PULSED ELECTRIC FIELD PROCESSING OF HIGH ACID LIQUID FOODS: A REVIEW

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I. INTRODUCTION

Pulsed electric field (PEF) is a nonthermal food preservation method using high voltage electric field to kill spoilage microorganisms in foods (Giese, 1998). PEF treatment maintains flavor, color, taste and nutritional value of foods while destroying microorganisms (Mertens and Knorr, 1992; Sizer and Balasubramaniam, 1999). PEF is useful in processing liquid foods where the food can flow between two electrodes (Hoover, 1997; Mermelstein, 1999).

II. PEF ENGINEERING ASPECTS

The generation of PEF processing requires a pulsed power supply, a series of treatment chambers and a temperature regulating system (Qiu *et al.*, 1998). Therefore, a PEF system usually consists of a high voltage pulse generator, a treatment chamber and a fluid handling system (Table I). To process a product using PEF in a continuous system, the product flows through a series of PEF treatment chambers where it is exposed to the desired electric field strength for a desired amount of time.

A. PULSE GENERATOR

The pulse generator is capable of converting low voltage electricity into high voltage energy to be stored in capacitors until discharged (Qin *et al.*, 1995). Three different shapes of high voltage waveforms can be generated and applied to foods. The three waveforms are square wave, exponential decay and under-damped RCL (resistive capacitive and inductive

TABLE I
PULSED ELECTRIC FIELDS SYSTEM

PEF system	Parameters
High voltage and pulse generator	Electric field strength (kV cm^{-1}) Pulse duration time (μsec) Frequency (Hz) Wave form (square, exponential decay, etc.)
Treatment chamber	Electrode material Electrode gap distance Electrode configuration Insulation material and geometry
Fluid handling system	Continuous or batch process Flow rate Cooling system (temperature control)

discharge circuit, Qiu *et al.*, 1998). According to Zhang *et al.* (1995a), exponential decay pulses are easier to obtain than square wave pulses. However, the square wave pulses minimize the energy absorption in foods (Knorr *et al.*, 1994) and are more effective for inactivating microorganisms than exponential decay pulses (Qin *et al.*, 1994). Figures 1, 2, 3 and 4 illustrate system diagrams and circuit diagrams for a pilot plant-scale pulse generator and a benchtop-scale pulse generator at the Ohio State University.

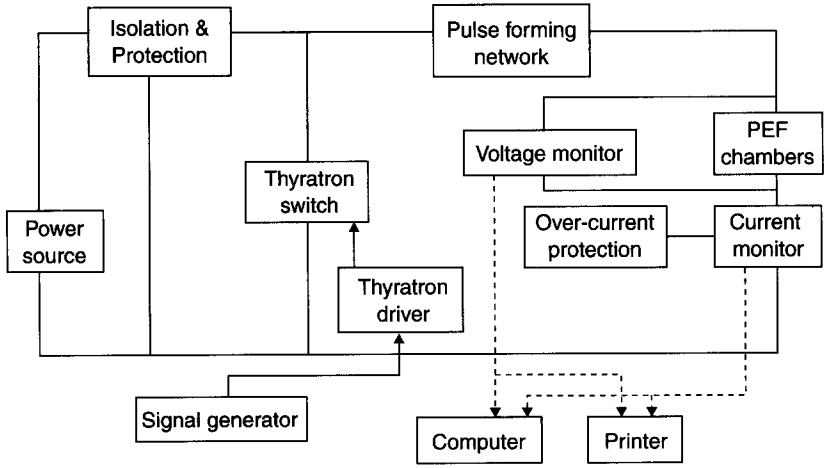

FIG. 1. System diagram of a pilot plant-scale high voltage pulse generator.

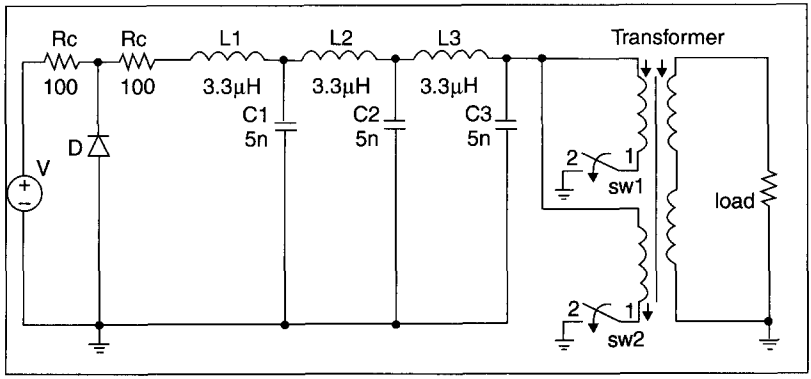

FIG. 2. Circuit diagram of a pilot plant-scale high voltage pulse generator.

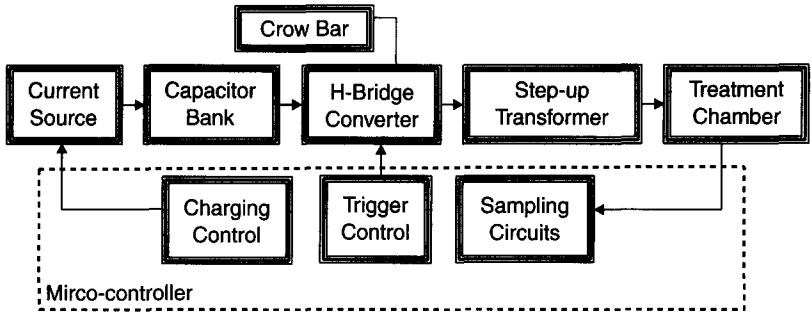

FIG. 3. System diagram of a benchtop-scale high voltage pulse generator (OSU-4A).

B. PEF TREATMENT CHAMBERS

High voltage electricity is transferred into the food product in the treatment chambers, which may be designed for either static (batch) or continuous processing. The earliest chambers were designed to treat a static volume using parallel plate geometry consisting of flat electrodes separated by an insulating spacer (Dunn, 2001). Sale and Hamilton (1967) developed a static chamber using two carbon electrodes and U-shaped polyethylene spacer. Dunn and Pearlman (1987) designed a circular parallel stainless steel electrode chamber for static treatment and a continuous flow treatment chamber for continuous processing. Zhang *et al.* (1995a) reported a disk-shaped static chamber using two round-edged stainless steel electrodes. Ho *et al.* (1997) used a static circular PEF treatment

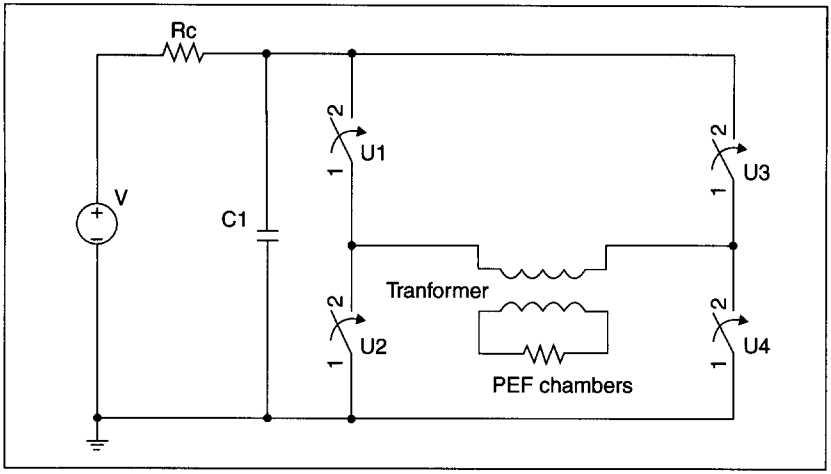

FIG. 4. Circuit diagram of a benchtop-scale high voltage pulse generator (OSU-3C).

chamber using two circular and parallel stainless steel electrodes. Qin *et al.* (1995) reported a parallel-plate static chamber, parallel-plate continuous chamber and co-axial continuous chamber. For treating flowing product, co-axial and co-field chambers are currently favored. Electrical current flows perpendicular to food flow in co-axial chambers and in parallel to food flow in co-field chambers (Dunn, 2001).

