Pulsed Electric Field Generators in food processing

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Abstract

High intensity pulsed electric field (PEF) processing involves the application of pulses of high voltage to foods placed between 2 electrodes. PEF treatment is conducted at ambient, sub-ambient, or slightly above ambient temperature, and energy loss due to heating of foods is minimized. For food quality attributes, PEF technology is considered superior to traditional heat treatment of foods because it avoids or greatly reduces the detrimental changes of the sensory and physical properties of foods. Some important aspects in pulsed electric field technology are the generation of high electric field intensities, the design of chambers that impart uniform treatment to foods with minimum increase in temperature, and the design of electrodes that minimize the effect of electrolysis. Pulse generator is a more important section of PEF system which is implemented in various manners. In this paper we present most commonly used techniques of signal generation required for PEF.

1. Introduction

The preference of consumers for fresh foods has led to the development of mild preservation technologies. Food producers are looking for solutions to prevent the growth of micro-organisms without compromising the initial quality of products. New processes are being evaluated and products have found their way to the market. Most remarkable are the preservation processes whereby products are subjected to a physical treatment at temperatures less than those required for heat pasteurization. Consequently, the initial quality of products is no longer adversely affected by heating. Preservatives are less frequently required to extend the shelf life of products.

There are several methods for electrical pasteurization having ohmic heating, microwave heating, field stimulation, high voltage arc discharge, low voltage alternating current, and High voltage pulse generator.

Ohmic heating is one of earlier methods in electrical food pasteurization. In this method, passing electrical energy through food bulk causes heat. Today, microwave heating have been widely used in home and industries, but processing of some foods dissipate too much energy and cost because they have low conductivity. Low electric field stimulation is considered as a way for bacteria control of meat. Electrical stimulus decreases meat’s bacteria count and strength.

PEF (Pulsed Electric Field) processing is a non-thermal method of food preservation that uses short bursts of electricity for microbial inactivation and causes minimal or no detrimental effect on food quality attributes.

PEF processing involves treating foods placed between electrodes by high voltage pulses in the order of 20–80 kV (usually for a couple of microseconds). 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.

One possible application of PEF is to improve the permeability of plant cell walls in order to make the recovery of valuable ingredients easier. This can be helpful, for example, in producing fruit juices, by improving the yields of extractable ingredients so that enzyme treatment can be avoided or reduced and the quality of the juice can be improved.

Pulsed Electrical Field technology is based on the phenomena that biological membranes are punctured when an external electrical impulse is applied. This process is often referred to as non-thermal as structural damage to membranes is realized at significantly low energy levels when compared to the process of heating. For food applications this has led to the formulations of two concepts. The first is a mild preservation concept of pumpable food products where PEF treatment is
targeted for the inactivation of bacteria to extend the shelf life. Secondly, a versatile process has been developed for the pre-treatment of plant foods. Pre-treatment enhances the excretion of compounds from tuberous plants and improves the drying and re-hydration properties of dried vegetables.

In the last years preservation based on PEF technology has reached the point of commercialization by the scientific and technological developments. The recent progresses that have been made in this field include: demonstrations of industrial applications, development of large-scale equipment, market evaluation, product assessment, economical and legislative issues. An integrated PEF system consists of a fluid handling unit, high voltage pulse generator, PEF treatment chambers, and packaging machine. Pulse generator is a more important section of PEF system which is implemented in various manners.

In the next section, some important method of high voltage Pulse Electric Field generator will be discussed. Then PE F application in food industries will be described. Finally, in conclusion section, we will compare various PEF generators, then some benefits and drawbacks of it will be listed.

2. High voltage pulse generators

Generation of pulsed electric fields requires a fast discharge of electrical energy within a short period of time. This is accomplished by using a pulse-forming network (PFN). In general, a PFN (Fig. 1c and d) is an electrical circuit consisting of one or more power supplies (charging voltages up to 60 kV), switches (igniton, thyatron, tetrode, spark gap, semiconductors), capacitors (0.1–10 mF), inductors (30 mH), resistors (2Ω–10MΩ), and treatment chambers. The relative electric values of each component in the PFN determine the shape of the pulse (Fig. 1a and b).

