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review

Non-thermal Methods of Food Preservation Based on Electromagnetic Energy

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Summary

Consumer's demand for preserved foods, particularly fruit and vegetables, that retain at most both sensory and nutritional properties, leads researchers to test new preserving methods either alternative or combined with traditional thermal processing. These include several techniques based on the use of different forms of electromagnetic energy. In this review, the principles, equipments and food applications of pulsed electric field, pulsed light and oscillating magnetic field techniques are described. Due to non-thermal nature of these processes, energy saving and product quality loss minimisation is achieved.

Key words: preserved foods, electromagnetic energy, pulsed light and oscillating magnetic field techniques

Pulsed Electric Fields

While ohmic heating uses electrical energy in order to deliver heat which destroys the micro-organisms in foods, pulsed electric field technique consists of a short electric discharge at high voltage over the food placed between two electrodes. High intensity electric fields may be generated in the form of exponential, square wave, bipolar and oscillating pulses *(1)*.

In an exponential pulse, food is subjected for a very short time to a fixed peak voltage, corresponding to the required value to obtain the bactericidal effect, after that the voltage decays exponentially. The electrical circuit (Fig. 1) consists of a DC power supply, which transforms alternating current (50–60 Hz) in high voltage direct current (10^3–10^7 V) and some capacitors in parallel (C_1, C_2, C_3), where energy is stored, connected in series with a charging resistor R_c, in order to increase the electric charges without extending surface plates. The resistance R_1 limits the discharges in the product while R_2 controls decay time for food having too high resistance. By closing the switch, the capacitors transfer the current to the product in the treatment chamber very rapidly (10^{-3} s). The alternate opening and closing of switch generates a voltage that decreases exponentially.

The energy density Q may be calculated, as a function of the initial charging voltage U_0, the circuit resistance R, the volume V of treatment chamber and the treatment time t,

$$Q = \frac{U_0^2 t}{2RV} \qquad /1/$$

The exponential pulses have a long tail with short voltage which could result in an unwanted increase of temperature without significant bactericidal effect. Therefore, square wave pulses are preferred, because they maintain a peak value of voltage longer than exponential ones, with a less energy consumption and cooling requirement. The circuit generating square wave pulses (Fig. 2) uses a number of inductors with ferromagnetic core to decrease the pulse width and to increase the peak voltage in the treatment chamber. Some problems may occur in matching the resistance of food with the impedance of transmission line in order to provide highest energy transfer to product *(2)* and for the high costs of long high voltage cables.

In this case, the energy density *Q* is:

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$$Q = \frac{U^2 t}{RV} \qquad /2/$$

Fluid foods contain ions and bipolar molecules; when subjected to an electric field, ions generate a resistive current, migrating, according to the charge, towards anode or cathode, while dipoles generate a capacitive current, orienting in accordance with their polarisation. This phenomenon may be modelled *(3)* as a capacitive system in parallel with a resistive one. The capacity *C* and resistance *R* of a food fluid may be calculated by the two equations:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \qquad /3/$$

$$R = \frac{\rho d}{A} \qquad /4/$$

where ε_0 and ε_r are the dielectric constants in vacuum and relative of the product, A and d, are the electrode surface and distance, respectively and ρ is the resistivity of product. The electric properties of food and biological products are reported by Kent *(4)*.

During a pulsed electric field process, a heating for Joule effect occurs, causing a temperature increase that can be calculated by an energy balance:

$$\Delta T = \frac{Q}{\delta c_p} \qquad /5/$$

where δ and c_p are the density and the specific heat of the food and Q is the energy per volume unity of chamber [see /1/ and /2/]. To preserve product quality, temperature has to be maintained low during the process, either by decreasing the process time or by cooling the product.

The plant that utilises the pulsed electric fields consists mainly of a power source and a treatment chamber. In designing the treatment chamber some criteria must be followed:

1) avoiding the dielectric breakdown of food due to the local enhancing of electric field intensity within the chamber;

2) careful consideration to the system of loading and unloading of food in order to avoid air bubbles that could become trigger sites for dielectric breakdown of food;

3) cooling of electrodes, particularly when the pulse electric fields are repeated at high frequency.

