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High Electric Field Technology in Post Harvest Drying

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ABSTRACT

The diversity of drying processes and equipment used in agricultural product processing reflects difficulty of handling and processing solid materials and the special requirements for various products. Undesirable product deteriorations in addition to economics of investment and operation costs involved in thermal processing have initiated the quest for alternative methods. Several studies on improvement of drying processes have been published recently. Research has identified application of high electric fields in drying as one such promising technology. The application of high electric fields as a non-thermal drying process is reviewed within this paper. In the reviewed literature are found a range of researches that utilize electric fields and their pulses to facilitate water removal from agricultural products. The merits of reduced energy consumption, quality sustenance particularly of heat sensitive products, augmentative effect on convective mass transfer during the drying of agricultural product and the synergism accorded by electrohydrodynamic (EHD) as a pretreatment measure in osmotic dehydration are herein described. Greater efforts perhaps need to be made to develop standard dryers based on this technology at industrial level. Scale up and transfer of laboratory- and pilot-scale experiments to prove industrial applicability and educating the diverse users of agricultural product drying equipment as to the potential benefits of this technique are necessary future directions in realizing the benefits associated with high electric field drying technology. Realizing industrial application of the non-thermal high electric field technology in drying is a priority due to the overwhelming worldwide concern over global warming attributed in large measure to greenhouse gases produced by the combustion of fossil fuels.

Keywords: agricultural product drying, high electric fields drying, electrohydrodynamic drying, Corona discharge, pulsed electric field, radio frequency technology, non-thermal drying

Abbreviations: AC, alternating current; **EHDD**, electrohydrodynamic drying; **HEF**, high electric field; **HEFD**, high electric field drying; **HELP**, high intensity electric field pulse; **HV**, high voltage; **HVEF**, high voltage electric field; **OD**, osmotic dehydration; **PEF**, pulsed electric field; **PFN**, pulse forming network; **RF**, radio frequency

CONTENTS

INTRODUCTION

Drying is one of the oldest methods of food preservation and it represents a very important aspect of food processing. With many of the drying operations in place, quality deterioration is observed either due to high processing temperatures or slow drying rates. Conventional hot air-drying often causes heat damage and adversely affects texture, color, flavor and nutritional value of dried products (Lin *et al*. 1999; Guanasedarn 1999). Whereas freeze-drying can be applied to circumvent heat damage and produce excellent structural retention of products during drying, it is costly (Liapis and

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Invited Review

Marchello 1984) and not suitable for low-value products. Furthermore, it is also reported that freeze-drying causes loss of flavor (Flink 1983). So far, a number of novel drying methods that claim to improve product quality or reduce energy consumption have been described in literature. In the technological quest for fast, gentle and non-thermal drying techniques, high electric field drying (HEFD) is one of the relatively new methods showing great potential for industrial application.

This review focuses on the application of high electric field in post harvest drying of agricultural products. A brief introduction to developments in non-thermal processing of agricultural product is followed by discussion on physical models, systems and applications of electric field drying as an agricultural product processing technology. The review of published information on the application of electric field dryers is concluded with suggestions on the way forward in future research.

DEVELOPMENTS IN ELECTRIC FIELD DRYING

There is growing interest in the application of non-thermal electric field drying and processing of food and similar materials. In this section, different types of electrode configuration and/or systems used in drying and their associated modeling parameters are reviewed. Pulsed electric field configuration is widely used and most documented in reviewed literature.

High electric field drying systems and electrode configuration

Different types of systems dependent on electrode configurations (parallel plate or pin and plate electrodes and pulsed electric fields) are found in practice. The electrical field between two flat plates is equal excluding the area around the contacts of the plates themselves. However, when voltage is applied between a flat plate and a needle, a remarkably uneven electrical field is generated. When the electrical field is remarkably uneven, ionization occurs in the strong part of the field, and partial electrical discharge, namely, local electrical discharge, is the result. This type of electrical discharge is called corona electrical discharge.

Corona discharge in drying

A high voltage created in between a pointed (pin or needle) and an earthed plate electrode system evaporates water from food material (**Fig. 1**). There are few reports available on high electric field (HEF) principle. When a high voltage is created in a pointed to plate alternating current (AC) HEF system the air particle and the water vapor in the surrounding atmosphere is charged and collision and ionization of originally neutral molecules take place resulting in input of the localized energy and evaporation of the water (electrohydrodynamic drying) (Barthakur and Arnold 1995; Bajgai and Hashinaga 2001). In electrohydrodynamic drying (EHDD) the air ions of N^{2+}, O^{2+}, N^+, O^+ and O^- are produced by static corona discharges from the sharp point, when an external electric field is applied to the point-to-plate electrode system. The mechanism for the generation of air ions (space charge) in an asymmetrical electric field has been described in detail by Charry and Kavet (1987). The air ions which originate from a small region around the needle-point are accelerated by the applied electric force; part of the energy is used for overcoming the frictional resistance due to collisions with neutral molecules. This causes the air movements as a whole, which constitutes the electric wind. The electric wind induced by electrohydrodynamic (EHD) is considered to be the principal driving force, which accelerates the drying rate through turbulent and vortex motions. Although the electric wind is being invoked as the main mechanism of EHDD, there may be other contributory factors.