The simplest PFN is an RC (resistance–capacitance) circuit in which a power supply charges a capacitor, which can deliver its stored energy to a resistive load (treatment chamber) in a couple of microseconds, by activation of a switch. The pulse generated is exponentially decaying (Fig. 1a and c)[6].

There are a lot of methods for implementation of high voltage pulse generators, that some of them are introduced as bellow:

2.1. High voltage pulse generator using energy storage components and transformer

Fig. 2 shows a circuit diagram of a high-voltage bipolar pulse generator, including a power source V, an energy storage components having inductors L11, L12, L13 and capacitors C11, C12, and C13, a set of switches U11 and U12, transformer T11, and a load 104 having one or more PEF treatment chambers. The power source V of circuit is a DC power source. Two charging resistors R11 and R12 and a protective diode D are optionally shown for the purpose of isolation and protection. The energy storage
component shown in FIG. 2 is a pulse forming network (PFN). During the energy storage component charging period, the capacitors thereof are charged up to the line voltage of the power source V.

A set of two switches U11 and U12 are closed periodically to discharge the energy storage component. Each time, only one switch is closed and involved in discharging the PFN while the other switch remains open. The switches U11 and U12 are preferably switching devices which are normally open and only close upon actuation such as, for example, thyristors. The PFN controls, through trigger device, the discharge of energy and assists in opening the switches again till energy stored in PFN is transferred to a load of PEF treatment chambers and current passing through the switch decreases to zero. The switches U11 and U12 are preferably grounded and, therefore, the corresponding driving circuits do not need to be floated at operating voltage. In all embodiments, the switches U11 and U22 are triggered by trigger device. However, switches U11 and U12 may also be triggered by a computer control system, such as a PEF treatment master control system, configured with particular frequency, voltage, and duty ratios[1].

2.2. High voltage pulse generator using a non-linear capacitor

FIG. 3 is a circuit diagram of an embodiment of a pulse generator. In this embodiment, a resistor R1 controls the charging current and a capacitor C1 stores the primary energy (1/2C1 V1), where the voltage across C1 is V1. An inductor L1 stores the secondary energy (1/2L1 I1) where the current flowing in L1 is I1. A capacitor C2 stores the tertiary energy (1/2C2 V2), where the voltage across C2 is V2. An inductor L2 causes charging in the capacitor C2 and the capacitor C3 in addition to facilitating the saturation of C3. First, AC voltage from an AC power source is converted to DC voltage through a rectification circuit comprising rectification diode, resistor (R1) and capacitor (C1). In this embodiment, a voltage of about 60V is applied to capacitor (C1). The DC voltage is converted to a pulse by control of semiconductor switch (Q1), which is controlled by drive circuit[2].

2.3. High voltage pulse generator using parallel and series MOSFETs

In general, High voltage pulse generator using MOSFETs can be used in 2 categories:

**High voltage pulse generator using parallel MOSFETs**: The motivation for using several MOSFETs in parallel is to decrease the effective on-state resistance of the switches. When the resistance of the load is small, the voltage of the output pulse can be significantly decreased. The reason for this is that the increased current due to the low resistance causes a larger voltage drop across the MOSFET’s on-state resistance (5.5 Ω), leaving less voltage to appear across the load. If it would be possible to reduce the value of on-state resistance, then the amount of voltage drop across the switch would decrease. By paralleling MOSFETs, the equivalent on-state resistance decreases, resulting in a smaller voltage loss across the switch, allowing more voltage to appear across the load. By switching two or three MOSFETs in parallel, the effective on-state resistance can be reduced by a half or a third, respectively (assuming the MOSFETs have identical values of on-state resistance).

