**Review**

**Pulsed Electric Field Processing of Foods: A Review**

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**ABSTRACT**

Use of pulsed electric fields (PEFs) for inactivation of microorganisms is one of the more promising nonthermal processing methods. Inactivation of microorganisms exposed to high-voltage PEFs is related to the electromechanical instability of the cell membrane. Electric field strength and treatment time are the two most important factors involved in PEF processing. Encouraging results are reported at the laboratory level, but scaling up to the industrial level escalates the cost of the command charging power supply and of the high-speed electrical switch. In this paper, we critically review the results of earlier experimental studies on PEFs and suggest the future work that is required in this field. Inactivation tests in viscous foods and in liquid food containing particulates must be conducted. A successful continuous PEF processing system for industrial applications has yet to be designed. The high initial cost of setting up the PEF processing system is the major obstacle confronting those who would encourage the system’s industrial application. Innovative developments in high-voltage pulse technology will reduce the cost of pulse generation and will make PEF processing competitive with thermal-processing methods.

Consumer requirements for foods are constantly changing. Today consumers demand foods that are both fresh and natural. Therefore, the steps used to process foods should be designed to preserve their natural quality. Thermal processing not only kills contaminating microorganisms but also degrades the taste, color, flavor, and nutritional quality of foods (25). Cold-pasteurization methods have been developed to kill microorganisms and to maintain quality without the application of heat. One such method is the use of pulsed electric fields (PEFs) for pasteurization and possibly sterilization, with integration of other processing hurdles such as pH (34), ionic strength (13, 34), temperature (12), and high-pressure processing (28).

PEFs are used for cell hybridization and electrofusion in the areas of genetic engineering and biotechnology (2). A PEF is applied to microbial cells in order to cause electroporation of the cell membrane. Foreign materials, such as DNA, are then added to infuse into the cell. When the PEF is removed, microbial cells repair their membranes, sealing the electropores. The same technique is used to fuse two microbial cells by creating electropores and by bringing the two cells together. In genetic engineering and biotechnology, the process has to be perfectly controlled in order to maintain viability of the microorganisms during the application of PEFs. The same principle is used for inactivation of microorganisms, which is accomplished by increasing the duration or intensity of treatment, thereby resulting in the irreversible breakdown of the cell membrane. Even though the application of PEFs for inactivation of microorganisms seems to be easier than the application of PEFs for cell hybridization, the former application has not yet been developed to the point of industrial application. Nonetheless, the large information database on the effects of PEFs on microorganisms, which is available in genetic engineering and biotechnology areas, can be gainfully used to design a successful PEF system for processing foods (5).

**The electropure process.** In the 1920s and 1930s, a procedure called the electropure process was introduced in the United States; this process allowed for the pasteurization of milk using electricity (21). The electropure process was one of the first attempts to use electric fields to inactivate microorganisms. The electric field was small, consisting of a 220-V alternating current, and it was not pulsed. In the United States, about 50 plants using the electropure process were in operation until the 1950s. However, none of these plants is in operation now because of the rising costs of electricity and because of competition from plants that use thermal-pasteurization methods. From today’s point of view, the electropure process is similar to ohmic heating (32), as heat generated from the direct passage of electricity into the milk was responsible for the lethal effect on microorganisms. Hence, the thermal effect was predominant in this process.

**Electrohydraulic treatment.** In the 1950s, electrohydraulic treatment was developed as a method to kill microorganisms. Electrohydraulic treatment involved a rapid discharge of high-voltage electricity across the electrodes, which were submerged in the liquid medium containing the microorganisms (21), thereby resulting in the formation of tremendously high transient pressure pulses that produced...
shock waves of about 1,000 bars (32). Electric arcs were created by high-voltage electric pulses. Ultraviolet light, electrochemical reactions, and shock waves were responsible for this method’s bactericidal effects (32). This process has not been developed to such a point that it is used to treat food on an industrial scale because of the contamination of the field (from electrode erosion) and the disintegration of particulates within the field (by the shock waves) (5). These limitations restricted the use of the electrohydraulic method to the treatment of wastewater alone.