Physical impact and models in corona discharge

The theory of EHD can be invoked to explain the physical action of air ions resulting from ionization in a corona discharge field. A fairly satisfactory relationship for electric force F in N m^{-3} which acts on a unit volume of fluid containing the space charge of ions has been derived by Panofsky and Phillip (1962):

$$F = E\rho + e_0(k-1)(E.\nabla)E \qquad (1)$$

where E is electric field in V m^{-1}, ρ is charge density in C m^{-3}, e_0 is permittivity of free space in F m^{-1}, k is the dielectric constant, and ∇ is the gradient vector. Equation (1) can be simplified if the variation of the electric field and the dielectric constant are ignored. The familiar Coulomb force of the product of field strength and charge density becomes the principal driving force for physical action of the air ions. When the air ions are subjected to a strong electric field, the charged particles will accelerate.

The kinetic energy gained by the particles is partly spent in ionizing other molecules via the Townsend effect according to researcher Townsend (1914) and partly in colliding with neutral molecules in the drift region of the fluid medium in which they travel. In the process of collisions, momentum is transferred to the molecules and the resulting frictional resistance produces the ion drag phenomenon with the associated electric wind when the air mass be-

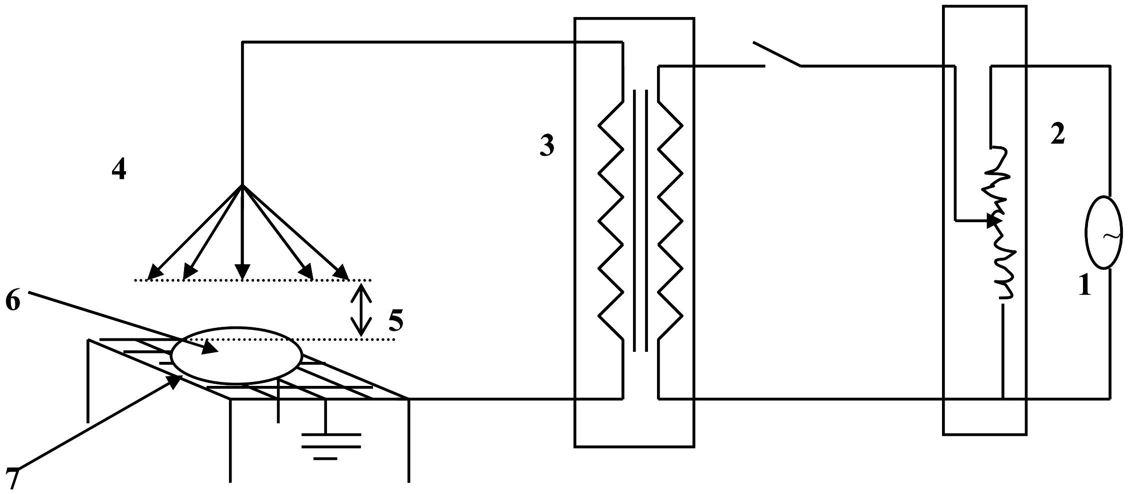


Fig. 1 High electric field set up (pin and flat plate electrode configuration) employed in drying. 1, high voltage generator; **2**, regulator; **3**, scale-up transformer; **4**, multiple pointed electrode; **5**, electrode gap; **6**, sample; **7**, copper mesh.

tween the electrodes moves towards the plate.

Modeling the heat transfer coefficient in electrohydrodynamics was performed by Kibler and Carter (1974) and such parameters as kinematic viscosity in $m^2 s^{-1}$, thermal conductivity in W $m^{-1} k^{-1}$, plate diameter in m, ion current in A and ion mobility in $m^2 V^{-1} s^{-1}$ were considered. On the basis of the similarity of heat and mass transfer processes, the corresponding equation for mass transfer was developed by considering the specific heat of the medium in J/kg K. The mass transfer coefficient depended on the ion current, electrode gap, mechanical and thermal properties of the fluid medium, and the ionic mobility. The average mobility of small positive and negative air ions are 1.4×10^{-4} and 2.0×10^{-4} $m^2 V^{-1} s^{-1}$, respectively. Thus, for a given fluid medium and identical currents, the mass transfer coefficient will be higher for positive than for negative air ions. The generation of vortex motions by corona current with associated enhancement in heat transfer has also been well documented in fluid mechanics by Jones (1978), Franke (1969) and Robinson (1961).

Physical impact and models in electric field void of discharge

Foods are primarily composed of the water and nutrients such as carbohydrates, proteins, vitamins, triglycerides and minerals and when subjected to an electric field, polarization of dipole molecules and bulk movement of charge carriers such as ions induce a capacitive current and a resistive current. The rotational effect on the dielectric molecules by the electric field may also be a factor in further enhancing the mass transfer rates from the sample (Panofsky and Phillip 1962)

$$C = \varepsilon_0 \varepsilon_r A / A \tag{2}$$

where C (µF) is the effective capacitance of drying material, ε_0 (µF/cm) is the permittivity of free space, ε_r (dimension less) is the relative permittivity of the drying material, A (cm^2) is the electrode area;

$$R = d / \sigma A = \rho d / A \tag{3}$$

where R (Ω) is effective resistance of food during HEF drying, d (cm) is the gap in between the two electrodes, σ (siemens/m) is the conductivity of the food and, ρ (g/m^3) is the density of the food. The decrease in free energy of a dielectric in the presence of an electric field compared to its absence may increase the escaping tendency of the molecule of the treated material.

Bottcher (1973) considered electric field void of discharge, as found in parallel plate electrode configurations and modeled the energy on a dielectric in an external electric field. He considered parameters such as total work on a molecule with zero net charge in J, permanent dipole moment in C m, polarizability factor in $C^2 J^{-1} m^2$ and the electric wind in m s^{-1}.