The average volume is 12.5–25 mL for static chambers, 8 mL for continuous ones and the fluid flow rate ranges within 100–500 mL/min.

Cell membrane can be viewed as a capacitor inside which there is a material with a dielectric constant lower than those inside and outside the cell. For this reason, on both sides of the membrane, there is an accumulation of free charges. The application of an external electric field causes a further accumulation of surface charges with a consequent increase of potential difference through the membrane; these opposite charges attract each other, causing the membrane compression. For values of E greater than a critical value E_c, the electrocompressive force exceeds the membrane elastic strength, and in several points of membrane the formation of pores (electroporation) occurs. At increasing dimension and number of pores, the membrane rupture may occur, followed by outgoing of intracellular material and, finally, by cell death *(5)*.

Lethal effect of pulsed electrical fields on suspended vegetative bacteria and on yeasts was studied by Sale *et al. (6,7)*, who demonstrated that cell death was due to cell explosion rather than to thermal effects or electrolysis.

Microbial inactivating power of pulsed electric fields increases at increasing electric field intensity E and time of treatment t (number of pulses multiplied by pulse duration), according to:

$$\frac{N}{N_0} = \left(\frac{t}{t_c}\right)^{-\left(\frac{E-E_c}{k}\right)}, \qquad /6/$$

where t_c and E_c are the extrapolated critical values of t and E for 100 % microbial survival, respectively, and k is a temperature dependent coefficient.

At Washington University, apple juice, eggs and pea soup were treated by pulsed electric fields *(3)*. In the apple juice treated at 40 kV/cm and stored at 4 °C for 3–4 weeks, both nutritional and sensory properties (ascorbic acid content, carbohydrates, fat and protein traces) were not significantly different between fresh and treated juice. Such a treatment resulted in doubling both colour and taste acceptability period, assuring, at the same time, the required microbial inactivation.

An application of pulsed electric fields different from microbial inactivation is juice extraction for the production of apple or carrot puree *(8)*. Apple puree subjected to electric fields, after pressing, gives a juice yield 12 % higher than that obtained by traditional systems and the juice is of a lighter colour and is less subject to oxidation than the traditional one. The same behavior is exhibited by carrot juice that has a higher beta-carotene content than the juice treated by pectines.

Pulsed electric fields may be used also in fish cell cracking to obtain protein coagulation and oil release, instead of cooking, in order to minimise thermal damage of product. This procedure was applied by Sitzmann *(9)* to herring fillets.

Pulsed Light

This technology uses pulses of light of high intensity and short duration in order to inactivate microorganisms. The light pulses are produced by a lamp filled by an inert gas that, under particular conditions, generates a spectrum of wavelengths from the ultraviolet (UV) to the near infrared (IR) region.

Selecting light wavelength depends on both product transparency and the requirement of killing the microorganism avoiding off-flavour development. The spectrum of produced light ranges from 100 nm to 1 mm, being similar to sunlight, but containing wavelengths between 200 and 300 nm that are not present in sunlight. Moreover, the intensity of pulsed light is 20 000 times the intensity of sunlight *(10)*. Water present in foods shows a good transparency to wavelengths typical of pulsed