Figure 5 is a diagram of a co-field flow PEF treatment chamber linked by high voltage and ground connections (Yin *et al.*, 1997; Hermawan, 1999).

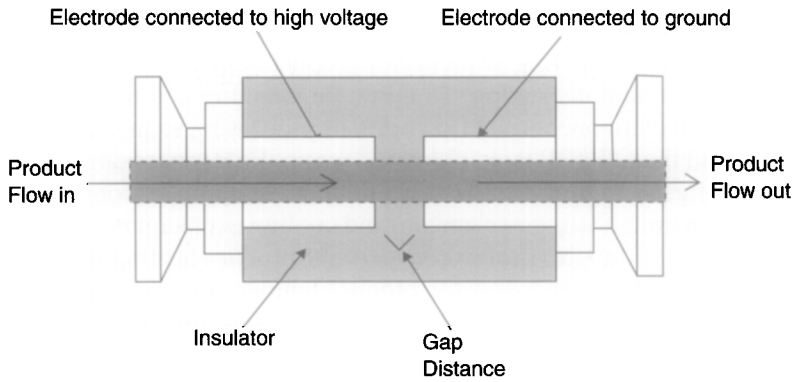

FIG. 5. A diagram of co-field flow PEF treatment chamber (modified from Yin *et al.*, 1997 and Hermawan, 1999).

As liquid food flows though the PEF chamber, a high voltage current or charge is applied to the product between the two electrodes (Qin *et al.*, 1995). When high electric voltage (10–50 kV) is discharged into foods, a large flux of electrical current flows through the foods due to the presence of ions which carry electrical charge (Zhang *et al.*, 1995a). Because of a very short period of discharge time (nsec or μsec), heating of foods is minimized. Figure 6 shows co-field flow PEF treatment chambers used for benchtop and pilot plant-scale PEF systems at the Ohio State University.

C. FLUID HANDLING SYSTEM

PEF processing of foods has been conducted with static treatment systems using a batch mode of processing (Dunn and Pearlman, 1987), as well as with continuous systems (Qin *et al.*, 1995; Qiu *et al.*, 1998). The basis for any continuous food processing operation is a means of product transfer for processing and packaging. For liquid products, a fluid handling system comprising pumps, tubing and accessories is used. For any calculated food process, the pumping must provide a constant product flow rate to ensure uniformity of treatment conditions (David *et al.*, 1996). This is especially true for PEF processing which involves such short time pulses that any pulsation in product flow can lead to inconsistent product treatment.

Qiu *et al.* (1998) describe a pilot plant-scale fluid handling system for PEF processing of fresh orange juice followed by aseptic packaging. A sanitary fluid handling system has been designed and constructed for the treatment of fluid and particulate food products in an integrated pilot plant-scale PEF processing and aseptic packaging system (Streaker, 1999). Figure 7 illustrates all fluid handling system components and the layout for the standard processing sequence of product heating, holding, cooling, PEF treatment, and packaging. To allow for cleaning and mobility of the major system components and flexibility of processing sequence, carts are used to hold the CIP/SIP tanks, Moyno® pump, PEF processing units, and heat exchangers. Figure 8 shows PEF treatment chambers connected to a PEF cooling unit, heating exchangers and cooling exchangers. The system employs a set of tubular heat exchangers for product heating and cooling as well as a PEF cooling unit for product temperature regulation during PEF treatment. Zhang *et al.* (1995a) notes that cooling may be used to reduce the effects of product temperature increases caused by the application of high voltage electric pulses. Figure 9 shows the PEF treatment unit connected to a high voltage pulse generator, heat exchangers, and a data logging system. To monitor system temperatures, a series of sanitary

FIG. 6. Co-field flow PEF treatment chambers for benchtop and pilot plant-scale PEF system using stainless steel electrodes (top), a PEF treatment chamber for pilot plant-scale PEF system using stainless steel electrodes (middle), a PEF treatment chamber for pilot plant-scale PEF system using boron carbide electrodes (bottom). See Plate 1.

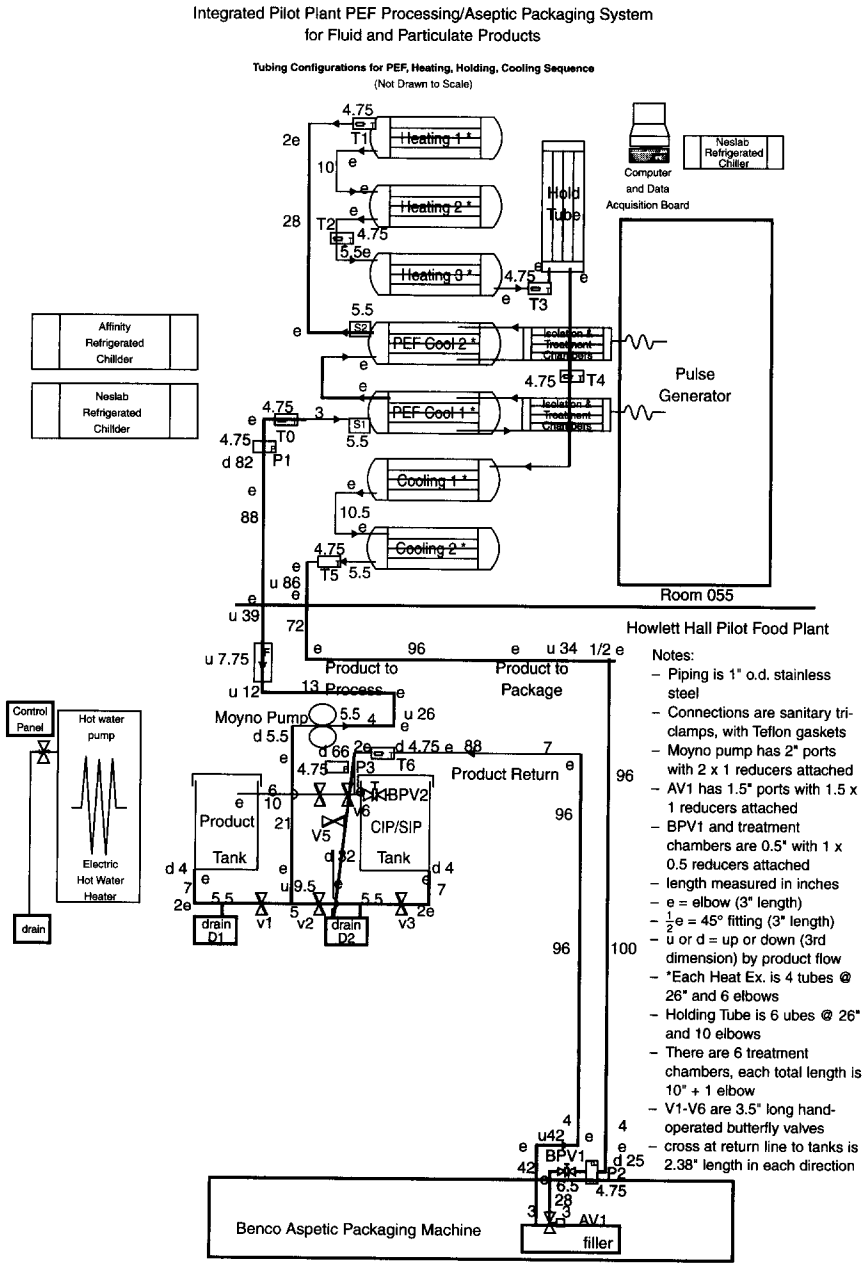

FIG. 7. Diagram of pilot plant fluid handling system for fluid and particulate foods (Streaker, 1999).