Pulsed electric field

Pulsed electric field (PEF) processing involves application of short burst of high voltage to a food item placed between two electrodes. Electric current flows only for microseconds through the food. In PEF, cell membranes are destroyed by mechanical effects with no significant heating of the food occurring (Zhang *et al.* 1995; Barbosa-Canovas *et al.* 1999; Rastogi 2003). General design of a PEF processsing system is shown in **Fig. 2**.

The major components of the processing system include a voltage power supply, an energy storage capacitor, a treatment chamber, and discharge and charging resistance switches. Energy from the high voltage power supply is stored in the capacitor. The generation of a pulse involves slow charging and rapid discharging of the capacitor. The energy stored in the capacitor is given by:

$$Q = 0.5 C_0 V^2 \tag{4}$$

where V is the charging voltage and C_0 is defined as capacitance of the energy storage capacitor, which is defined as:

$$C_0 = t / R = t \sigma A / d \tag{5}$$

where t is the pulse duration, R is the resistance, σ is the electrical conductivity of the food, d is the discharge gap between the electrodes and A is the area of the electrode surface. Energy stored in the capacitor can be discharged almost instantaneously (in a millionth of a second) at very high levels of power. The treatment chamber is used to transfer high intensity pulses to foods. The pulses can be monitored online with oscilloscope and voltage, as well as pulse duration can be recorded. Equipment requirement of PEF processing is reviewed by Zhang *et al.* (1995).

Numerous experimental design set ups can be traced in literature involving PEF drying post harvest. Some recently reported include that of Nikolai *et al.* (2007) illustrated in **Figs. 3** and **4**. In their set up an air flow rate was adjusted and air heating performed in an electrical flow heating quartz tube with a power of 2.3 kW. The PEF drying chamber, **Fig. 4**, was constructed in a form of two concentric polypropylene rings.

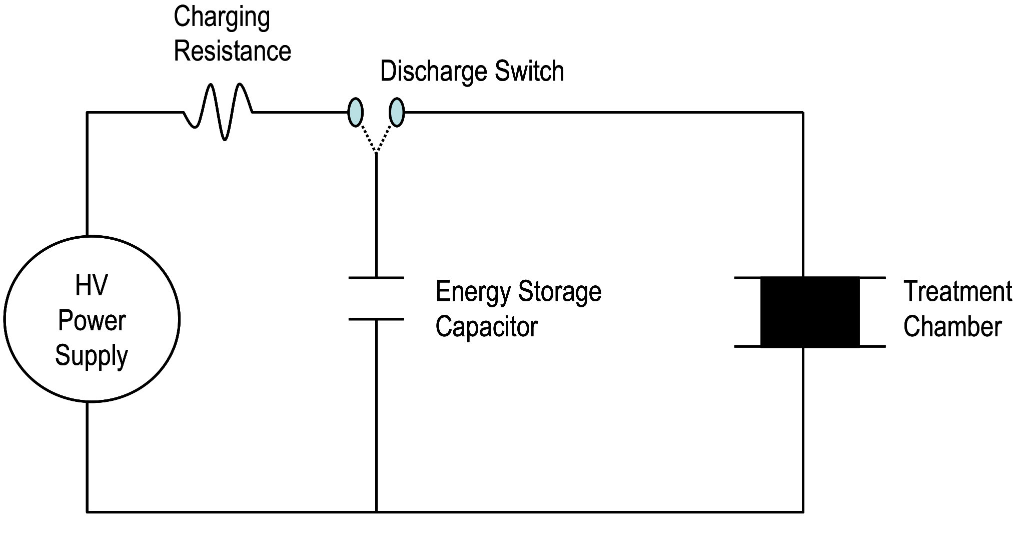


Fig. 2 General design of a pulsed electric field processsing system.

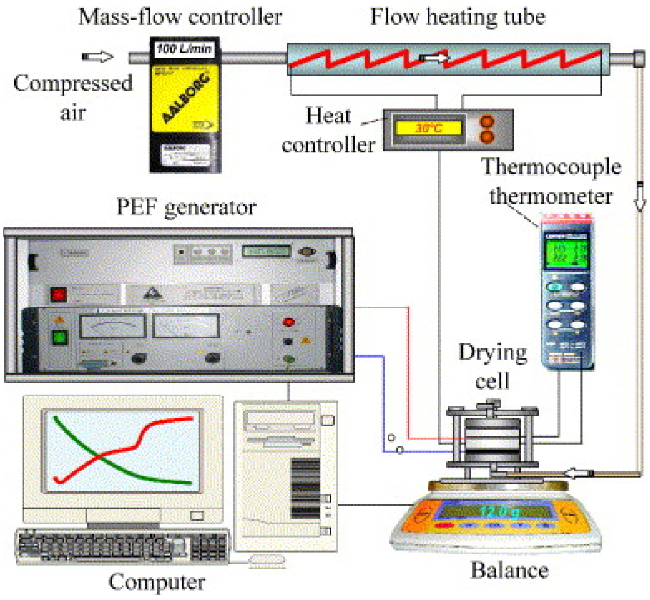


Fig. 3 A scheme of the setup for PEF-enhanced drying experiments. (Reprinted from **Nikolai IL, Nikolai VS, Eugene V** (2007) Pulsed electric field enhanced drying of potato tissue. *Journal of Food Engineering* **78**, 606-613, ©2007 with kind permission from Elsevier Ltd).