**PEF PROCESSING**

Sale and Hamilton (29) were the first to conduct systematic studies on the effect of PEFs on the inactivation of microorganisms. They showed that the electric field strength and treatment time (which is the product of the number of pulses and pulse width) were the two most important factors involved in microbial inactivation. By suspending microorganisms in a gel that was impermeable to products of electrolysis, they proved that inactivation was not the result of products of electrolysis. In all their experiments, the temperature rise was less than 10°C, and therefore they concluded that inactivation was not due to thermal effects. Sale and Hamilton (30) proposed that the electric field caused an irreversible loss of the membrane’s function as a semipermeable barrier between the bacterial cell and its environment and that this was the cause of cell death. They obtained an approximately 2-log reduction of various microorganisms. They reported that the PEF treatment caused the loss of motility and inhibited synthesis of enzymes in microorganisms but that it had no effect on those enzymes already present.

**Mechanisms of Inactivation by PEFs.** Inactivation of a microorganism exposed to PEFs results from the electromechanical instability of the cell membrane (1, 41). The cell membrane protects the microorganism from the surrounding environmental conditions. It acts as a semipermeable barrier (i.e., it controls the passage of nutrients into the cell and the passage of end products of metabolic activities out of the cell). By maintaining an effective osmotic boundary between the cell and its environment, the cell membrane controls the cell’s metabolic activities. When high-voltage PEFs are applied, the cell membrane is disrupted (31). This results in the leakage of intracellular contents, which in turn leads to the loss of cell metabolic activities. Microbial cells that have lost the ability to grow and divide in a nutrient medium are considered to be inactivated.

Sale and Hamilton (31) developed a theory for microbial inactivation under PEFs. Under the application of an external electric field, a transmembrane potential (TMP) is developed across the cell membrane. The TMP of the cell membrane in the direction of an applied electric-field strength ($E$) is given as follows:

$$U(t) = 1.5rE$$  \hspace{1cm} (1)$$

where

$U(t) = \text{transmembrane potential in the direction of applied electric field strength (V)},$

$r = \text{radius of the cell (\(\mu m\)),}$

$E = \text{applied electric field strength (kV/mm)},$

Sale and Hamilton (31) reported that lysis of the cell resulting from loss of membrane integrity occurred when the TMP reached about 1 V. This value was termed the “breakdown” TMP.

Next, we will discuss dielectric rupture theory. Zimmermann (41) proposed an idea similar to that of Sale and Hamilton (31), a concept that he called the “dielectric rupture theory” in order to explain microbial inactivation under PEFs. According to this theory, the cell membrane is considered to be a capacitor that is filled with a dielectric material, the dielectric constant of which is of the order of two. Most foods have a dielectric constant in the range of 60 to 80. Because of the difference in dielectric constants, free charges accumulate at both membrane surfaces. The normal TMP is about 10 mV. Exposure of the cell membrane to an electric field leads to an increase in TMP (equation 1). The increase in TMP leads to a reduction in the membrane thickness. A viscoelastic restoring force opposes the electrocompression of the membrane. As the electrocompressive force increases more rapidly than the viscoelastic force (with decreasing membrane thickness), a local breakdown of the membrane occurs at a TMP of about 1 V. This is because any local perturbations in the membrane surface (due to thermal fluctuations or other causes) will grow spontaneously in an electric field that has sufficient intensity to overcome the opposing viscoelastic force. Taking a typical value of 0.5 \(\mu m\) as the cell radius, 13.33 kV/cm is required to increase the TMP to the threshold value (equation 1), thus inducing the formation of pores. When the electric field strength is further increased, large pores are formed, and an irreversible breakdown occurs, resulting in the inactivation of the cell.

The membrane has an ordered structure. When modest potentials are applied, dipolar reorientation occurs in phospholipid monolayers. Sale and Hamilton (31) suggested that such polarized reorientation may well be a triggering process that leads to conformational changes in membrane structure, thereby resulting in the irreversible loss of the membrane’s function as a semipermeable barrier, which in turn leads to the inactivation of the cell. A similar idea, called the “electroporation theory,” was proposed by Tsong (33).

The electroporation technique is extensively used for genetic transformation of bacterial cells, and the technique may yield insight into microbial inactivation under PEF treatment (21). The cell membrane is susceptible to electric fields because of the dipole nature of lipid molecules and because of its finite permeability to ions (33). Application of an electric field causes both electrical and thermal effects in cell membranes.

The lipid bilayer is susceptible to applied electric fields because of its net electric charge (33). The application of an electric field causes changes in the conformation of lipid
molecules by expanding the existing pores or by creating new hydrophilic pores that are more structurally stable. Hydrophilic pores conduct current, thus generating localized Joule heating ($V^2/R$, where $V$ is the potential across the cell membrane and $R$ is the resistance offered by the protein channel for current flow). A local temperature rise of several degrees may be reached in microseconds to milliseconds, which will in turn induce thermal transitions of the lipid bilayer from a rigid gel structure to a liquid crystalline structure. This impairs the semipermeable nature of cell membrane.