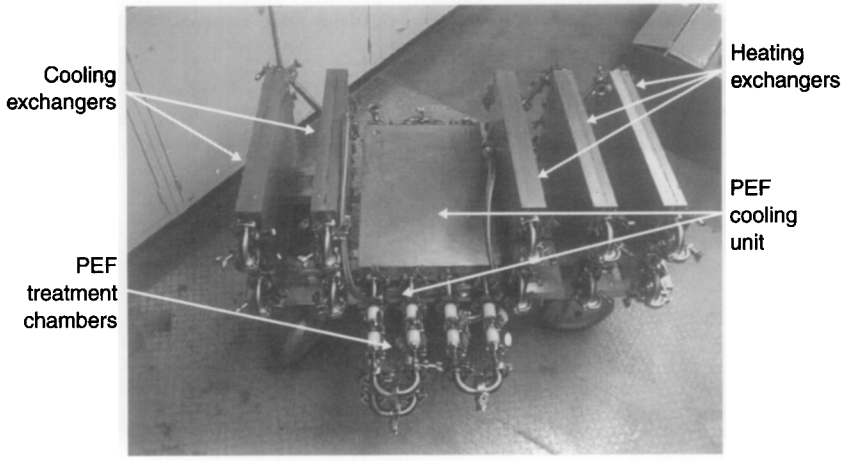

FIG. 8. PEF treatment chambers connected to PEF cooling unit, heating exchangers and cooling exchangers (Streaker, 1999). See Plate 2.

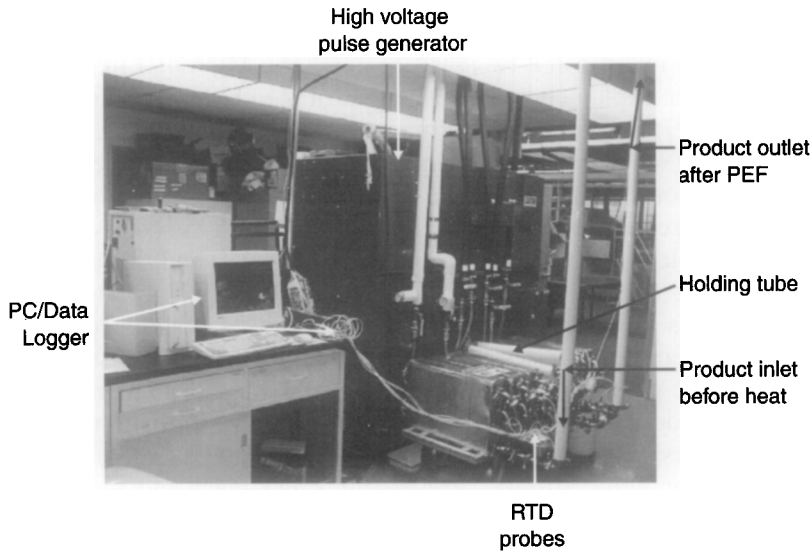

FIG. 9. PEF treatment unit connected to a high voltage pulse generator, heat exchangers, and a data logging system (Streaker, 1999). See Plate 3.

RTD (Resistance Temperature Device) probes with dual sensing elements are placed in the inlet and outlet of the PEF chambers and the outlet of the cooling system. These probes were connected to an RTD input module connected to a network module wired to a personal computer with the LabView® data logging software (National Instruments, Austin, TX).

D. PEF PARAMETERS

There are several important PEF treatment parameters. Electric field strength (E, kV cm^{-1}) refers to the applied voltage gradient (V, kV) across the electrodes divided by the distance between two electrodes (d, cm) within the treatment chambers (Sensoy, 1996). Total treatment time (t) is equal to the pulse duration time (τ) of one pulse multiplied by the number of pulses applied (n). The current flow into the product (I) is directly related to voltage (V) and product conductivity (σ) (Zhang *et al.*, 1995a). The parameters E and t can be adjusted by changing the frequency of the pulses, the applied voltage, the pulse duration time, the distance between electrodes or the flow rate of the product (Ruhlman, 1999).

III. INACTIVATION OF MICROORGANISMS BY PEF

Mechanism of microbial inactivation by high voltage pulsed electrical fields has been investigated by many researchers. Microbial inactivation by PEF has been explained by the formation of membrane pores (Kinosita and Tsong, 1977; Benz and Zimmermann, 1980; Dimitrov, 1984; Rols and Teissie, 1990; Tsong, 1991). Zimmermann (1986) defined electrical breakdown of microorganisms by PEF as follows: the cell membrane can be considered as a capacitor filled with a dielectric. When the cell is exposed to an external electric field with high voltage (kV cm^{-1}) and short duration (nsec to μsec), the cell membrane capacitor is charged due to charge movement, thus a corresponding membrane potential is induced. As the membrane potential increases the membrane thickness decreases. If the total membrane potential exceeds a critical value of about 1 V, reversible electrical breakdown occurs. The breakdown causes the formation of transmembrane pores. If the size and number of pores become large in relation to the total membrane surface, irreversible breakdown and mechanical destruction of the cell occurs. Tsong (1989) suggested that the main effect of the PEF is electroperforation of the cell membranes. Unbalanced osmotic pressure between the cytosol and the external medium causes overswelling of cell and destruction of the cell membrane.

A. FACTORS AFFECTING MICROBIAL INACTIVATION OF PEF

The effectiveness of the PEF process in the inactivation of microorganisms depends on PEF parameters such as electric field strength and total treatment time (Sale and Hamilton, 1968; Hulsheger *et al.*, 1981; Gupta and Murray, 1988; Knorr *et al.*, 1994). Hulsheger and Niemann (1980) reported that there was a linear relationship between the inactivation of *E. coli* and electric field strength. Survival rates of PEF-treated microorganisms depended on field strength and number of pulses. Lethality of the field strength increased as the number of pulses increased (Peleg, 1995). At constant total treatment time, higher electric field strength, 35 kV cm^{-1}, resulted in more reduction of *L. monocytogenes* in milk than lower electric field strength, 25 kV cm^{-1} (Reina *et al.*, 1998). Jayaram *et al.* (1992) reported that high electric field strengths are more effective than long treatment time in causing destruction of *L. brevis* cells.

The type of microorganism also affects the effectiveness of PEF in the inactivation of microorganisms. Sale and Hamilton (1967) found that yeast was more easily inactivated by PEF than other vegetative cells. Researchers reported that the smaller microorganisms are more difficult to inactivate than the larger microorganisms because cross-membrane potential depends on the size of the cell. Smaller cells develop smaller membrane potential resulting in less inactivation of cells (Liu *et al.*, 1990; Knorr *et al.*, 1994). Therefore, higher field intensity is required to inactivate smaller microorganisms than larger microorganisms (Mertens and Knorr, 1992). Yeast cells are larger than bacterial cells, thus yeast cells must be more sensitive to the PEF process (Jeyamkondan *et al.*, 1999).

Growth stage of microorganisms is also related to the effectiveness of microbial inactivation by PEF. Bacteria and yeast cells at their logarithmic stage are more sensitive to PEF than those at the stationary and lag growth stage (Jacob *et al.*, 1981; Pothakamury *et al.*, 1996). Bacterial spores, the most resistant microorganisms to external stress including severe heat treatment, are also known to be highly resistant to PEF treatment (Matsumoto *et al.*, 1991; Yonemoto *et al.*, 1993).

A synergistic effect between PEF treatment and moderate temperature on the inactivation of microorganisms was discussed (Barbosa-Canovas *et al.*, 1997). Zhang *et al.* (1995b) demonstrated that raising the temperature from 7 to 20°C remarkably increased PEF inactivation of *E. coli*. Jayaram *et al.* (1992) reported the high lethal effects of PEF on *Lactobacillus brevis* cells with 25 kV cm^{-1} of electric field strength at 60°C. They explained the increased lethal effects of PEF at the higher temperature by the temperature-related phase transition of cell membrane. Sensoy *et al.* (1997) reported that increasing the temperature from 10 to 50°C increased

the sensitivity of *Salmonella dublin* to PEF treatment. Dunn and Pearlman (1987) suggested that a temperature of at least 45°C, or most preferably at a pasteurization temperature (60–75°C), during PEF treatment will substantially extend the shelf-life of fluid food products. Mertens and Knorr (1992) also suggested that high electric fields should be combined with a moderate temperature to inactivate vegetative cells or even spores more efficiently.