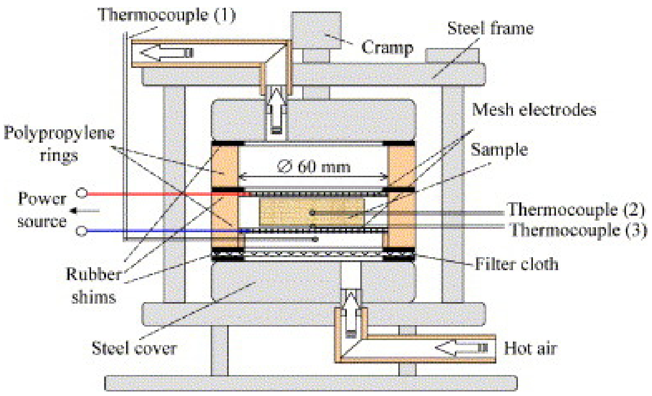


Fig. 4 The construction of a PEF-drying chamber. (Reprinted from **Nikolai IL, Nikolai VS, Eugene V** (2007) Pulsed electric field enhanced drying of potato tissue. *Journal of Food Engineering* **78**, 606-613, ©2007 with kind permission from Elsevier Ltd).

Critical process factors of pulsed electric field

Some process factors that affect the PEF technology have been identified: electric field intensity, pulse width, treatment time and temperature, and pulse waveshape.

a) Electric field intensity. According to the electroporation theory, the induced potential difference across the cell membrane is proportional to the applied electric field membrane potential of the cell.

b) Treatment time. Treatment time is defined as the product of the number pulses and the pulse duration. An increase in pulse duration may also result in an undesirable food temperature increase. Optimum processing conditions should therefore be established. Critical treatment time also depends on the electric field intensity applied. Above the critical electric field, critical treatment time decreases with higher electric fields.

c) Pulse waveshape. Electric field pulses may be applied in the form of exponential decaying, square-wave, oscillatory, bipolar, or instant reverse charges. Different effects of these waveshapes have been discussed greatly with respect to microbial inactivation: Oscillatory pulses are the least efficient for microbial inactivation, and square wave pulses are more energy and lethally efficient than exponential decaying pulses. Bipolar pulses are more lethal than monopolar pulses because a PEF causes movement of charged molecules in the cell membranes of microorganisms, and reversal in the orientation or polarity of the electric field causes a corresponding change in the direction of charged molecules (Qin *et al*. 1994; Ho *et al*. 1995). With bipolar pulses, the alternating changes in the movement of charged molecules cause a stress in the cell membrane and enhance its electric breakdown. Bipolar pulses also offer the advantages of minimum energy utilization, reduced deposition of solids on the electrode surface, and decreased food electrolysis (Barbosa-Cánovas *et al*. 1999).

d) Treatment temperature. PEF treatments at moderate temperatures (~50 to 60°C) have been shown to exhibit synergistic effects on the inactivation of microorganisms (Dunn and Pearlman 1987; Jayaram *et al*. 1992). The application of electric field intensity does cause some increase in the temperature of the foods, proper cooling is necessary to maintain food temperatures far below those generated by thermal pasteurization.

Additional effects of high treatment temperatures are changes in cell membrane fluidity and permeability, which increases the susceptibility of the cell to mechanical disruption (Hulsheger *et al*. 1981).

Description of pulsed waveforms

PEF may be applied in the form of exponentially decaying, square wave, bipolar, or oscillatory pulses. An exponential decay voltage wave is a unidirectional voltage that rises rapidly to a maximum value and decays slowly to zero. A DC power supply charges a capacitor bank connected in series with a charging resistor. When a trigger signal is applied, the charge stored in the capacitor flows though the food in the treatment chamber.

Square pulse waveforms are more lethal and more energy efficient than exponential decaying pulses. A square waveform can be obtained by using a pulse-forming network (PFN) consisting of an array of capacitors and inductors and solid state switching devices.

The instant-charge-reversal pulses are characterized by a $+v_e$ part and $-v_e$ part with various widths and peak field strengths (**Fig. 5**). An instant-charge-reversal pulse width with charge-reversal at the end of the pulse is considerably different from a standard bipolar pulse. In the latter, the polarity of the pulses is reversed alternately with relaxation time between pulses.

Even with a high frequency pulser (for example, 1000 Hz), the dielectric relaxation time at zero voltage between 4 µs square wave pulses is 0.996 ms (Quass 1997). Instant-charge-reversal pulses can drastically reduce energy requirements to as low as 1.3 J/ml (EPRI 1998). Oscillatory decay pulses are the least efficient, because they prevent the cell from being continuously exposed to a high intensity electric field for an extended period of time, thus preventing the cell membrane from irreversible breakdown over a large area (Jeyamkondan 1999).

Pulsed electric field treatment chambers and equipment

Two commercial systems are so far available. One by PurePulse Technologies, Inc. and another by Thomson-CSF. Different laboratory- and pilot-scale treatment chambers have been designed and used for PEF treatments (static U-shaped polystyrene and glass coil static chambers or continuous chambers with ion conductive membrane, chambers with baffles, enhanced electric field treatment chambers and coaxial chambers). The test apparatus consists of 5 major components: a high-voltage power supply, an energy storage capacitor, a treatment chamber(s), a pump to conduct products though the treatment chamber(s), a cooling device, voltage, current, temperature measurement devices, and a computer to control operations.