In a cell membrane, protein channels, pores, and pumps are present. The opening and closing of many channels formed by proteins is dependent on TMP. The gating potential of the channels formed by proteins is in the 50-mV range, which is considerably less than that of the breakdown TMP (33). When an electric field is applied, many voltage-sensitive protein channels will open. Protein channels, once open, will experience current much greater than the current normally experienced by the protein channels during metabolic activities. As a result, protein channels become irreversibly denatured (denaturation of a protein molecule is the disruption of its three-dimensional shape, which eliminates its structural and functional activities) by Joule heating or by electric modification of functional subunits, such as hydroxyl, carboxyl, sulfhydryl, or amino groups. Thus, electroporation of the cell membrane yields changes both in the lipid bilayer and in the protein channels, ultimately resulting in the inactivation of the cell.

**MODELING OF THE INACTIVATION RATE**

Despite earlier work by Sale and Hamilton (29–31), the next report on this subject was published 13 years later. Hulsheger and Niemann (9) studied the inactivation of *Escherichia coli* in a static treatment chamber using an exponential pulse generator. Three-log reduction of *E. coli* was obtained at 10 pulses of 30-μs pulse width and 20-kV/cm electric-field strength. The inactivation (log reduction) of *E. coli* had a linear relationship with applied electric-field strength. The electric fields below a threshold value of 3 kV/cm had no lethal effect on *E. coli*.

Hulsheger et al. (10) developed a mathematical model for the survival rate as a function of electric-field strength and treatment time:

$$s = \left( \frac{t}{t_c} \right)^{-(E - E_c)/k}$$

where

- $s$ = survival ratio; ratio of number of microorganisms present in the food after treatment and initial number of microorganisms present before the treatment,
- $t$ = treatment time, which is the product of number of pulses and pulse width (μs),
- $t_c$ = critical treatment time, which is a threshold value above which inactivation occurs (μs),
- $E$ = electric field strength (kV/cm),
- $E_c$ = critical electric field strength, which is a threshold value above which inactivation occurs (kV/cm), and
- $k$ = specific constant for a microorganism.

Taking the logarithms to base 10 on both sides of equation 2 gives us the following:

$$-\log(s) = \frac{(E - E_c)}{k} \cdot \log \left( \frac{t}{t_c} \right)$$  \hspace{1cm} (3)

The left-hand side of the above equation is commonly referred to as the inactivation ratio or log reduction. One log reduction refers to 90% reduction in the initial population of microorganisms. Inactivation ratio is directly proportional to the applied electric field strength and is proportional to the logarithm of treatment time (equation 3). It follows that electric field strength has a more pronounced effect on inactivation of microorganisms than does the treatment time, but both are important elements.

Hulsheger et al. (10) reported a 5-log reduction of *E. coli* K12 at 20 kV/cm and 30 pulses. By statistical analysis of the experimental data, they found the values of $E_c$, $t_c$, and $k$ to be 4.9 ± 0.9 kV/cm, 12 ± 3μs, and 6.3 ± 0.5, respectively.

**FACTORS AFFECTING THE INACTIVATION RATIO**

Electric-field strength and treatment time are the two major factors influencing the inactivation ratio in PEF processing (10, 29). The other factors influencing the inactivation ratio are discussed below.

**Pulse characteristics: Shape, polarization, and frequency.** Qin et al. (26) studied the effects of differently shaped voltage waveforms (square, exponential, and oscillatory) on inactivation rate. They reported that square wave pulses are more efficient than are exponential pulses. Oscillatory decay pulses are the least efficient, because they prevent the cells from being continuously exposed to a high-intensity electric field for an extended period of time, thereby preventing the cell membrane from irreversible breakdown over a large area.

In terms of pulse polarization, bipolar pulses are more efficient than are monopolar pulses (7, 26). A sudden reversal of the applied electric-field orientation will change the movement direction of the charged groups on the cell membrane. The alternating stress produced by bipolar pulses results in a structural fatigue of the membrane and in the enhanced susceptibility of the cell membrane to electrical breakdown.