B. MICROBIAL INACTIVATION IN HIGH ACID LIQUID FOODS BY PEF

Generally, microorganisms causing public health concern do not survive in fruit juices and carbonated soft drinks due to low pH and low content of oxygen (Tsai, 1992). However, these beverages are excellent nutritive media for certain acidophillic microorganisms such as yeasts and, to a lesser extent, molds and lactic acid bacteria. Fruit juices are most susceptible to yeast spoilage due to the highest amounts of nitrogenous compounds and vitamins (Deak and Beuchat, 1996). More than 90% of all cases of microbial spoilage of carbonated soft drinks are caused by yeast (Woodroof and Phillips, 1981).

1. Orange juice

Dunn and Pearlman (1987) observed greater than a 5 log reduction of natural microbial contaminants such as yeasts, molds and bacteria in orange juice after PEF treatment at 33.6 kV cm^{-1}. The temperature during PEF treatment was 42–65°C.

Qiu *et al.* (1998) reported a minimum of 3.6 log cycles of reduction in microbial count of reconstituted orange juice after PEF treatment in a pilot plant system. The square-wave form of pulses was more effective in inactivating total aerobic microorganisms than the exponential decay-wave form of pulses.

Total yeast and mold counts reduced from 1.35×10^5 cfu ml^{-1} to less than 40 cfu ml^{-1} in whey protein fortified orange juice by a pilot plant-scale PEF treatment at 32 kV cm^{-1} for 92 μs (Sharma *et al.*, 1998). When the beverage was treated on a bench-scale PEF system, the yeast and mold count was significantly reduced from an initial total count of 900 cfu ml^{-1} to less than 20 cfu ml^{-1} after PEF treatment at 28 kV cm^{-1}. They suggested that PEF treatment is significantly effective in reducing total yeast and mold in the protein fortified orange juice.

Jia *et al.* (1999) compared the effectiveness of PEF treatment at 30 kV cm^{-1} for 240 and 480 μs with heat process at 90°C for 1 min in inactivating spoilage microorganisms in fresh squeezed orange juice.

About 3 log cycles of reduction in total plate counts and yeast and mold counts were observed after PEF treatment which was comparable to the heat process.

McDonald *et al.* (2000) reported inactivation of four types of microorganisms in orange juice at 30 kV cm^{-1} and 50 kV cm^{-1} using a pilot plant PEF system and a laboratory prototype PEF system. A 5 to 6 log reduction of *E. coli*, *Listeria innocua* and *L. mesenteroides* was observed at 30 kV cm^{-1} and more than 2 logs of inactivation of *S. cerevisiae* ascospores was achieved at 50 kV cm^{-1}.

Yeom *et al.* (2000a) treated orange juice in a pilot plant PEF system with electric field strengths of 20, 25, 30 and 35 kV cm^{-1} and total treatment time of 39, 49 and 59 μs. They reported that the higher electric field strength and longer total treatment time is more effective for inactivation of natural microbial flora in orange juice. PEF treatment of orange juice at 35 kV cm^{-1} for 59 μs caused a 7 log reduction in the total aerobic plate counts and the yeast and mold counts.

2. *Apple juice*

Zhang *et al.* (1994a) reported a 3 to 4 log reduction of *S. cerevisiae* in apple juice using a static PEF treatment chamber and a bench-scale PEF system. They observed that a higher concentration of *S. cerevisiae* had a lower inactivation rate due to the protective effect of clustered cells. Zhang *et al.* (1994b) investigated the effectiveness of different wave forms in inactivating *S. cerevisiae* suspended in apple juice. They observed about 4 log cycles of reduction in yeast cells at 12 kV cm^{-1} and reported that square-wave pulses were more effective than exponential-decay pulses.

Harrison *et al.* (1997) reported that PEF treatment of apple juice at 40 kV cm^{-1} reduced the *S. cerevisiae* population from 8×10^7 cfu ml^{-1} to 4×10^4 cfu ml^{-1}. TEM (Transmission Electron Microscopy) micrographs of PEF treated *S. cerevisiae* exhibited disruption of yeast cellular organelles and almost total absence of ribosome bodies. They suggested cytological disruption as an alternative microbial inactivation mechanism to the electroporation theory based on damaged organelles and lack of ribosomes in PEF treated *S. cerevisiae*.

Evrendilek *et al.* (1999) reported a 5 log reduction in *E. coli* O157:H7 and *E. coli* 8739 inoculated in apple juice after PEF treatment at 30 kV cm^{-1} for 114.96 μs. Treatment temperature was kept below 35°C and there was no difference in the sensitivities of *E. coli* O157:H7 and *E. coli* 8739 against PEF treatment.

Apple juice samples were inoculated with *E. coli* O157:H7 and PEF treated using a bench-scale PEF system (Evrendilek *et al.*, 2000). PEF

treatment of the apple juice at 34 kV cm^{-1} for 166 μs resulted in a 4.5 log reduction of *E. coli* O157:H7. Temperature of apple juice during the PEF treatment was kept under 38°C.

3. CRANBERRY JUICE

Jin *et al.* (1998) processed cranberry juice using a pilot plant-scale PEF system at 35 kV cm^{-1} for 195 μs to determine the effectiveness of pilot plant scale PEF treatment in the inactivation of microorganisms in cranberry juice. Figure 10 shows number of viable cells in cranberry juice before and after PEF treatment at 35 kV cm^{-1} for 195 μs. After PEF treatment, about 4 log cycle of reduction in microbial population of cranberry juice was observed by total aerobic plate counts and yeast and mold counts.

Raso *et al.* (1998) reported that inactivation of mold spores suspended in fruit juices by PEF treatment. Effectiveness for *B. fulva* conidiospore inactivation was cranberry > grape > pineapple > orange > apple > tomato.

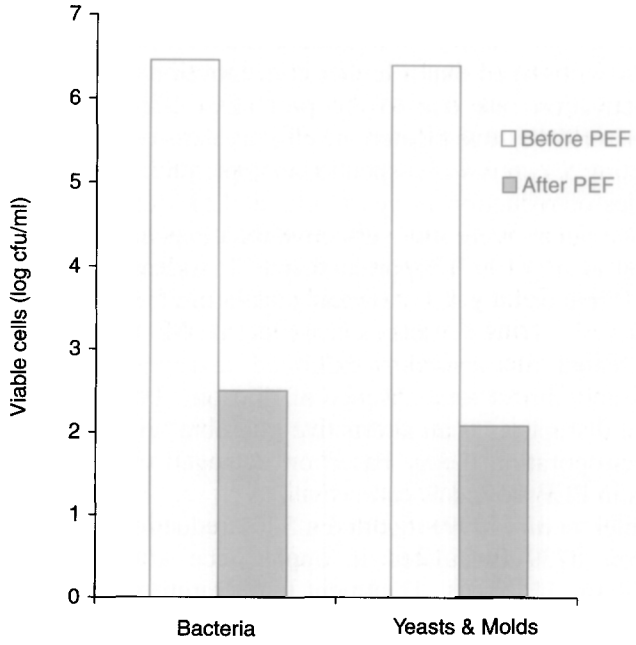

FIG. 10. Number of viable cells in cranberry juice before and after PEF treatment at 35 kV cm^{-1} for 195 μs (Jin *et al.*, 1998).

About 6 log cycles of reduction in the population of *B. fulva* conidiospores was observed in cranberry juice by PEF treatment at 36.5 kV cm^{-1}.

Jin and Zhang (1999) reported that PEF treatment of cranberry juice using a bench scale PEF system at 40 kV cm^{-1} for 150 μs resulted in about 5 log cycle reduction in aerobic bacteria, yeasts and molds, which was as effective as thermal treatment at 90°C for 90 s.

IV. SHELF-LIFE OF PEF TREATED HIGH ACID LIQUID FOODS

A. ORANGE JUICE

Dunn and Pearlman (1987) reported that PEF treatment significantly extended the shelf-life of orange juice. The orange juice was treated using 35 high voltage pulses at temperature range from 42 to 65°C and had over a week of shelf-life extension beyond the normal shelf-life.