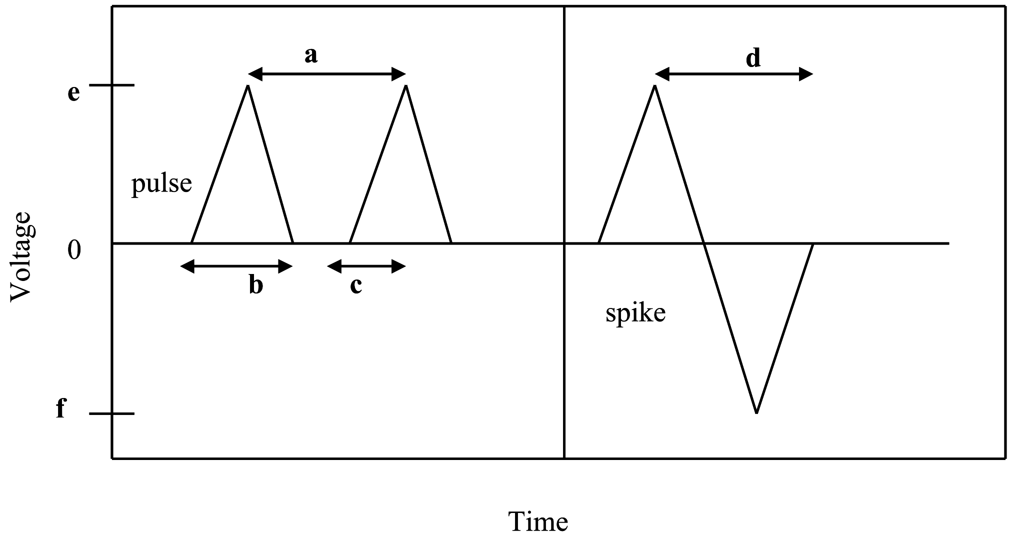
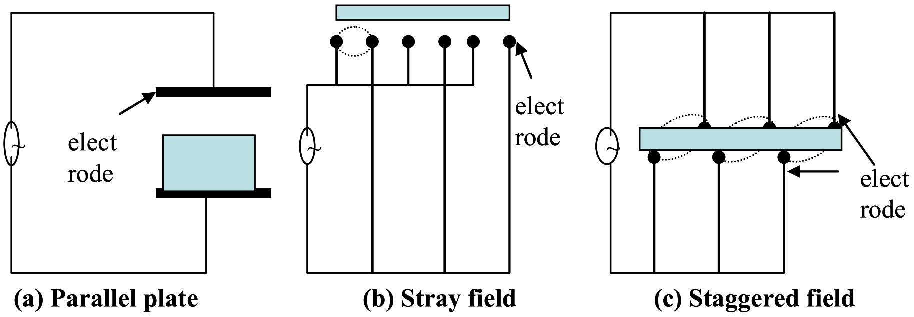


Fig. 5 A voltage (V) trace of an instant-charge-reversal pulse. **a** is pulse period (s), **b** is pulse width (µs), **c** is a pulse rise time(s) to reach e (kV), **d** is a spike width(s), **e** is a peak voltage (kV), and **f** is a spike voltage (kV).



(a) Parallel plate **(b) Stray field** **(c) Staggered field**

Fig. 6 Electrode designs in radio frequency technology. (a) Parallel plate electrodes are designed for thick products; **(b)** stray field electrodes are designed for thin materials; **(c)** the staggered stray field design allows uniform heating of thicker webs.

Limitations of pulsed electric field technology

Some of the most important current technical drawbacks or limitations of the PEF technology are:

a) The availability of commercial units, which is limited to one by PurePulse Technologies, Inc., and one by Thomson-CSF. Many pulse-power suppliers are capable of designing and constructing reliable pulsers, but except for these 2 mentioned, the complete PEF systems must be assembled independently. The systems (including treatment chambers and power supply equipments) need to be scaled up to commercial systems.

b) The presence of bubbles, which may lead to non-uniform treatment as well as operational and safety problems. When the applied electric field exceeds the dielectric strength of the gas bubbles, partial discharges take place inside the bubbles that can volatize the liquid and therefore increase the volume of the bubbles. PEF method is not suitable for most of the solid food products containing air bubbles when placed in the treatment chamber.

c) Limited application, which is restricted to products that can withstand high electric fields. The dielectric property of a biological product is closely related to its physiccal structure and chemical composition. Homogeneous liquids with low electrical conductivity provide ideal conditions for continuous treatment with the PEF method. Products without the addition of salt have conductivity in the range of 0.1 to 0.5 S/m. Products with high electrical conductivity reduce the resistance of the chamber and consequently require more energy to achieve a specific electrical field.

d) The lack of methods to accurately measure treatment delivery. The number and diversity in equipment, limits the validity of conclusions that can be drawn about the effectiveness of particular process conditions. A method to measure treatment delivery would prevent inconsistent results due to variations in PEF systems.

Radio frequency technology

In radio frequency (RF) technology, parallel plate electrodes are designed for thick products, stray field electrodes are designed for thin materials and the staggered stray field design allows uniform heating of thicker webs (**Fig. 6**). Each design creates a field between alternating parallel rods or plates. Each design creates a field between alternating parallel rods or plates. The basic theory of radio frequency heating involves exposing dielectric materials to a high voltage, high frequency electric field.

RF heating uses two heating mechanisms: dipole rotation and ionic conduction. In dipole rotation, individual molecules rotate to align themselves with the electric field. In the radio frequency oven or dryer, the polarity of the electric field is reversed millions of times per second, causing the individual molecules to rotate millions of times per second. This molecular movement causes friction and creates heat.

Radio frequency is being used for precooking, sterilization, tempering, and baking processes in the food industry and likely to find greater use in dehydration as research in this field grow. Similar to microwaves, RF uses electromagnetic energy to heat products with exceptional results in terms of time cycle and efficiency. Unlike conventional conduction, convection, and radiant methods that depend on the heat transfer capability of the product, dielectric heating occurs instantly inside the product. Heating is more effective since the process does not depend on a temperature gradient. RF electromagnetic waves cover the frequency spectrum from 30 to 300 MHz. Microwaves and RF technologies, affect materials differently and require different equipment. RF energy mainly acts through the electrical conductivity of the material, so the presence of ionic species (e.g., dissolved salts) tends to make materials good heating candidates, therefore RF generally heats more uniformly and is less expensive per kilowatt than other technologies like microwaves. The benefits of radio frequency heating include:

- Faster heating times, which allow faster, line speeds and shorter line lengths.