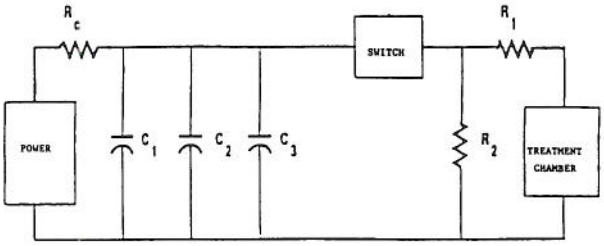

Fig. 1. Electrical circuit for generating exponential pulsed electric fields

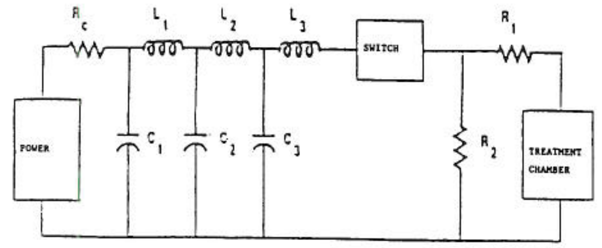

Fig. 2. Electrical circuit for generating square pulsed electric fields

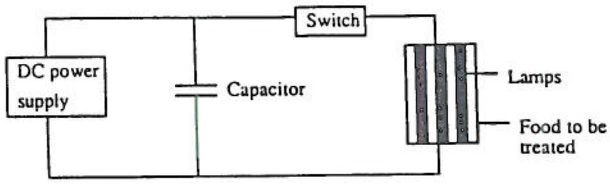

Fig. 3. PureBright™ system layout

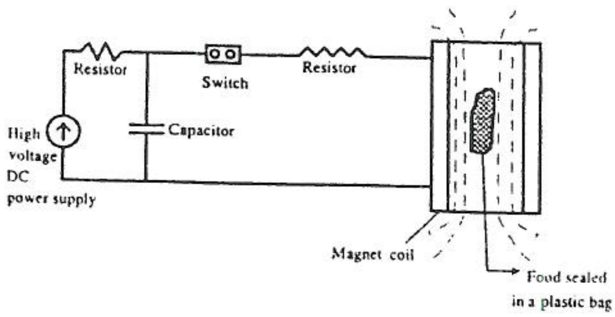

Fig. 4. Electrical circuit for generating oscillating magnetic fields

light process, while other food fluids, such as sugar solutions, have a reduced transparency, so that some absorption-enhancing agents have to be used, including edible colorants such as carotene, which may be sprayed, spread as dust or vaporised onto the surface that is to be treated. In order to eliminate wavelengths that can induce off-flavours in the products, spectrum filters may be used.

When a light ray of initial intensity I_0 incises a surface, a certain amount is reflected, another amount penetrates through the material, decaying, along a distance x below the surface, by:

$$I = T\,I_0\,e^{-x} \qquad /7/$$

where T is a transparency coefficient of the material, and, finally, the residual amount is dissipated as heat, transferred to inner layers by conduction. Due to the short pulse duration, there is no time for the heat conduction within the product, therefore, no significant product heating occurs.

PureBright™ system (Fig. 3) consists of two components, a power source and a lamp unit. The power source converts the alternate current into high voltage direct current that is used to charge a capacitor, which, when closing the circuit by means of a switch, discharges the light energy to lamp. The lamp unit uses this energy to ionise the inert gas inside it (xenon or krypton) causing the emission of an intense (0.1–3.0 J/cm^2) and instantaneous (1 µs to 1ms) flashlight that illuminates the area where the sample to be treated is placed. By opening and closing the switch, pulsed light flashes are obtained, at a rate of 1 to 20 flashes per second.

Since light intensity rapidly decreases while penetrating into the bulk, this technique is mainly applicable in sterilising the surfaces, particularly those of aseptic packaging materials *(11)*, as an alternative to usage of hydrogen peroxide or other chemical disinfectants, whose residues are not fully acceptable in foods.

Bactericidal effect of pulse light (intensity about 1 to 12 J/cm^2) on some micro-organisms (*E. coli, Staphilococcus aureus, Bacillus subtilis, Saccharomyces cerevisiae*) in model solutions was demonstrated by Dunn *et al. (12)*. Several foods, such as vegetables, fruit, tomatoes and ready meals with rice and pasta, can improve their shelf life if treated by pulse light.

A continuous system to sterilise fluids such as fruit juices consists of a reflective cylinder inside which there is a source of pulsed light; the product is pumped through the cylinder and it is subjected to a number of pulses controlled by the flow rate of circulation pump. For fluids transparent to light, there is no attenuation of incident energy, while for the ones having a significant absorption, it is necessary to ensure a good mixing in order to have the required flux density.

Oscillating Magnetic Fields

A magnetic field is defined as the region in which a magnetic material is able to magnetise the surrounding particles. It is described by the magnetic field intensity B, measured in ampere/meter (A/m). Magnetic fields may be static or oscillating according to whether B is constant with time, both in module and in direction, or not. A particular oscillating magnetic field is the pulsed magnetic field, in which the direction of B reverses for each pulse and intensity decreases by about ten times for each pulse. Another important quantity is the magnetic flux density, defined as the number of lines of force per unit area and measured in tesla (T). It depends on both magnetic field intensity and magnetic permeability of material in which magnetisation is induced. In order to inactivate micro-organisms, flux density of 5 to 50 T is required, corresponding to very high intensity magnetic fields.