Qiu *et al.* (1998) reported that the aseptically packaged, PEF treated orange juice had an extended shelf-life at 4°C compared to the untreated orange juice, which spoiled after 30 days with a total plate count of more than 10^6 cfu ml^{-1}. A minimum seven months of shelf-life was achieved with the PEF-treated orange juice during storage at 4°C.

Microbial stability of the PEF treated and aseptically packaged protein-fortified orange juice was tested (Sharma *et al.*, 1998). The protein-fortified orange juice treated in a pilot plant PEF system was microbiologically stable for 5 months at 4°C, however it was not stable at room temperature for more than 5 days.

PEF treatment at 30 kV cm^{-1} was as effective as heat treatment at 90°C in preventing growth of yeast and molds in single strength orange juice (Jia *et al.*, 1999). Total yeast and mold counts of PEF treated orange juice was less than 1 during 6 weeks of storage at 4°C while control orange juice was spoiled after 2 weeks at 4°C.

Effects of PEF treatment at 35 kV cm^{-1} for 59 μs on the microbial stability of orange juice were compared with heat pasteurization at 94.6°C for 30 s (Yeom *et al.*, 2000b). The PEF treatment of orange juice using a pilot plant PEF system integrated with aseptic packaging system kept the number of natural microorganisms in orange juice about 1 log cfu ml^{-1} at 4, 22 and 37°C for 112 days, which was as effective as the heat pasteurization.

Ayhan *et al.* (2001) also reported microbial stability of PEF treated orange juice using a pilot plant PEF system integrated with a glove box packaging system. After PEF treatment at 35 kV cm^{-1} for 59 μs, orange juice had a total aerobic plate count of < 1 log cfu ml^{-1} during storage at

4 and 22°C for 112 days. The PEF treated orange juice was reported negative for the pathogens, *Salmonella* spp., *L. monocytogenes*, and *E. coli* O157:H7 by Silliker Laboratories (Columbus, OH).

B. APPLE JUICE AND APPLE CIDER

Qin *et al.* (1995) treated two kinds of apple juices using a bench-scale continuous PEF system at 50 kV cm^{-1}. PEF treated apple juice from concentrate had 4 weeks of shelf-life at room temperature. Shelf-life of PEF treated apple juice from fresh squeezed apple juice was 3 weeks at refrigeration temperature. They reported that PEF technology is successful in processing liquid foods and the food temperature during PEF treatment can be controlled below traditional thermal processing temperature.

Apple juice and apple cider were PEF treated in a pilot plant system (Evrendilek *et al.*, 2000). Shelf-life of PEF treated apple juice and apple cider at 35 kV cm^{-1} for 94 μs was more than 67 days at 4°C and approximately 67 days at 22°C, and 14 days at 37°C. Combination of heat treatment at 60°C for 30 s and PEF treatment at 35 kV cm^{-1} for 94 μs further increased the shelf-life of apple cider.

C. CRANBERRY JUICE

Reconstituted cranberry juice was PEF treated at 35 kV cm^{-1} for 195 μs using a pilot plant PEF system and aseptically packaged using aseptic packaging machine (Jin *et al.*, 1998). Shelf-life study indicated that PEF treatment of cranberry juice resulted in less growth or delayed growth of bacteria and fungi during storage at 4, 22 and 37°C. The PEF-treated and aseptically packaged cranberry juice had a minimum shelf-life of 8 months, 37 days and 30 days at 4, 22 and 37°C, respectively.

Jin and Zhang (1999) treated cranberry juice with a bench scale continuous PEF system. Growth of yeasts and molds was not observed in the PEF treated cranberry juice during 14 days of storage at 4°C and during 12 days of storage at room temperature, respectively.

V. QUALITY OF PEF TREATED HIGH ACID LIQUID FOODS

Many researchers have reported quality degradation of juices by heat processing. Flavor compounds are sensitive to thermal degradation and heat load incurred during heat pasteurization can negatively impact the flavor of juice (Ekasari *et al.*, 1988). Irreversible damage to the citrus juice

flavor results from chemical reactions initiated or occurred during the heating process (Braddock, 1999). Ascorbic acid is one of the most important nutrients in fruit and vegetable juices and high temperature during heat pasteurization causes loss of ascorbic acid (Nagy and Smoot, 1977; Saguy *et al.*, 1978). Ascorbic acid degradation is considered a major chemical reaction responsible for the browning of citrus juices (Marcy *et al.*, 1984). The detrimental changes in color, primarily caused by non-enzymatic browning, reduce consumer acceptance for citrus juices (Klim and Nagy, 1988).

A. ORANGE JUICE

Qiu *et al.* (1998) reported that there was higher retention of flavor and vitamin C in PEF treated orange juice than heat pasteurized orange juice. Only 5–9% flavor loss was observed in PEF treated orange juice, however up to 25% flavor loss occurred in heat pasteurized orange juice. After 90 days of storage at 4°C, vitamin C content of PEF treated orange juice was 68% while that of heat pasteurized orange juice was 46% compared to 100% of fresh orange juice.

PEF caused less protein denaturation and higher retention of vitamin C in protein fortified orange juice compared to heat treatment (Sharma *et al.*, 1998). Whey protein denaturation in protein fortified orange juice was 6–7% by PEF treatment at 32 kV cm^{-1} and 55% by heat treatment at 80°C. The color of PEF treated samples was close to control samples.

Jia *et al.* (1999) reported the average loss of flavor compounds in orange juice after PEF treatment at 30 kV cm^{-1} for 240 μs or 480 μs, or heat treatment at 90°C for 1 min was 3.0%, 9.0% and 22.0%, respectively. Loss of flavor compounds in orange juice was greatly influenced by the types of flavor compounds as well as processing methods. Effects of PEF or heat process on the retention of flavor compound (%) in fresh squeezed orange juice are shown in Figure 11. Loss of ethyl butyrate in orange juice by PEF treatment at 30 kV cm^{-1} and heat treatment at 90°C was 9.7 and 22.4%, respectively. Decanal was not reduced by PEF, but the 41% of decanal was reduced by heat process.

Yeom *et al.* (2000b) compared quality of PEF treated orange juice at 35 kV cm^{-1} for 59 μs with that of heat pasteurized orange juice at 94.6°C for 30 s. The PEF treated orange juice retained significantly more vitamin C and flavor compounds than the heat pasteurized orange juice during storage at 4°C ($p < 0.05$). Linear decomposition of ascorbic acid in PEF or heat-treated orange juice during storage at 4°C is shown in Figure 12. To provide 100% of the US Recommended Daily Allowances (USRDA) requirement for vitamin C, the concentration of ascorbic acid in orange

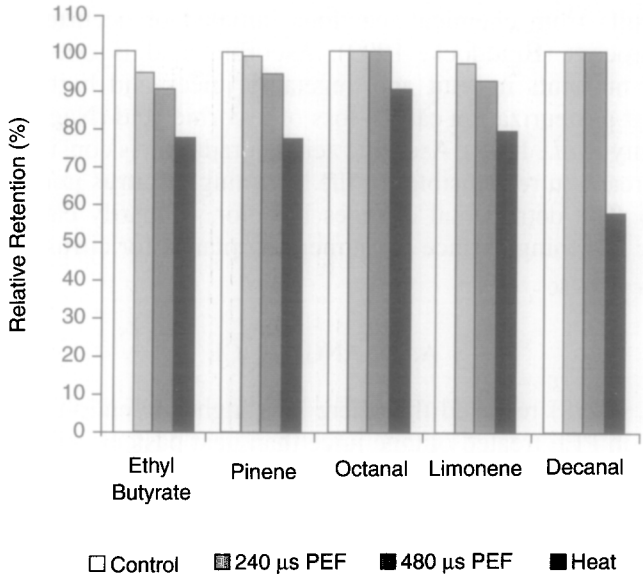

FIG. 11. Effects of PEF or heat process on the retention of flavor compounds (%) in fresh squeezed orange juice (modified from Jia, 1997).

juice should be at least 25 mg per 100 ml at the time of expiration date (Ting, 1977; Squires and Hanna, 1979). The concentration of ascorbic acid in PEF treated orange juice reached 25 mg/100 ml at 4°C after 47 days, which is significantly longer than 31 days of heat pasteurized orange juice ($p < 0.05$). The PEF treated orange juice also had lower browning index, higher whiteness (L) and higher hue angle values than the heat pasteurized orange juice during storage at 4°C.