- Even heating with a consistent temperature gradient and less solids migration.
- No overheating of base material during drying. Radio frequency heating is self-limiting.
- Selective heating. Water is heated and removed with little heating of the base product.
- Moisture profiling or leveling to create more consistent product quality.
- Fast shutdowns and startups due to instant-on/instant-off heating.
- Fewer environmental issues because there are no combustion byproducts.

DRIED PRODUCTS AND HIGH ELECTRIC FIELD SYSTEMS

High electric fields applications vary with the product as well as the end use. This section reviews some HEFD applications in post harvest and cites influences on various processing parameters.

Key requirements and processing parameters

The influences of corona electrical discharge, electric field between parallel aluminum plate and the direction of electric field on apples (*Malus domestica* Borkh, cv. 'Fuji' and 'Golden Delicious') have been investigated by Atungulu *et al.* (2003, 2004a, 2004b, 2004c 2005a, 2005b, 2006). In our studies the effects on apples weight changes as well as other physicochemical properties (colour change, respiration, and soluble sugar concentration) post harvest were investigated. From the study, effects on the physicochemical properties depended on field type (corona electrical discharge or electric field between parallel plates). Physiologically, apples stored between parallel plate electric field had suppressed respiration and climacteric peak. Apples stored in the corona discharge field had suppressed respiration rate for a limited time followed by increased respiration in the treated sample over the untreated. Weight loss was suppressed by treatment in the parallel plate electric field unlike in the corona discharge. From a quality analysis perspective, treatments with electric field suppressed soluble sugar concentration change. The influence on the apple physicochemical properties depended on the magnitude and the direction of the applied electric field. The 'reversed' (apples on cathode plate) electric field treatment gave high weight loss than the corresponding 'non reversed' (apples on anode plate) electric field treatment. **Table 1** summarizes some of the physiological effects associated with field reversal.

Cao *et al.* (2004a) investigated wheat drying characteristics when HVEF is applied. Their study revealed that drying rate of wheat in a HVEF was significantly higher than that of control for various drying temperatures and electric field strengths. The authors found that a multiple point-to-plate corona discharge electrode of HVEF improved the average drying rate by 2.1, 2.0, and 1.7 respectively for 10, 7.5, and 5 kV/cm electric field strength compared with the values of the corresponding air-dried control samples. Drying enhancement by a HVEF at lower drying temperature was more marked than that at higher temperature. The drying rate increased when the voltage increased and the discharge gap decreased. The power consumption was very small with the current of a few microamperes. The authors further developed a regression model to describe the drying characteristics of wheat treated by a HVEF. In a similar but separate study the same author, Cao *et al.* (2004b) conducted another experiment in which corona discharge produced by a multiple point-to-plate high-voltage electric field was used to investigate the enhancement of rough rice drying and subsequent effect on rice fissuring and germination. In their design a 16 needle point cathode with a direct current power supply, and a grounded stainless steel plate anode were used. The findings showed that the drying rate of the treated rough rice was notably greater than that of the control, and that the drying rate could be described by an exponential model. The electric field treatment significantly enhanced drying but had no effect on rice fissuring at a lower temperature. The average drying rate of the treated rice increased 2·83, 1·59 and 1·63 times at 25, 40 and 50°C, respectively, compared to the corresponding control. The drying rate also increased with increasing electric field strength. The electric field treatment did not have significant effects on the percentage of kernels having heavy fissures or the germination rate of rough rice (probability $P>0.05$). The total number of fissured kernels in the treated sample was increased compared to the control.

Table 1 Effect of electric field direction on various indices of Golden Delicious apple. (Reprinted from **Atungulu G, Atungulu E, Nishiyama Y** (2004a) Electrode configuration and polarity effects on physicochemical properties of electric field treated apples postharvest. *Biosystem Engineering* **87**, 313-323, ©2004 with kind permission from Elsevier Ltd.).

Measured index	Applied Voltage and direction			
	36 kV Forward	36 kV Reversed	48 kV Forward	48 kV Reversed
Weight loss, %	high	highest	low	lowest
Color difference	high	highest	low	lowest
Respiration, ppm g-1	lowest	highest	low	high
Soluble sugar concentration, %	high	highest	-	-

The terms highest, high, low and lowest represent comparison based on quantity and declines in the respective order.

PEF treatment for enhancement of food dewatering during pressing and drying processes has been proposed (Ade-Omowaye *et al.* 2003; Lebovka *et al.* 2003; Fincan *et al.* 2004; Vorobiev *et al.* 2005). Effective plant tissue disintegration under PEF treatment can be achieved at moderate electric fields of 200–1000 V/cm and short treatment time within 10^{-4}–10^{-2} s (Lebovka *et al.* 2000, 2001, 2002). PEF treatment at mild thermal conditions further improves the effectiveness of PEF-induced damage (Lebovka *et al.* 2004a, 2004b).