Hulsheger et al. (10) reported that there was no effect of pulse frequency on inactivation ratio. The capacity of a continuous PEF processing unit can be increased by increasing the pulse frequency. But, as the pulse frequency increases, the command charging power supply and the high-speed electrical switch become expensive (35). This also increases the energy added to the medium. Hence, a cooling system must be built in order to maintain the tem-
perature below the ambient conditions in order to reduce thermal degradation.

**Medium characteristics: Temperature, electrical conductivity, ionic strength, and pH.** Hulsheger et al. (10) reported the existence of a synergistic effect of the temperature of the medium with PEF treatment on the inactivation ratio. Increasing the medium temperature decreases the breakdown TMP of the cell membrane in addition to causing thermal-injury effects, thus resulting in a higher inactivation ratio (22).

Jayaram et al. (13) studied the effects of liquid-medium conductivity on the inactivation ratio of Lactobacillus brevis during PEF treatment. As the conductivity of the fluid was increased, the resistance of the treatment chamber was reduced. This reduced the pulse width, which consequently reduced the inactivation ratio (equation 3). In order to study the effects of conductivity exclusively, they studied the inactivation ratio while keeping the pulse width constant by connecting external resistors in parallel with the treatment chamber. They observed higher inactivation in lower conductivity medium. Lowering conductivity of the medium increased the difference in ionic concentration between the cytoplasm and the medium, thus facilitating an increased flow of ionic substances across the membrane. Jayaram et al. (13) believed that this, in turn, caused a drain on cell energy reserves and eventually weakened the membrane structure, thereby making the membrane susceptible to pulse application.

Vega-Mercado et al. (34) studied the effects of pH and ionic strength of the medium during PEF treatment. The inactivation ratio was reduced in higher ionic strength solutions. As the pH was reduced from neutral, the inactivation ratio increased. The PEF treatment and ionic strength were responsible for poration and compression of the cell membrane, whereas the pH of the medium affected the cytoplasm when the poration was completed. Vega-Mercado et al. (34) believed that these factors disturbed the homeostasis of the microorganisms, thereby leading to an increased inactivation ratio.

**Microorganism characteristics: Type and growth stage of microorganisms.** Sale and Hamilton (29) reported that microorganisms differed in their sensitivity to PEF exposure, yeasts being more sensitive than vegetative bacteria. Sale and Hamilton (31) reported experimental values of breakdown TMP for various microorganisms and they ranged from 0.7 to 1.15 V. Hulsheger et al. (11) conducted comparative studies on the lethal effects of PEFs on gram-negative and gram-positive bacteria and on yeast cells. They reported that gram-positive bacteria and yeasts were less sensitive to PEF treatment than were gram-negative bacteria. Qin et al. (23) studied the inactivation of E. coli and Saccharomyces cerevisiae by PEF treatment. Their results showed that yeast was more sensitive than was gram-negative bacteria, which is in agreement with the results of Sale and Hamilton (29), but which is contrary to the result of Hulsheger et al. (11). Yeast cells are larger than bacterial cells; thus, they exhibit a lower breakdown TMP (equation 1). Therefore, yeast must be more sensitive to PEF processing, and, hence, the results obtained by Qin et al. (23) and by Sale and Hamilton (29) would seem to be more logical.

As PEF treatment inactivates microorganisms based on the electromechanical instability of microorganisms, lethal effects vary not only for different species but also for different growth phases of each species. Hulsheger et al. (11) reported that cells harvested from the logarithmic growth phase were more sensitive to PEF treatment than were those from the stationary growth phase. Pothakamury et al. (22) also reported that E. coli cells in the logarithmic phase were most sensitive to PEF treatment when compared with cells in the stationary and lag phases.

**Treatment chamber characteristics: Electrode configurations and mode of operation.** Treatment chambers usually consist of two electrodes held in position by insulating material that also forms an enclosure that contains the food materials to be treated. Parallel plates, wire-cylinder, rod–rod, rod–plate, and coaxial (concentric) cylinders are all potential electrode configurations (35). Parallel plates and coaxial electrode configurations have been used in most of the studies reported. Parallel plates produce uniform distribution of electric field strength and are simple in design. Coaxial electrodes (Fig. 1), on the other hand, provide smooth and uniform product flow and are attractive for industrial applications (35).

