures safety but generally results in a cooked flavor (Wirjantoro and Lewis, 1997).

6. Factors affecting the outcome of pulsed electric fields treatments

In order to use PEF technology as a pasteurization process it is necessary to estimate its efficacy against pathogenic and spoilage food-borne microorganisms. To obtain this objective there is a need to accumulate knowledge on the critical factors affecting microbial inactivation, to describe the PEF inactivation kinetics and to understand the mechanisms involved in microbial PEF inactivation. The lethality factors contributing to the effectiveness of pulsed electric field technology can be grouped as technological, biological, and media factors. Each group of determinant factors is related to type of equipment, processing parameters, target microorganism, and type and condition of media used.

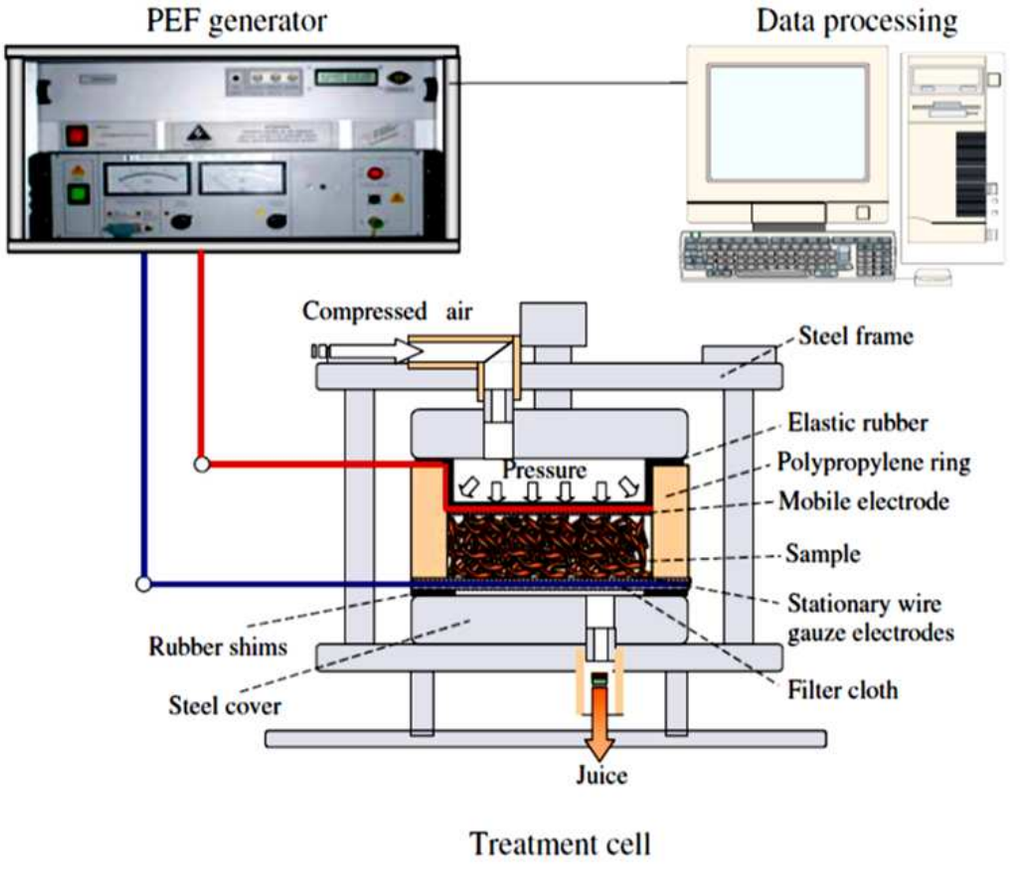


Figure 15. Experimental setup for permits both pretreatment and intermediate treatment by PEF.

6.1. Technological factors

A number of other factors during PEF processing can affect specific microbial inactivation as well. Some of these critical factors include the field strength, treatment time, treatment temperature, pulse shape, type of microorganism, growth stage of microorganism, and characteristics of the treatment substrate.

Microbial inactivation increases with an increase in the electric field intensity, above a critical trans membrane potential (Qin et al., 1998)

It is important that the electric field intensity should be evenly distributed in the treatment chamber to achieve an efficient treatment. Electric field intensities of smaller than 4-8 kV cm"' usually do not affect microbial inactivation (Peleg, 1995).

In general, the electric field intensity required to inactivate microorganisms in foods in the range of 12-45 kV cm"1. The fact that microbial inactivation increases with increases in the applied electric field intensity and can be attributed to the high energy supplied to the cell suspension in a liquid product (Wouters et al., 1999).

An important aspect that differentiates between PEF processing and other microbial inactivation technologies is that the PEF treatment is delivered by pulsing. The pulses

commonly used in PEF treatments are usually either exponential or square wave pulses (Jeyamkondan *et aI.,* 1999).

There is some controversy with respect to the influence of the pulse width on the PEF microbial lethality. Some authors have indicated that after the same treatment time, inactivation tested in several microorganisms was independent of the pulse width (Hülsheger *et al.,* 1981; Raso *et al.,* 2000; Alvarez *et al.,* 2003b,).