Nikolai *et al.* (2007) determined the effect of PEF treatment on the drying rate of potato tissues. According to their drying experiment the dimensionless moisture ratio ω versus time t and the damage degree after PEF treatment were studied. The value of ω was determined as

$$\omega = \frac{M(t) - M_e}{M_0 - M_e} \qquad (6)$$

where M is the moisture content in a sample, and the subscripts '0' and 'e' refer to the initial and equilibrium (final) moisture contents, respectively. For the damage degree estimation after the PEF treatment, the electrical conductivity disintegration index Z_σ was used (Lebovka *et al.* 2002):

$$Z_\sigma = \frac{\sigma - \sigma_i}{\sigma_d - \sigma_i} \qquad (7)$$

where σ is the measured electrical conductivity value and the subscripts 'i' and 'd' refer to conductivities of the intact and maximally destroyed tissues, respectively. Hence $Z_\sigma = 0$ for an intact tissue and $Z_\sigma = 1$ for a disintegrated material. The conductivity of the maximally destroyed material σ_d was determined for samples after the PEF treatment in the electric field $E = 500$ V/cm during the period t_{PEF} of order 1 s (Lebovka *et al.* 2002; Bazhal *et al.* 2003). Nikolai *et al.* (2007) thus reported that the higher the damage degree of the PEF-treated tissue the more rapid is the drying process (**Fig. 7**). PEF treatment of material releases moisture from the damaged cells and enhances transport processes, which results in increase of the drying rate. The drying rate depends not only on the quantity of the released water, but also on the structure, density and porosity of material (Wang

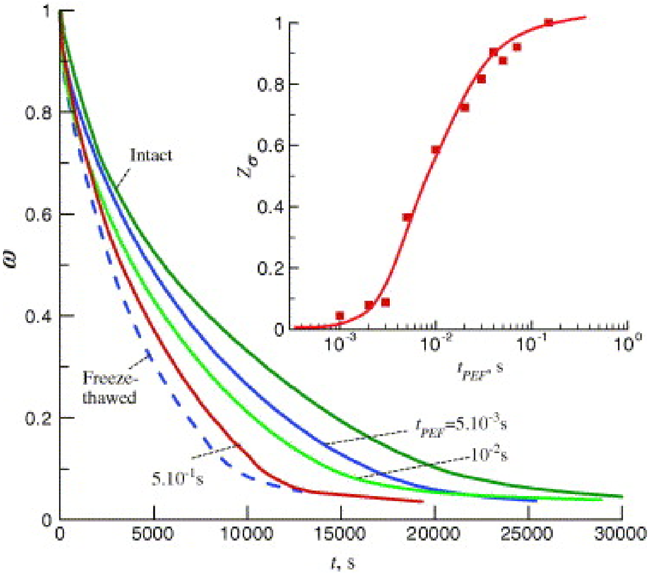


Fig. 7 The moisture ratio *ω* versus drying time. *t*: for intact, PEF-treated and freeze-thawed treated (dashed line) tissues at 50°C drying temperature. The PEF-pre-treatment was done at room temperature, $T = 25$°C, electric field strength $E = 400$ V/cm, pulse duration $t_i = 10^{-3}$ s, pulse repetition time $\Delta t = 10^{-2}$ s, and different treatment time t_{PEF}, shown at the figure. Insert shows the electrical conductivity disintegration index $Z\sigma$ versus treatment time t_{PEF} for the same PEF treatment conditions. (Reprinted from **Nikolai IL, Nikolai VS, Eugene V** (2007) Pulsed electric field enhanced drying of potato tissue. *Journal of Food Engineering* **78**, 606-613, ©2007 with kind permission from Elsevier Ltd).

and Brennan 1995; May and Perré 2002). The effective moisture diffusivity increase with increasing degree of PEF induced damage is a sensitive detail of thermal pre-treatment procedures. Though the highest drying rates are always observed for freeze-thawed pre-treatment, this process is more energy expensive.

Combination processes of electric field for enhanced dehydration

Pulsed electric field treatment of biological cells results in permeabilization of cell membranes, a phenomenon known as electroporation. This effect is used to enhance mass transport process within plants tissue to achieve gentle, non-thermal dehydration.

Pulsed electric field and osmotic dehydration

Use of electric field, more specifically PEF, is an efficient complimentary processing step to osmotic dehydration (OD). Recently, researchers have reported on various combination processes that can improve the mass transfer rate either in sequence or simultaneously with osmotic dehydration. These include application of high pressure processing (Bolin *et al.* 1998) or PEF treatment of food material (Rastogi *et al.* 1999) prior to OD. Similar application of ultrasound (Simal *et al.* 1998), partial vacuum (Rastogi and Raghavarao 1996) or centrifugal force (Azuara *et al.* 1996) are used simultaneously with OD.

The combined effects of PEF pre-treatment and partial osmotic dehydration on air drying behavior of red bell pepper has been addressed by Ade-Omowaye *et al.* (2003). PEF using varying field strengths (1.0, 1.5 and 2.0 kV/cm with application of 20 pulses having duration of 400 µs each) and pulse numbers (10–80) at a constant field strength of 2.0 kV/cm were applied to bell peppers as a pre-treatment to study their influence on the products' air drying kinetics. Air drying characteristics of PEF pre-treated pepper samples immersed in sucrose/sodium chloride solutions for either 30 or 60 min were also evaluated. Air drying was carried out at 60°C in a fluidised bed dryer with an air velocity of 1 m^2/s. The authors concluded that cell membrane permeabilisation increased with increasing field strength and higher pulse number. However, the increase became marginal after application of more than 30 pulses. Pretreating pepper with PEF enhanced initial drying rates significantly. The initial rates of drying of all the PEF pre-treated samples (0.18-0.052 kg/kg min) were consistently higher than the untreated ones (0.13-0.051 kg/kg min) until average moisture content of 3.12 kg/kg in untreated and approximately 2.2 kg/kg in the treated samples (75 min of drying) beyond which the rate of losing water was faster in the untreated than the treated ones. The effective water diffusivity (D_{eff}) values for PEF pre-treated samples pre-concentrated in osmotic solution for 30 or 60 min ranged from 0.94 to 1.36×10^{-9} m^2/s depending on the treatment conditions while untreated samples immersed in osmotic solution for 30 or 60 min had 0.87 and 0.99×10^{-9} m^2/s respectively. Partial osmotic dehydration before air drying resulted in minimal decrease in D_{eff} values in all cases studied. The results also showed that the air drying of untreated, PEF pre-treated and partially osmotically PEF pre-treated pepper samples occurred in the falling rate period having two different slopes.