**High voltage pulse generator using series MOSFETs**: Fig. 4 the design and operation of a MOSFET-based pulsed power supply, which is capable of producing controllable square pulses with amplitudes up to 3000 V, and widths of a few hundred nanoseconds to dc. Since the MOSFETs that were used are rated for 1500

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**Fig. 3 A circuit diagram of a pulse generator using non-linear capacitor**

**Fig. 4 a circuit diagram of a pulse generator using series MOSFETs**
V, and exceeding this rating can damage them, two MOSFETs were connected in series. Connecting the two MOSFETs in series enables them to share the voltage, thereby allowing the total applied voltage to be twice that of the rating of one MOSFET. Reference source not found. This pulsed power supply uses one driver circuit to drive two MOSFETs that are connected in series, which reduces the number of components and simplifies the board layout.

2.4. Square wave generators

For better control of electric field parameters, square wave pulse generator has been introduced. The device still comprises a variable high voltage power supply (V) and a capacitor (C) for energy storage, yet the switch is replaced with a fast power MOSFET (metal oxide silicon field effect transistor) or IGBT (insulated gate bipolar transistor) (Q) and a triggering circuit (Fig. 5). In principle, such a device can continuously deliver square wave pulses to the output, provided that the high voltage power supply is able to recharge the capacitor during the delay between two consecutive pulses. The output amplitude of pulses is defined by amplitude of variable power supply, while pulse duration, pulse repetition frequency and possibly number of pulses are programmed by a computer that also comprises triggering circuit[4].

2.5. Analogue generator of unipolar arbitrary signals

Although square wave and exponentially decaying pulses were and probably still are most frequently used signals for electroporation, in some experiments pulses of different shape (e.g. trapezoidal pulses with possibility of control of rise and fall time or square wave pulses modulated with high-frequency sinusoidal signals) have been used.

For generation of arbitrary unipolar signals, technique requires at least two amplification stages (voltage and current) and appropriate driving stage (Fig. 6). The driving stage consists of a signal generator (FG), which is usually a computer with a digital-to-analog converter, and a unity-gain amplifier (AD) that meets power and impedance requirements at the input of a voltage stage.

2.6. Analogue generator of bipolar arbitrary signals

Today probably one of the best techniques that have been evaluated is a class AB bipolar amplifier, in other words the closed-loop push-pull amplifier (Fig. 7). The signal generated by an arbitrary signal source (F_G) is delivered to the input stage where the signal is subtracted from appropriately reduced output signal delivered through the feedback network. The difference of the two signals is delivered to the input of a bipolar voltage amplifier that comprises two transconductance stages, one for the positive and one for the negative period of the signal. Each amplifying stage is composed of two bipolar transistors (PNP-type for positive and NPN-type for negative period) connected in cascade and a resistor network necessary for normal operation.

2.7. Modular high voltage source

Another possible improvement of a square wave generator is a modular high voltage source that consists of several (N) individually controlled and electrically isolated DC voltage modules (Fig. 8). Its operation is
based on a principle of a digital-to-analog converter, thus the amplitude of the particular source VN is twice as high as the predecessor. The voltage of the individual source is constant and can participate in a generation of a common output pulse at any time. With an appropriate control of output transistors Q1–QN that operate as switches and connect the modules in series, a total of 2N different output voltage levels with the resolution of V1 are obtained [5].

3. Application of high voltage pulse generators
The use of pulsed electric fields (PEFs) has found applications in biotechnology, medicine, food processing and industrial applications. Industrial applications of PEFs include the filtering of flue gas particles using electrostatic precipitators. The use of high-voltage pulsed electric fields in biotechnology and medicine has lead to new methods of cancer treatment, gene therapy, drug delivery, and non-thermal inactivation of microorganisms. Regardless of the application, the objective is to open pores in the cell membrane and hence, either facilitate the delivery of foreign materials inside the cell or to kill the cell completely.