Ayhan *et al.* (2001) investigated the effects of packaging materials on the quality of PEF processed orange juice. Single strength orange juice was treated with PEF at 35 kV cm^{-1} for 59 μs using a pilot plant-scale PEF system and filled into four different sanitized bottles such as glass, polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) using a sanitized glove box. Packaging material had a significant effect on the retention of orange juice flavor compounds, color, and vitamin C ($p < 0.05$). Glass and PET bottles were effective to keep flavor compounds, vitamin C and color of PEF treated orange juice during storage. Flavor intensity of PEF treated orange juice was determined as 6 on a 9-point scale by a trained sensory panel. PEF treated orange juice had a shelf life of > 16 weeks in glass and PET bottles at 4°C.

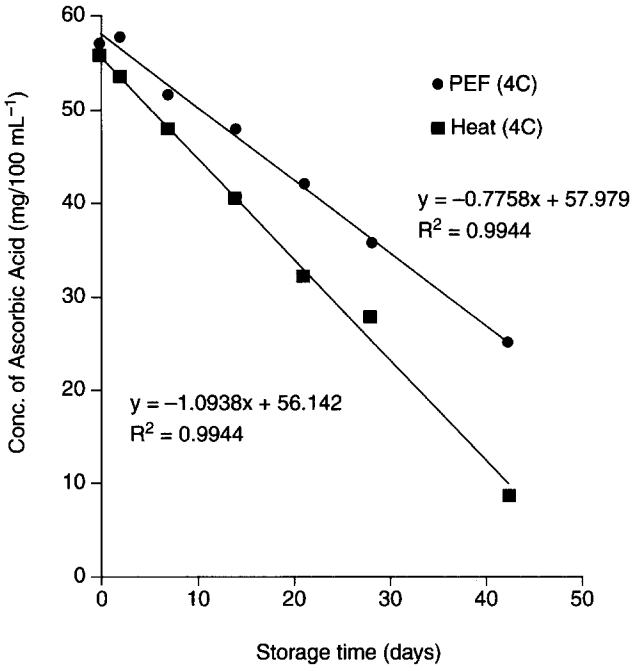

FIG. 12. Linear decomposition of ascorbic acid in PEF or heat-treated orange juice during storage at 4°C (Yeom, 2000c).

Effects of packaging materials on the concentration of ascorbic acid in PEF treated orange juice during storage at 4°C are shown in Figure 13. The concentration of ascorbic acid in glass and PET bottles was higher than that of HDPE, LDPE bottles and the aseptic packaging material during storage at 4°C. The aseptic packaging material consisting of low density polyethylene (LDPE), polyvinyledene chloride (PVDC), and high impact polystyrene (HIPS) showed the lowest concentration of ascorbic acid during storage at 4°C. Vitamin and flavor are destabilized in containers that are permeable to atmospheric oxygen (Hendrix and Redd, 1995). Marshall *et al.* (1986) reported that permeability of oxygen by soft-pack containers is the most critical factor in the shelf stability of aseptic-processed juices. LDPE is known to be not a good barrier to gases (Robertson, 1993). It explains that significant reduction of ascorbic acid in LDPE bottle and the aseptic packaging material (LDPE/PVDC/HIPS) compared to glass, PET and HDPE bottles. Marshall *et al.* (1986) also reported greater reduction in ascorbic acid levels with higher concentration of air in the headspace. The presence of oxygen in the juice and

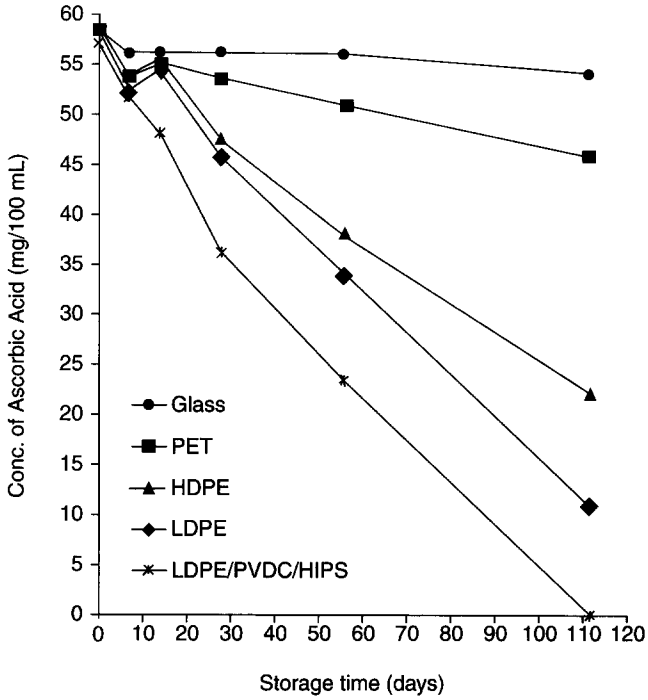

FIG. 13. Effects of packaging materials on the concentration of ascorbic acid in PEF treated orange juice during storage at 4°C (Yeom, 2000c).

headspace gases above juice plays a role in the shelf-life of chilled juice products (Shaw, 1992). The orange juice packaged in the aseptic packaging machine (Benco Aseptic/2, Placenza, Italy) contained significant amount of headspace compared to manually packaged bottles. Therefore, the ascorbic acid was rapidly degraded in the aseptic packaging material (LDPE/PVDC/HIPS) due to high oxygen permeability and the presence of headspace. Selection of proper packaging material and method is important in keeping high quality of PEF processed juices.

B. APPLE JUICE

PEF treated apple juice had similar sensory characteristics compared to the non-PEF treated apple juice (Qin *et al.*, 1995). A taste panel could not find any significant difference between fresh-squeezed apple juice and the PEF-treated apple juice. There was no apparent change in the physical and chemical properties of apple juice after PEF treatment.

PEF processing of reconstituted apple juice was effective in retaining vitamin C during storage (Evrendilek *et al.*, 2000). PEF treatment of apple juice and PEF or PEF + heat treatment of apple cider did not affect their color stability during storage. A paired preference test was conducted for the apple cider using a consumer panel to determine if there was any difference in the PEF treated and untreated cider samples. Figure 14 illustrates preference results of apple cider sensory evaluation. These data indicates that the acceptability of fresh apple juice is not affected by PEF processing.

C. CRANBERRY JUICE

PEF treated cranberry juice showed similar flavor or aroma profiles as control products (Jin and Zhang, 1999). No statistically significant difference was observed in the content of anthocyanin pigments and L values between PEF treated cranberry juice and control cranberry juice. However, thermal treatment significantly altered the overall flavor profile and reduced the anthocyanin pigment content. Effects of PEF or heat on the total GC peak area of cranberry juice are shown in Figure 15. There was significant difference in the total GC peak area between heat-treated cranberry juice and control or PEF treated cranberry juice.

VI. PHYSICAL PROPERTIES OF LIQUID FOODS FOR PEF TREATMENT

To design and optimize the operation of PEF processing units, information on the physical properties of the products being processed is required over

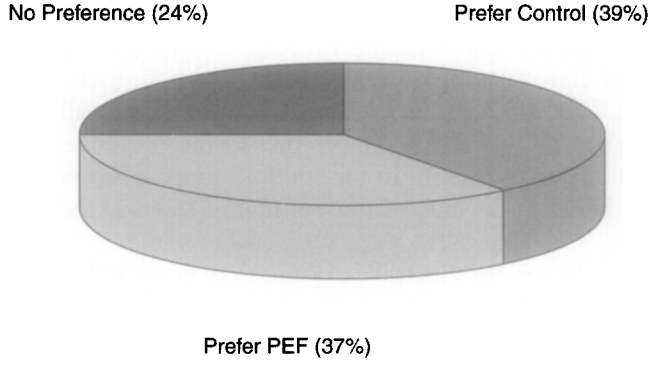

FIG. 14. Preference results of apple cider sensory evaluation (Ruhlman, 1999).