High intensity magnetic fields are generated by an electric current passing through a coil. In order to obtain an oscillating magnetic field, an equipment as in Fig. 4 may be used. The capacitor is charged by a high voltage DC power supply; by closing the switch, an oscillating current is produced inside the capacitor and then an oscillating magnetic field is induced to the food placed inside the magnet coil. When the current changes direction, the magnetic field changes polarity, rapidly decaying. To obtain such high magnetic fields, special coils have to be used, such as superconductor magnetic coils or hybrid magnetos in helium environment to cool the magnetic core; the current required is about 40 kA *(13)*.

Problems may occur in producing such intense magnetic fields, both for high power requirements and for difficulties in removing heat delivered by the large currents for Joule effect.

The induced magnetic field intensity depends on both applied field intensity and properties of the product being magnetised, in particular the electrical resistance that has to be as high as possible, and the thickness, that should be not too great.

The technique of oscillating magnetic fields is safe for the operators, because the high values of magnetic field intensity exist only inside the coil and in the nearest surroundings, while they strongly decrease with the distance and, at the distance of just 2 m, they reach values absolutely harmless for humans.

The inactivation mechanism of microorganisms by means of magnetic fields has not been fully explained; probably, magnetic fields alter the growth and the reproductions of microorganisms by both genetic and biochemical phenomena. The effect may be due to either magnetic field or induced electric field. Depending on both the features of magnetic field and the properties of foods and microbials, the growth of microbials may be inhibited, stimulated, or unaltered by this technique.

Preliminary studies of the effect of magnetic fields on microorganisms were carried out by Kimball *(14)*, who verified the inhibition of growth of yeasts after a treatment by a magnetic field of 40 mT. In 1962 Gerenscer *et al. (15)* carried out experiments on *Serratia marcescens* at values of magnetic field of 1.5 T at 27 °C, finding that the percentage decrease of growth was due to increasing of cells inactivation rather that the decrease of duplication (division) time. Moore *(16)* obtained the same result, working on 5 genera of bacteria and one yeast.

Most foods exhibit high electric resistance, greater than 25 Ω/cm, and may be successfully treated by high magnetic oscillating fields, in particular some packed liquid foods such as milk, yoghurt, orange juice, *etc.* They may be subjected to oscillating magnetic field with a frequency between 5 and 550 kHz for a total exposure time between 25 μs and 10 ms. The oscillating magnetic field process is performed at atmospheric pressure and room temperature, resulting in a temperature increase not higher than 5 °C, therefore a good retention of both nutritional and sensory properties of foods is assured. Any packaging material used in food industry has a good resistance and may be used in this process, with the exception of metal materials and plastic with aluminium sheet inside.

Conclusions

Pulsed electric fields, pulsed light and oscillating magnetic fields may be considered as very promising techniques in food stabilization, particularly if combined with other mild technologies or soft thermal treatments, in order to obtain high degree of preservation of food properties.

Further studies should be carried out in order to establish more exactly their killing power on enzymes and resistant bacteria, as well as studies of engineering, law, safety and acceptability aspects.

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Netoplinski postupci za čuvanje hrane elektromagnetskom energijom

Sažetak

Zahtjevi potrošača za očuvanjem senzornih i hranjivih sastojaka, osobito voća i povrća, ponukali su istraživače da ispituju nove postupke, bilo alternativne, bilo one povezane s uobičajenom toplinskom obradbom. Ti su postupci zasnovani na primjeni različitih oblika elektromagnetske energije. U ovom prikazu opisana su načela, uređaji i primjena postupaka pulsirajućeg električnog polja, pulsirajućeg svjetlosnog i oscilirajućeg magnetskog polja. Zbog netoplinske prirode tih postupaka postignuta je ušteda energije i minimalni gubitak kakvoće proizvoda.