Matsumoto et al. (20) studied three different electrode configurations, namely, a wire-cylinder electrode system, a “converged electric field” electrode system, and a rod–rod electrode system. In the wire-cylinder electrode system, a high-voltage wire was positioned at the center of a grounded cylindrical electrode, and the liquid medium was placed in the annular space. As expected, the electric field was not uniform, thus rendering the treatment less effective. In the rod–rod electrode system, two rod electrodes were placed in the treatment chamber, and a high-voltage electric field was created between the two points of the electrode rods. This yielded effects similar to those associated with the electrohydraulic treatment; therefore, the formation of arcs

![Coaxial treatment chamber](image-url)
makes it unacceptable for use in the treatment of food. The converged electric field–type electrode system (Fig. 2) is suitable for continuous treatment of food. In this system, liquid food was continuously fed through holes in the disc electrode. An insulating plate (Teflon, 1 cm thickness) with small holes was placed between parallel disc electrodes. The size and number of holes in the Teflon plate varied. Since the current was converted into the small holes of the Teflon plate, a converged high-voltage electric field was formed on these holes. The advantage of this electrode system is that the overall resistance of the load in the treatment chamber was increased, thus reducing the cost for production of pulses (explained in detail in a later section).

Zhang et al. (39) obtained a 9-log reduction of E. coli using stepwise PEF treatment in a static parallel-plate treatment chamber, with 16 pulses at each step. After each step, the fluid was recovered and retreated. The authors suggested that a space charge can develop about 10 μm from the electrode surface where the electric field strength is much lower than it is in the bulk sample. These space-charge layers serve as protective regions for some microorganisms. Hence, a static PEF treatment system may be limited in the number of log reduction in microbial viability that it can achieve. In order to overcome this problem, a stepwise treatment was performed, in which the sample was recovered after each step, mixed, and retreated; these actions forced microbial cells to receive an equal amount of PEF exposure, and this resulted in a higher degree of inactivation. Qin et al. (23) reported that a continuous treatment chamber was more efficient than a static treatment chamber for the same reason stated above. Martin-Belloso et al. (19) compared the inactivation ratio between continuous circulation treatment and a stepwise treatment and reported that there was no significant difference between the two treatment methods.

OTHER EXPERIMENTAL STUDIES

Jayaram et al. (12) studied the synergistic effects of temperature and PEFs on the inactivation of Lactobacillus brevis cells in a phosphate-buffer solution. An electroporator (0.5-ml volume) was used for the study. The electroporator was immersed in an oil bath, in which temperature varied between 24 and 80°C. When the temperature of the medium was 80°C, all cells were killed by the thermal effect prior to application of pulses. The authors reported that a 9-log reduction was achieved within 10 ms of treatment time (200 pulses of 46-μs pulse width) at 25 kV/cm and at a temperature of 60°C. The point to be noted is that the pulse frequency was 1 Hz: i.e., the medium was in the oil bath for 200 s. Because of the application of pulses, the temperature of the medium was raised to 69.5°C. Therefore, the thermal effect was more dominant than was the PEF effect. Unfortunately, the effect of PEF treatment could not be separated from the thermal effect because of the limitations of the group’s equipment and experimental set-up.

Lubicki et al. (17) designed a treatment chamber with a coaxial (concentric cylinder) electrode configuration (Fig. 3). Food material was placed in a spiral glass tube that was immersed in distilled water (conductivity, 10⁻³ S/m) that filled the electrode gap. Such a configuration allowed for the separation of food material from the electrodes. This reduced the possibility of dielectric breakdown of food samples. Also, the presence of distilled water increased the overall resistance of the treatment chamber, reducing the cost of the circuit for the production of pulses (discussed in detail in a latter section). A 6-log reduction of Yersinia enterocolitica was reported at 60 kV/cm and 250 pulses.

**Maxwell patents.** Dunn and Pearlman (4, cited in 35) designed a static treatment chamber (2 by 10 cm) with parallel-plate electrodes. The fluid food was passed through a hole in one of the electrodes to completely fill the chamber. The authors treated orange juice, milk, and liquid egg and obtained over a 5-log reduction of naturally present microorganisms. It is worthwhile to note that the temperature
FIGURE 4. Con®guration of a continuous treatment chamber with fluid switching, designed by Dunn and Pearlman (4).

during the treatment was 42 to 65°C. Later they designed a continuous¯ow treatment chamber that had a fluid-switching configuration. A high-voltage direct current potential was directly applied to the electrodes and was not pulsed. Instead of pulsing the voltage, the electrode gap was varied intermittently (Fig. 4). This allowed the food to be subjected to high-voltage electric fields when it passed through the smaller electrode gaps and to low-voltage electric fields when it passed through the larger electrode gaps. This con®guration eliminated the need for an electrical switch, thus making the system less expensive. Until the engineering aspects of the®ow of liquid through varying cross-sections under high- and low-voltage electric fields and high-voltage components involved in continuous PEF processing have been addressed completely, the®uid-switching system cannot be implemented (35).