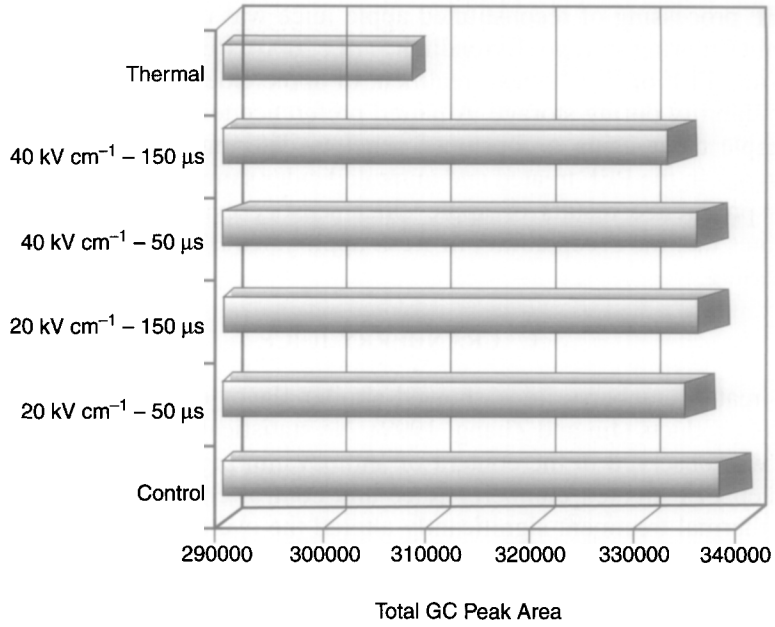

FIG. 15. Effects of PEF or heat on total GC peak area of cranberry juice (unpublished data from Jin and Zhang, 1999).

a wide range of temperatures. The most critical physical properties of foods are electric conductivity, viscosity, density, and specific heat (Ruhlman, 1999).

A. ELECTRIC CONDUCTIVITY

Electric conductivity versus temperature for fruit juices and vegetable juices are shown in Figures 16 and 17, respectively. Electric conductivity of fruit juices and vegetable juices increased with an increase in product temperature. The vegetable juices had the greatest overall electric conductivity compared to the fruit juices due to the presence of salt in the product. Ionic species present in the food, such as salts and acids, act as electrolytes that allow an electric current to pass through the food (Halden *et al.*, 1990).

At a given voltage, the electrical current flow is directly proportional to the electric conductivity of the food (Zhang *et al.*, 1995a). Raso *et al.* (1998) reported the dependence of electric field intensity on electric conductivity of fruit juices. The highest electric field intensity was reached in cranberry juice having the lowest electric conductivity, so highest

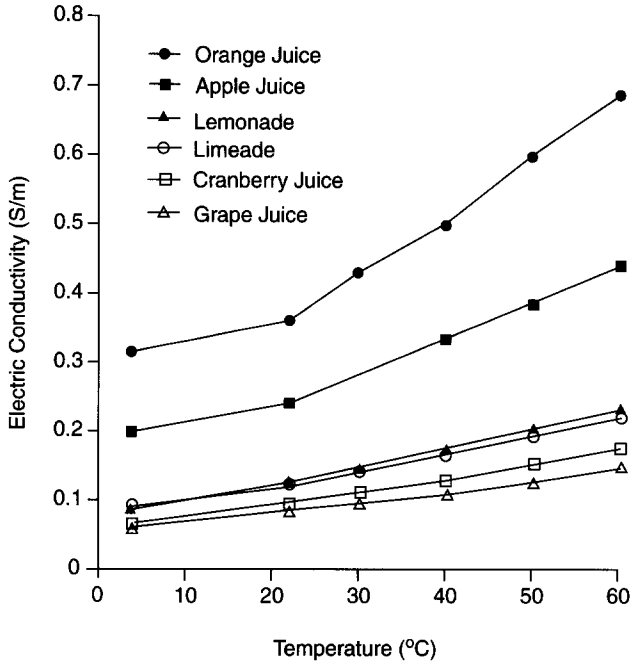

FIG. 16. Electric conductivity versus temperature for fruit juices (modified from Ruhlman, 1999).

microbial inactivation was observed in cranberry juice at constant input voltage. Ruhlman *et al.* (2001) calculated total possible temperature change of products during PEF treatment. An increase in electric conductivity causes an increase in the overall energy input and change in temperature during PEF processing at a defined dosage.

B. VISCOSITY

Viscosity versus temperature for fruit juices and vegetable juices are shown in Figures 18 and 19, respectively. Viscosity of fruit juices and vegetable juices decreased as product temperature increased. According to the Arrhenius relationship, as the product is heated, the viscosity decreases since the thermal energy of the molecules increases and the intermolecular distances increase due to the thermal expansion (Constenla *et al.*, 1989). The viscosity of the product determines the flow characteristics, and a uniform velocity profile of food product in the PEF treatment chamber can provide a uniform PEF process.

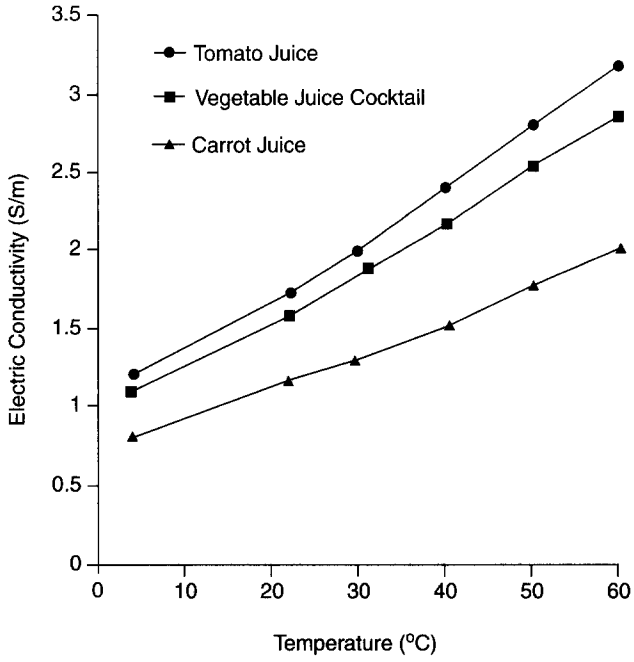

FIG. 17. Electric conductivity versus temperature for vegetable juices (modified from Ruhlman, 1999).

C. DENSITY AND SPECIFIC HEAT

Density versus temperature for fruit juices and vegetable juices are shown in Figures 20 and 21, respectively. Density of fruit juices and vegetable juices decreased with the increase in temperature. Density of the products depends on the intermolecular forces and water solute interactions, which are affected by temperature (Constenla *et al.*, 1989). Specific heat (C_p) of foods can be calculated using a model estimation for food materials of high water content (w) at room temperature as follows (Singh and Heldman, 1993).

$$C_p = 1.675 + 0.025w$$

Density and specific heat of foods affects the amount of temperature change during PEF treatment. As the density of the product decreases, the total temperature change increases Similarly, a decrease in specific heat also increases the total temperature change during PEF processing (Ruhlman *et al.*, 2001).

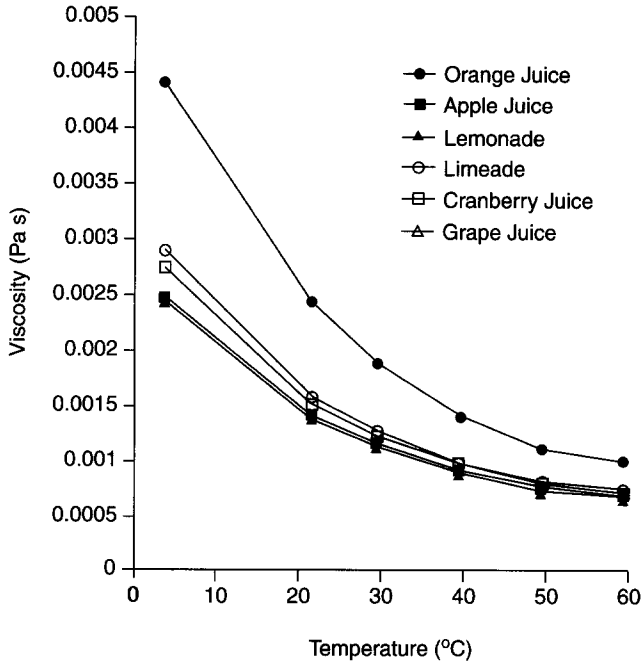

FIG. 18. Viscosity versus temperature for fruit juices (modified from Ruhlman, 1999).