Electropermeabilization
The use of high voltage electric pulse technology, electropermeabilization, in cell biology, biotechnology and medicine has attracted significant interest ever since first reports were published several decades ago. Electropermeabilization is a transient phenomenon that increases permeability of the cell plasma membrane. In the state of high permeability, the plasma membrane allows ions, small and large molecules to be introduced into the cytoplasm, although the cell plasma membrane in its normal state represents a considerable barrier for them. Efficacy of electropermeabilization and its applications strongly depends on many parameters that can be divided into parameters of the electric field (i.e. pulse amplitude, pulse duration, pulse repetition frequency, number of pulses and pulse shape), and parameters that define the state of Permeabilization of cell plasma membrane is achieved by exposure of the cell to a short but intense electric field. With properly chosen values of the electric field parameters, the process of electropermeabilization is reversible and cells return into their normal physiological state. If these parameters exceed certain values (e.g. amplitude of pulses is too high or duration of pulses is too long), cells are irreversibly permeabilized and lose their viability.

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

Processing of orange juice: The PEF system consisted of a series of co-field chambers. Temperatures were maintained near ambient with cooling devices between chambers. Three waveshape pulses were used to compare the effectiveness of the processing conditions. Their results confirmed that the square wave is the most effective pulse shape.

Processing of milk: It is studied that the shelf-life of raw skim milk (0.2% milk fat), treated with PEF at 40 kV/cm, 30 pulses, and treatment time of 2 µs using exponential decaying pulses. The shelf-life of the milk was 2 wk stored at 4 ° C; however, treatment of raw skim milk with 80 ° C for 6 s followed by PEF treatment at 30 kV/cm, 30 pulses, and pulse width of 2 µs increased the shelf-life up to 22 d, with a total aerobic plate count of 3.6-log cfu/ml and no coliform.

Processing of apple juice: It is reported that there were no physical or chemical changes in ascorbic acid or sugars in the PEF-treated apple juice and a sensory panel found no significant differences between untreated and electric field treated juices.

Processing of eggs: Some of the earliest studies in egg products were conducted in a static parallel electrode treatment chamber with 2-cm gap using 25 exponentially decaying pulses with peak voltages of around 36 kV. Comparisons were
made with regular heat-pasteurized egg products with and without the addition of food preservatives when the eggs were stored at low (4 °C) and high (10 °C) refrigeration temperatures.

Processing of green pea soup: The shelf-life of the PEF-treated pea soup stored at refrigeration temperature exceeded 4 wk, while 22 or 32 °C were found inappropriate to store the product. There were no apparent changes in the physical and chemical properties or sensory attributes of the pea soup directly after PEF processing or during the 4 wk of storage at refrigeration temperatures.

4. Conclusion and discussion

Discussion: Nowadays electropermeabilization is widely used in various biological, medical, and biotechnological applications such as electrochemotherapy, gene transfer, electroinsertion of proteins into cell plasma membrane, electrofusion of cells, transdermal drug delivery, water treatment and food preservation. Efficiency of all these applications strongly depends on parameters of electric pulses, which are delivered to the treated object using specially developed electrodes and electronic devices—electroporators. Both parts of equipment play equally important role in process of electropermeabilization, but in this paper we have focused exclusively on electroporators and advantages and disadvantages of techniques used for generating required signals (Table 1). At this point we did not discuss how each of the presented techniques can solve different problems like tissue burning, electrolytic contamination, etc., since this would require additional analysis of electrode designs and materials.

Current Limitations of PEF method: Some of the most important current technical drawbacks or limitations of the PEF technology are: 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 pumpable. In addition, different applications require different time variation of electric fields (i.e. exponentially decaying, square wave, etc.) and different exposure times.

Conclusion: Application of PEF technology has been successfully demonstrated for the pasteurization of foods such as juices, milk, yogurt, soups, and liquid eggs. PEF processing offers high quality fresh-like liquid foods with excellent flavor, nutritional value, and shelf-life. Since it preserves foods without using heat, foods treated this way retain their fresh aroma, taste, and appearance. In general, the shelf-life of PEF-treated and thermally pasteurized foods is comparable. PEF pasteurization kills microorganisms and inactivates some enzymes and, unless the product is acidic, it requires refrigerated storage. For heat-sensitive liquid foods where thermal pasteurization is not an option (due to flavor, texture, or color changes), PEF treatment would be advantageous.

5. References