Dunn and Pearlman (4, cited in 35) assigned the patents for the above processes to PurePulse technologies, Maxwell Laboratories, Inc. (San Diego, Calif.). Their PEF system was designated as the CoolPure process. A 220 liter/h continuous-¯ow treatment chamber is currently undergoing extensive testing on milk, liquid eggs, juices, emulsions, and food ingredients (3).

Washington State University PEF study. Washington State University has a comprehensive research program in PEF pasteurization of foods. The ﬁrst reported results were obtained using a modiﬁed version of an electroporator to treat 0.1 ml of inoculated simulated milk ultraﬁltrate (25). Later, the Washington State University group developed a static treatment unit with parallel-plate electrodes. Subsequently, the static treatment chamber was modiﬁed to operate as a continuous treatment chamber by adding baf®ed-¯ow channels inside the chamber. Later, a coaxial treatment chamber with cylindrical electrodes (Fig. 1) was constructed (25). The results reported by the Washington State University group are shown in Table 1, and it should be noted that they contain some inconsistencies. Zhang et al. (37) reported a 3-log reduction of E. coli in simulated milk ultraﬁltrate in the static treatment chamber at 25 kV/cm and 20 pulses. Qin et al. (27) tested the same microorganism in simulated milk ultraﬁltrate in the same treatment chamber and reported less than a 3-log reduction when a higher number of pulses and a higher electric ®eld strength were applied, compared with the earlier study. Qin et al. (27) also reported less than a 6-log reduction of Saccharomyces cerevisiae in apple juice in a coaxial treatment chamber at 25 kV, 6-mm coaxial electrode gap, and 64 pulses. In the same year, Qin et al. (24) reported a 6-log reduction of the same microorganism in the same medium in a coaxial treatment chamber with just 8 pulses at 35 kV/cm. They did not report that any improvements had been made to the treatment chamber. They also claimed that their treatment chamber, at 35 kV/cm and 8 pulses, was 10 times more energy efﬁcient than was the high-temperature short-time method. If an energy efﬁciency evaluation had presented for the earlier study (25 kV, 6 mm, and 64 pulses), the conclusions reached may have been different.

Zhang et al. (36) studied the inactivation of microorganisms in a semisolid model food in a static treatment chamber. The microorganisms were inoculated in a molten potato dextrose agar mixture and allowed to solidify in the static treatment chamber. Thus, the medium was a homogeneous solid matrix that immobilized the microorganisms that were present. Six-log reductions in microbial viability were achieved with 64 pulses for E. coli and Staphylococcus aureus and with 16 pulses for S. cerevisiae, at an electric ®eld strength of 40 kV/cm. Zhang et al. (36) reported that there was signi®cantly more microbial reduction in semisolid medium than in skim milk. The fact that micro-

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<td>E. coli in simulated milk ultra®ltrate</td>
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<td>Zhang et al. (37)</td>
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TABLE 1. Results of PEF experiments conducted at Washington State University
Bacterial cells were fixed in a gel matrix increased the uniformity of inactivation.

University of Guelph PEF study. Ho et al. (7) studied the inactivation of Pseudomonas fluorescens in 0.1% peptone water at three electrode gaps: 3, 6, and 9 mm. Electric field strengths ranging from 10 to 49 kV/cm and pulse numbers ranging from 10 to 100 were applied. They reported that electric field strength and number of pulses had no effect on the inactivation ratio, which is in contrast with the results of all earlier studies. Less than a 0.5-log reduction was obtained with all combinations of electric field strength and pulse number tested at electrode gaps of 6 and 9 mm. When the electrode gap was reduced to 3 mm, 6- to 7-log reduction was obtained with all combinations of electric field strength and pulse number. There was no relationship between electric field strength, treatment time, and inactivation ratio, which is contrary to the results of all other studies. Under the same fluid medium and electrical conditions, a decrease in electrode gap to 3 mm gave rise to an exponential pulse and a spike (a low-amplitude pulse with reverse polarity). The authors did not explain why an exponential pulse with a spike occurred, but they speculated that the spike was responsible for the high inactivation ratio at 3 mm. They also reported that their treatment chamber was about 900 times more energy efficient than the high-temperature short-time method.