Treatment time could be defined as the effective time during which range microorganisms are subjected to the field strength. It depends on the number of pulses and the width of the pulses applied. This parameter and the electric field strength are the main factors determining the lethal effect of PEF treatments (Sale and Hamilton, 1967; Jayaram *et al.,* 1991; Barsotti and Cheftel, 1999; Wouters *et al.,* 2001).

Studies on microbial inactivation by PEF have been conducted at frequencies ranged from 1 to 500 Hz. If the same number of pulses is applied, microbial inactivation is generally independent of the number of pulses applied per second (Hülsheger *et al.,* 1981; Jeantet *et al.,* 1999; Raso *et al.,* 2000; Alvarez *et al.,* 2003b,).

PEF treatment time is calculated by multiplying the pulse number by the pulse duration. An increase in any of these variables increases microbial inactivation (Sale and Hamilton 1967).

A good understanding of the electrical principles behind PEF technology is essential for a comprehensive analysis of the PEF system. The electrical field concept, introduced by Faraday, explains the electrical field force acting between two charges. When unit positive charge q located at a certain point within the electric field is generated in the treatment gap (Er) , it experiences force F identified by position vector r (Blatt, 1989). The electrical field per unit charge is then defined as shown in Eq. (3):

$$E_r = \frac{F_{qr}}{q} \tag{3}$$

The electrical potential difference (V) between voltage across two points, separated by a nonconductive material , results in generation of an electric field between these points , with an electrical intensity (E) directly proportional to the magnitude of potential difference (V) and inversely proportional to the distance (d) between points, as given in Eq. (4):

$$E = \frac{V}{d} \tag{4}$$

The type of electrical field waveform applied is one of the important descriptive characteristics of a pulsed electric field treatment system. The exponentially decaying or square waves are among the most common waveforms used. To generate an exponentially decaying voltage wave, a DC power supply charges the bank of capacitors that are connected in series with a charging resistor. When a trigger signal is applied, the charge stored in the capacitor flows through the food in the treatment chamber. Exponential waveforms are easier to generate from the generator point of view. Generation of square waveform generally requires a pulse forming network (PFN) consisting of an array of capacitors and inductors. It is more challenging to design a square waveform system

compared to an exponential waveform system. However, square waveforms may be more lethal and energy efficient than exponentially decaying pulses since square pulses have longer peak voltage duration compared to exponential pulses (Amiali et al. 2006).

The electric field should be evenly distributed in the treatment chamber in order to achieve an efficient treatment. An electric field intensity of 16 kV/cm or greater is usually sufficient to reduce the viability of Gram negative bacteria by 4 to 5 log cycles and Gram positive bacteria by 3 to 4 log cycles (Pothakamury et al. 1995)

6.2. Biological factors

Biological factors that include the individual characteristics of target microorganisms and their physiological and growth states are determinant factors affecting PEF application. The susceptibility of a microorganism to PEF inactivation is highly related to the intrinsic parameters of the microorganism such as size, shape, species or growth state. Generally, Gram-positive vegetative cells are more resistant to PEF than Gram-negative bacteria, while yeasts show a higher sensitivity than bacteria. Induction of electric fields into cell membranes is greater when larger cells are exposed to PEF treatment (Sale and Hamilton, 1967; Htilsheger et al., 1983; Zhang et al., 1994). Most of the research focuses on the inactivation of vegetative cells of bacteria, while only a few reports are available on the inactivation of spores describ ing a limited effect of PEF. *Bacillus cereus* spores were mostly resistant (approximately I log reduction) to a mild PEF treatment at electric field strength of 20 kV/cm and 10.4 pulses in a study conducted on apple juice (Cserhalmi *et al., 2002).*

Another study conducted by Pagan *et al.* (1998) found that *Bacillus cereus* spores were not affected with PEF treatment of 60 kV/cm for 75 pulses at room temperature. On the other hand, Marquez *et al.* (1997) reported 3.42-log and 5-log reductions of *Bacillus subtiLis* and *Bacillus cereus* spores, respectively, with PEF treatment of 50 kV/cm for 50 pulses at 25°C in salt solution. Additionally, mold Condi spores were reported to be sensitive to PEF in fruit juices whereas *Neosartorya fischeri*asco spores were resistant to PEF treatments (Raso *et al.*, 1998).

Compared to the number of studies reported for enzyme inactivation by PEF, little information is available on the mechanism of inactivation, which may be due to the lack of analysis of enzyme structural data (Yeom et al., 1999).

6.3. Media factors

The effects of PEF on the food system are related to the PEF system and the properties of the liquid food. The most important factors in the PEF system are the electric field intensity, number of pulses, pulse waveform, pulse width, treatment time and treatment temperature. But enzymes and proteins are generally more resistant to electric field intensity and pulses than microorganisms. This requires further investigation, especially on the effects of pH, temperature, resistivity and composition of the enzyme or protein-containing medium or food system (Barsotti & Cheftel, 1999).