Ade-Omowaye *et al.* (2002) used electric field pulses as a synergistic treatment to improve osmotic dehydration of bell peppers. The authors performed osmotic dehydration of bell peppers using sucrose and sodium chloride as osmotic agents and examined the influenced of moderate thermal treatment (25-55°C) and high intensity electric field pulses at varying field strengths (E = 0.5-2.5 kV/cm). Two product quality indicators (vitamin C and carotenoids) were evaluated. The authors observed that increasing temperature resulted in water loss from 32% to 48% and increasing field strength resulted in water loss from 36% to 50% of initial moisture content. Both conditions enhanced solid gain during osmotic dehydration of bell pepper. Air drying reduced vitamin C to approximately 5% of initial concentration while increasing temperature (25-55°C) during osmotic dehydration decreased residual vitamin C concentration after osmotic dehydration from 20% to 4% and high intensity electric field (2.5-0.5 kV/cm) decreased it from 13% to 7% of initial value. Carotenoids reduced from 80% to 55% as a result of temperature increase and from 74% to 62% of initial fresh content as a result of high intensity electric field pre-treatment. Results obtained at field strength 2.5 kV/cm were comparable and in some cases better than those at elevated temperature of 55°C suggesting high intensity electric field as an attractive alternative to conventional thermal processing. Another study on paprika, by the same authors: effects of high intensity electrical field pulse pre-treatment on dehydration characteristics of red paprika, showed that the application of high intensity electric field pulses (2.4 kV/cm, pulse width 300 µs, 10 pulses, pulse frequency 1 Hz) pretreatments resulted in cell disintegration indexes of 0.61. Cell permeabilisation of the physical treatment resulted in higher drying rates, as well as higher mass and heat transfer coefficients, as compared to conventional pre-treatments.

Taiwo *et al.* (2002) studied the influence of high intensity electric field pulses (HELP) and OD on the rehydration characteristics of apple slices at different temperatures. Their objectives were to investigate the influence of predrying treatments of HELP with 20 pulses having 48 J/kg for 400 µs per pulse and OD in 50% sucrose solution) on some characteristics of rehydrated apples at different temperatures (24-90°C). Rehydration rate increased with temperature but higher rehydration capacity (RC) values were obtained at low temperatures (24°C and 45°C). RC of HELP treated + OD samples was 10-30% higher than the RC of the untreated + OD samples. Solid retention after rehydration was highest in HELP treated samples which also had firmer texture at full rehydration. Sugar gained during OD increased product firmness. Electrolyte release during rehydration was temperature dependent. The colour of the rehydrated apples darkened with increase in rehydration temperature and/or time.

Limitation of combined pulsed electric field and osmotic dehydration technologies

Further research may be needed to evaluate various PEF chamber configurations that can provide optimal handling of solid products for subsequent OD operation. Attention must be paid to potential safety problems due to the presence of air entrapped in the food matrix that can cause dielectric breakdown during treatment.

Radio frequency and convection heating

Conventional heating methods remove moisture from the surface of materials while radio frequency heats the middle of a product and drives moisture to the surface. Combining these two technologies allows the advantage of the benefits each provides. The combination of radio frequency and conventional drying has been employed in several different ways, and each has resulted in significantly improved drying processes. There are four main radio frequency/conventional heating combinations: RF preheat, RF boost, RF finish and full RF/conventional.

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Dried product quality, energy as well as environmental concerns put research priority on seeking alternate technologies such as HEFD. Possibility of improved quality of products, besides drying is a unique advantage endowing the EHDD with a great potential application to thermally sensitive materials.

As directions to future research, the following aspects need to be addressed for the electric field associated drying operations:

- Substantial research and development activities on PEF technology are required to understand, optimize and supply the processes to their full potential. Of the current limitations to these technologies are the unavailability of commercial units and high costs in the case of PEF that prevent widespread industrial adoption. These need to be addressed to make the technologies as industrially competitive as conventional thermal processing and make them widely accepted by the food industry.
- The evaluation of product microstructure changes resulting from the treatments may provide useful information.
- The kinetics of nutrient degradation, rehydration studies and optimization of process conditions for a wide variety of products may be essential. Most agricultural products vary a lot in their characteristics calling for optimization of various parameters such as field strength, electrode configuration, air humidity, air temperature and product variety for best results. Carlon and Latham (1992) optimized on accelerated drying of water-wetted materials in electric fields and the electric currents, I, associated with drying rates of discs of paper toweling and cotton cloth wetted with water were measured as functions of several parameters: E, the strength of the electric field in which the discs were placed; T, the temperature; H, the percent relative humidity. The drying rates increased monotonically with E, and typical drying times decreased by factors of up to about 10 as E rose from 0 to above 7 kV/cm. Measured electric currents over this range of E increased 3-4 orders of magnitude.
- Techno-economic study on the energy saving aspect of electric field drying would be beneficial so as to promote acceptance on an industrial scale.
- It is clear from review that little has been done on intermittent treatments using parallel plate electrode configurations and the effects of field reversals with the object of optimizing drying have not be thoroughly researched.

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