Marquez et al. (18) studied the inactivation of Bacillus subtilis in an NaCl solution using the same treatment chamber designed by Ho et al. (7). Electric field strengths ranging from 20 to 50 kV/cm, with pulse numbers ranging from 15 to 30, were applied. Marquez et al. (18) tested only at a 3-mm gap and obtained a 3.5-log reduction of B. subtilis at 50 kV/cm and 30 pulses. In all other combinations of electric field strength and pulse number, less than a 1-log reduction was reported. In this case also, there was no gradual change in inactivation ratio. These authors did not mention anything about the occurrence of the spikes.

Keith et al. (15, 16) investigated the effect of PEFs on dry powders (spice powders and dark rye flour) in a static treatment chamber. Their studies showed that PEFs had less pronounced effects (less than a log reduction) on dry solid powders compared to those reported for liquids. They reported that corona flashes and arcs were formed in onion, dill, and basil powder when the electric field strengths were 40, 28, and 26 kV/cm, respectively, for bipolar pulses. When 620-kPa pressure was applied, the arcs were formed at substantially higher electric field strengths (86 kV/cm for onion), but pressure did not have any significant effect on overall microbial reduction. The authors did not discuss the reason why PEFs had limited effects on dry solid powders. A possible explanation can be deduced from the dielectric rupture theory. Dry solid powders have lower dielectric constants (on the order of 10) when compared to liquid foods (around 60). As the difference in dielectric constant between the cell membrane and the solid powder is less, free charge accumulation at the membrane surface is also less. The mobility of the charged particles is highly restricted in the dry powders because of the lower moisture contents present during the application of PEFs. This lowers the electrocompressive force on the cell membrane, resulting in less pronounced lytic effects on the cell membrane. But it is worthwhile to note that the resistance of the treatment chamber was on the order of megohms because of the high resistivity of dry solid powders, thereby making the circuit for production of pulses less expensive.

PULSE GENERATOR

The shape of the pulse used for PEF processing can be square, exponential, or oscillatory. Energy efficiency has been found to be maximum for square wave pulses, followed by exponential and oscillatory pulses (26). However, the generation of square waves requires expensive pulse-forming networks. Also, when impedance matching between the circuit and the treatment chamber is performed, the peak voltage at the electrodes is reduced to one-half the peak voltage delivered by the power source (38). Therefore, the peak voltage of the power source for a square-wave generator should be set at twice the level required for an exponential-pulse generator. This makes the circuit more expensive. Zhang et al. (38) reported that after a considerable number of pulses (20 pulses for S. cerevisiae in apple juice), both square waves and exponential waves resulted in the same inactivation. Since an exponential-pulse generator is less expensive, it is more suitable for practical applications.

Exponential pulses can be generated using a simple resistor–capacitor circuit. High-voltage direct current has to be produced first. The high-voltage direct current charges a capacitor bank for an extended period and is suddenly discharged on the resistive load (treatment chamber) within a few microseconds, with the help of an electrical switch. The circuit becomes complicated and expensive because of the high voltage involved and because of the low resistance of the treatment chamber (14). At a high pulse frequency and large scale of operation for industrial applications, the command charging power supply and high-speed electrical switch represent the major costs of the pulse generator (35).

DISCUSSION AND RECOMMENDATIONS

Development of a continuous treatment chamber for industrial applications. The coaxial treatment chamber, designed by the Washington State University group, is suitable for continuous processing applications and shows promise for industrial applications (Fig. 1). Liquid food is a highly conductive material, and, hence, the resistance of the treatment chamber is very low (on the order of a few ohms), making the cost of pulse generation expensive. If PEFs were to be applied for the industrial pasteurization of foods, the chamber must be scaled up to a larger capacity than is available for those used for laboratory studies.

The capacity of the treatment chamber can be increased by increasing the electrode gap, electrode area, or flow rate. If the electrode gap is increased, the voltage of the command charging power supply has to be increased in order to maintain the electric field strength. This escalates the costs of the command charging power supply and of the electrical switch. If the electrode area is increased, the re-
sistance of the treatment chamber will be reduced, and, consequently, the pulse width will be reduced. The pulse width cannot be reduced to less than 1 μs, because a few hundred nanoseconds are required to develop the potential across the cell membrane. Also, as the pulse width is reduced, the inactivation ratio is reduced (equation 3), and as the resistance is reduced, more current flows through the treatment chamber, which, in turn, increases the probability for dielectric breakdown of foods. This brings us to the last option: if the flow rate has to be increased for a given volume of the chamber, pulse frequency must be increased in order to maintain the number of pulses received by the food. The increase in pulse frequency also increases the costs of the high-speed electrical switch and of the command charging power supply. In summary, the low resistance of the treatment chamber and the high cost of the pulse generator are the main obstacles confronting the industrial application of PEF processing (14).