The physical and chemical characteristics of food products are known to strongly influence the effectiveness of microbial inactivation during PEF application (Wouters et al., 2001), thus the challenge experienced using real food systems was due to the important role of the media 's chemical and physical characteristics. These factors most likely influence the recovery of injured microbial cells and their subsequent growth following PEF exposure, since the presence of food components, such as fats and proteins , has reportedly had a preventive effect on microorganisms against PEF treatment (Ho et aI., 1995; Grahl and Markl, 1996; Martin et al., 1997).

Similar to the intrinsic parameters of microorganisms, treated media has its own intrinsic factor s such as conductivity, resistivity, dielectric properties, ionic strength, pH, and composition . Each of these parameter sinfluences the PEF treatment either alone or in combination. PEF technology has recently been used in alternative applications including drying enhancement, enzyme activity modification, preservation of solid and semisolid food products, and waste water treatment, besides pretreatment applications for improvement of metabolite extraction. 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. Studies conducted on different plant tissues such as potato tissue (Angersbach and Knorr, 1997), coconut (Ade-Omowaye *et al.,* 2000), carrots (Rastogi *et al.,* 1999), mango (Tedjo *et al.,* 2002), and apple slices (Ade-Omowaye *et al.,* 2002) reported increased yield of water removal by 20-30% when exposed to low intensity electric fields.

Temperature is one factor proposed that has been correlated with microbial inactivation, and although PEF application is strictly a nonthermal processing technology, the synergistic effect of temperature on foods (due to changes in the properties of cell membranes) becomes greater when foods are subjected to high intensity pulse electric fields (Jayaram et al., 1993). In general, the lethality of PEF treatments increases with an increase in processing temperature; therefore, a proper cooling device is necessary to maintain temperatures below levels. that affect nutritional, sensory or functional properties of food products (Wouters et al., 1999).

The influence of pH and water activity (aw) on microbial growth was documented by (Jay, 1992).

Sepulveda (2003) proposed that a PEF treatment time between 0.1 to 0.5 ms produced the best results for microbial inactivation. The pulse width is defined as the time where the peak field is maintained for square wave pulses or the time until decay to 37% for exponential decay pulses. Typically, increasing the number of pulses causes an increase in treatment time, as the pulse width is fixed by the impulse generation setup.

Dunn and Pearlman (1987) found that a combination of PEF and heat was more efficient than conventional heat treatment alone. A higher level of inactivation was obtained using a combination of 55°C temperature and PEF to treat milk.

Zhang et al (1995) reported that increasing treatment temperature from 7 to 20°C significantly increased PEF inactivation of *E. coli* in simulated milk ultra-filtrate (SMUF).

However, additional increase in temperature from 20 to 33°C did not result in any further increase in PEF inactivation.

7. Conclusion

The objective of food preservation technologies used by the food industry is to control microorganisms once they are contaminating foods. Food preservation technologies are based on the prevention of microbial growth or on the microbial inactivation.

Pulsed electric field (PEF) is a potential non-thermal food preservation technique to replace conventional thermal processing. When exposed to high electrical field pulses, cell membranes develop pores either by enlargement of existing pores or by creation of new ones. These pores may be permanent or temporary, depending on the condition of treatment. The pulsed electric processing system is composed basically of a high power pulse generator, a treatment cell, voltage and current measuring devices. A traditional treatment cell consists of two electrodes held in parallel by insulating material that form an enclosure containing the food to be treated. The application of high intensity pulsed electric fields consists of the generation of short time pulses of electric fields between two parallel plate electrodes enclosing a dielectric material. Pulsed electric fields technology is the application of very short pulses (micro – to milliseconds), at electric field intensities ranging from 10-80 kV/cm, applied to a food product held between two electrodes inside a chamber, usually at room temperature.

Research of pulsed electric fields technology is ongoing around the world. Most of the research conducted up until now has been in the laboratory and on a pilot plant scale level, and has shown promising results.

The basis for this prediction is because of PEF's ability to inactivate microorganisms in the food, reduce enzymatic activity, and extend shelf-life with negligible changes in the quality of the final product as compared to the original one. According to the intensity of the field strength, electroporation can be either reversible (cell membrane discharge)

The present chapter reviews the current state of the art in microbial inactivation by PEE after discussing critical factors determining microbial inactivation by PEF and mathematical kinetic models used for describing PEF death, the most successful combinations of PEF with other preservation techniques for enhancing the safety of minimally processed foods are presented. The chapter concludes with some aspects that need further investigation for the development of PEF processes to supply safe food products of high organoleptic and nutritional quality.

The chapters focus on the electrical bases, various equipment configurations, and principal components of pulsed electric field systems, including various types of electric circuits and processing chambers, By explaining the following points

1. What is main electrical fundamental parameter of pulsed electric field treatments?
2. How pulsed electric field works?

3. What is pulsed electric field processing?
4. What is a pulsed electric field treatment chamber?
5. Application of pulsed electric field technology in food processing.
6. Pulsed Power Systems for Application of Pulsed Electric Fields.

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