As shown in Figures 16–21, physical properties of foods are significantly affected by processing temperature, therefore temperature control of food products during PEF treatment is important. Small change in physical property of foods caused by temperature change during PEF treatment could alter the PEF treatment dosage of the foods. The temperature of foods during PEF treatment can be controlled using a cooling heat exchanger in between each pair of PEF treatment chambers.

VII. FUTURE PROSPECTS FOR PEF

To date, work with PEF has been conducted extensively on the microscopic, bench, and pilot plant levels. Certainly the next step and the ultimate determinant of the viability of PEF as a food preservation method is commercialization. A PEF Consortium for Technology Commercialization has been formed to combine the resources and unique capabilities of academic and industrial partners (Table II). As PEF research has progressed from the description of the mechanism for microbial lethality (Sale and

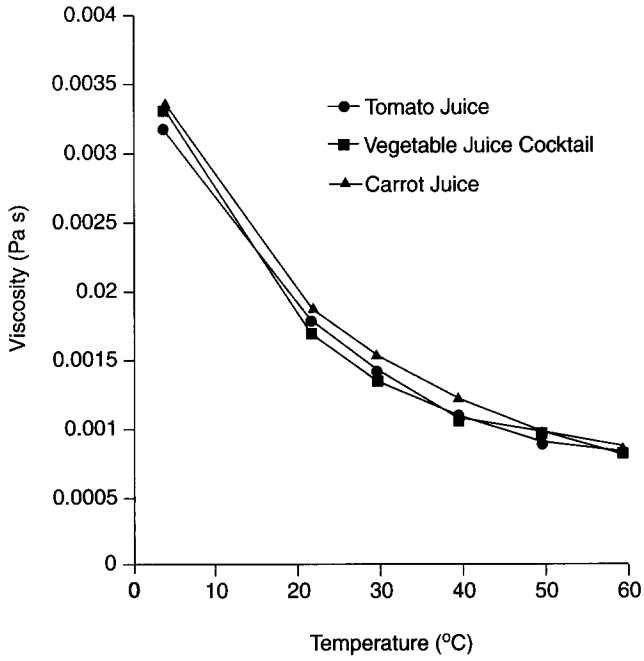

FIG. 19. Viscosity versus temperature for vegetable juices (modified from Ruhlman, 1999).

TABLE II
MEMBERS OF A PEF CONSORTIUM FOR TECHNOLOGY COMMERCIALIZATION

American Electric Power
Diversified Technologies Inc.
General Mills
Hirzel Canning
Kraft Foods
Tetra Pak Processing AB (Sweden)
The Ohio State University
US Army Natick & Soldier System Center
A carbonated beverage company

Hamilton, 1967) to the extension of shelf-life of orange juice (Yeom *et al.*, 2000b), interesting prospects for the future application have emerged.

High acid liquid foods, specifically orange juice and apple juice, are at the forefront of commercial application for several reasons. These include the marketability of "fresh-squeezed" products, the relative ease of PEF processing, and lower regulatory hurdles when compared to other food

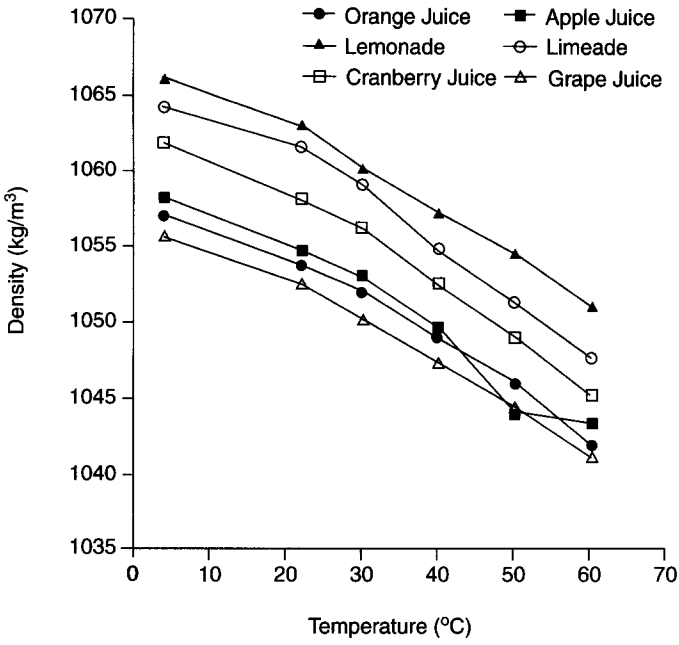

FIG. 20. Density versus temperature for fruit juices (modified from Ruhlman, 1999).

products. Sensory tests conducted by Qin *et al.* (1995) and Ruhlman (1999) have substantiated consumer acceptance of PEF processed liquid beverages. For PEF to enter a market where traditional thermal processing methods dominate, value must be added to the product, such as improved quality while providing the same level of food safety. Secondly, orange and apple juices are most easily PEF processed since they have a low viscosity and a relatively low electrical conductivity as described by Ruhlman (1999) and are also easily pumpable and contain little trapped air to interfere with electrical processing. On the regulatory side, high acid products are not impeded by the stringent regulations associated with the Code of Federal Regulation for low acid products (21 CFR, 1998 – US Government Printing Office, Washington DC).

While the work of researchers has been promising, a market for PEF technology must be present. Consumer demand for a higher quality, fresh-appearing and safe food supply is the ultimate catalyst for the emergence of PEF on a commercial scale. Product category, cost of production and marking positioning are important factors to consider in the commercialization of PEF technology. The production cost of PEF treated orange juice was expected to be 6 cents per liter, which is higher than

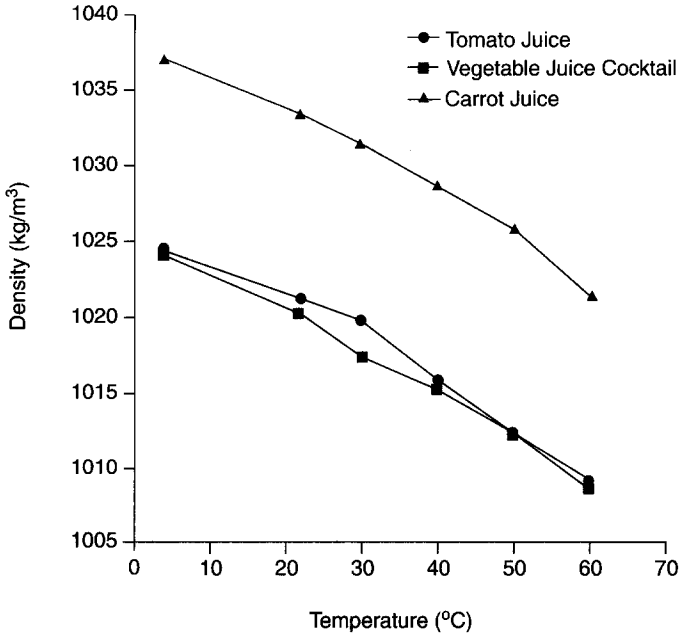

FIG. 21. Density versus temperature for vegetable juice (modified from Ruhlman, 1999).

5 cents per liter of heat pasteurized orange juice (Tetrapak Processing AB personal communication, 1998). The cost of PEF processing may be reduced by developing a PEF system that requires low cost for construction and maintenance and optimization of process parameters for minimization of electric power use. Indeed, through the combined efforts of the PEF Consortium, a commercial-scale PEF system for high acid liquid foods is made available.

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