With respect to increasing the resistance of the treatment chamber, the converged electric field–type treatment chambers designed by Matsumoto et al. (20) and Lubicki et al. (17) are promising. In Matsumoto’s system, the overall resistance of the treatment chamber can be increased by increasing the resistance of the insulated plate (Fig. 2). Lubicki’s treatment chamber is a static treatment unit, but it can be modified to operate as a continuous treatment chamber by extending the spiral tube downward and by continuously pumping the food through the tube (Fig. 3). The annular space is filled with distilled water (resistivity is 1,000 Ω.m), which increased the overall resistance of the treatment chamber. This will reduce the cost of pulse generation. Also, cooling channels can be built inside the electrodes so that the electrodes will be maintained at low temperatures in order to minimize dielectric breakdown of foods and thermal degradation.

The flow-switching electrode system designed by Dunn and Pearlman (4) eliminates the need for an electrical switch (Fig. 4). The disadvantage of this system is its lack of flexibility (35), but the lower operating cost of this configuration should stimulate further study of this design.

Innovations in high-voltage pulse technology will reduce the cost of the pulse generator. For example, a magnetic compression pulse generator is an attractive alternative to conventional pulse generators. In a magnetic compression pulse generator, the electrical energy is compressed by magnetic energy and is then suddenly discharged to give an exponential pulse. This eliminates the need for a switch and a trigger source. The power supply can be alternating current instead of direct current, which eliminates the cost of rectification (8, cited in 35). The suitability of a magnetic compression pulse generator for PEF processing has yet to be studied.

Effect of pulse spike shape. Ho et al. (7) designed an exponential pulse generator but obtained an exponential pulse with a short spike when using a 3-mm electrode gap. They speculated that the spike was responsible for both the higher inactivation ratio and the higher energy efficiency. Further work is required to study the effect of pulse spike shape on inactivation ratio.

Viscous foods. In most of the earlier studies, the medium tested was a solution such as NaCl, 0.1% peptone water, or a phosphate buffer. In some studies, skim milk and apple juice were tested. Zhang et al. (36) studied the inactivation of microorganisms in a homogeneous solid matrix. However, viscous foods have not yet been tested (14), and this should be an area for future work.

Particulate foods. Inactivation of microorganisms in liquid foods containing particulates by PEFs has not yet been tested. Qin et al. (25) reported that dielectric breakdown occurs when air or liquid vapor is present in the food because of the differences in dielectric constant between liquid and gas. Similarly, dielectric breakdown may occur at a particle-to-liquid interface because of differences in dielectric constants. In order to create a model particulate food, starch granules could be mixed with a binding agent using the following method: starch granules are dispersed to a 30% concentration in water containing microbial culture plus a binding agent consisting of 1% alginate and 10% calcium chloride. The mixture can then be spray dried in order to produce spheres of 10 to 40 μm in diameter. Zhao and Whistler (40) reported that these spheres are 100% stable after they are stirred in water (at 25°C) with a magnetic stirring bar at 100 rpm for 1 day. These microorganisms-containing spheres can then be dispersed in 0.1% peptone water; and inactivation tests can be carried out (14).

CONCLUSIONS

Encouraging results have been obtained with PEF treatment of foods at the laboratory level, but there were some inconsistencies. The high initial cost of setting up the PEF processing system is the major obstacle confronting the concept of industrial application of this method. Nonetheless, PEF systems are attractive because of their lower operating costs and because they yield high-quality, minimally processed products. A continuous PEF processing system suitable for industrial application has yet to be developed. It is a challenge for food and electrical engineers to design a continuous treatment chamber and a pulse generator that are capable of satisfying industrial requirements. Inactivation tests in viscous and particulate foods need to be conducted. Further experiments have to be conducted to optimize process conditions (i.e., validation of different combinations of electric field strength and treatment time required to pasteurize various foods). The treatment chamber designed by Lubicki et al. (17) shows promise and needs to be further modified. Innovative developments in high-voltage pulse technology will reduce the cost of the pulse generator and make PEF processing competitive with thermal-processing methods.

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