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Treatment of potato tissue by pulsed electric fields with time-variable strength: Theoretical and experimental analysis

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ABSTRACT

This work discusses efficiency of pulsed electric field (PEF) treatment of cellular material with time-variable electric field strength, *E*. The potato was selected as a model tissue. Computer model, based on electroporation theory, was developed to simulate different strategies of *E* value changes. In the experimental part of this work, the PEF treatment was applied to disk-shaped and sliced samples using a laboratory compression chamber, equipped with a PEF-treatment system. The experiments were done using PEF generator that provided pulses of near-rectangular shape, the pulse duration was $t_i = 1000$ µs, the value of *E* was varied within 200 and 800 V/cm, and the total time of PEF treatment, t_{PEF}, was varied within 0 and 0.1 s. The electrical conductivity disintegration index, *Z*, was used for characterization of the PEF-induced damage of potato tissue. Both theory and experiment predicted the minimum power consumption W_o at the optimal value of $E_o \approx 400$ V/cm. The computer simulation predicted that application of protocols with time-variable electric fields would allow optimization of PEF treatment with initial electric field E_i deviating from the optimal value E_o. PEF experiments revealed that exponential increase of *E* values can be useful at small initial electric field strengths, $E < E_o$, as far as it allows significant improvement of PEF-treatment efficiency. The PEF experiments with pressing of potato slices have shown that PEF treatment before pressing was more efficient than treatment during the pressing, and the specific energy consumption for the both samples was approximately the same ($W \approx 7.5$ kJ/kg).

1. Introduction

The pulsed electric fields (PEF) became popular in different food processing applications during the last decades (Barbosa-Canovas et al., 2000; Fryer and Versteeg, 2008; Knorr et al., 2008; Vorobiev and Lebovka, 2010). It was demonstrated that PEF treatment of different agricultural products allowed acceleration of the mass transfer processes (Donsi et al., 2010; Porras-Parral et al., 2012), pressing (Lebovka et al., 2004; Vorobiev et al., 2007), drying (Adedeji et al., 2008; Ade-Omowaye et al., 2001; Amami et al., 2008, 2005), freezing (Ben Ammar et al., 2011a,b; Jalte et al., 2009), extraction (Loginova et al., 2011a,b, 2010) and osmotic dehydration (Amami et al., 2008; Maftoonazad, 2010). The important merits of this technique are related with possibility of preservation of the quality of fresh food products (e.g., bioactive compound purity, colour, texture, aroma, flavour, and nutrients) (Mittal, 2009; Nielsen et al., 2009; Odriozola-Serrano et al., 2013) at rather low power consumption (typically lying within 1–15 kJ/kg (Vorobiev et al., 2007)).

Efficiency of PEF treatment of a cellular material strongly depends upon the strength of electric field that is applied to the system. Both theory and experiment predict the minimum power consumption W_o at the certain optimal value of $E = E_o$ (Ben Ammar et al., 2011a,b; Lebovka and Vorobiev, 2010). This optimal value depends on the cellular material characteristics, and choice of the proper E_o value requires careful experimental testing at different values of *E*. Moreover, PEF treatment at small $E (< E_o)$ values can cause the effects of incomplete damage (Lebovka et al., 2001, 2007), whereas PEF treatment at large values of $E (> E_o)$ can result in a noticeable ohmic heating, which is undesirable for temperature-sensible materials (Parniakov et al., 2014). It was shown that PEF treatment at electric field strength *E* from 0.5 to 1 kV/cm and treatment time between 10^{-4} and 10^{-2} s allowed effective disintegration of cell membranes in the whole samples of agricultural species (whole sugar beet, potatoes, etc.) (Bluhm et al., 2004;

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Nomenclature

d	thickness of membrane, nm
E	electric field strength, V/cm
E_e	parameters of tissue electroporation response, V/cm
f	electroporation coefficient
h	thickness of slices, mm.
I	current intensity, A
m	mass of sample, kg
m_i	initial mass of slices, kg
m_j	mass of juice, kg
n	number of pulses in the series
N	number of cells in the tissue
N_s	number of series of pulses
N_t	total number of cells in the tissue
$N(r)$	distribution function of the cell radii
P	degree of tissue damage
P_c	value of P at the percolation threshold
r	radius of the cell, µm
$\langle r \rangle$	mean radius of the cell, µm
s_p	exponent of the percolation theory
t	time of pressing, s
t_i	pulse duration, µs
t_p	exponent of the percolation theory
t_{PEF}	time of PEF treatment, s
Δt	pulse repetition time, ms
Δt_t	pause between series, s
T	temperature, K
Q	reduced activation energy
U	voltage, V
W	specific energy consumption, kJ/kg
Y	juice yield, %
Z	electrical conductivity disintegration index

Greek symbols

α_e	parameters of tissue electroporation response
δ	standard deviation of the cell radius, µm
ρ	density, g/cm^3
σ	electrical conductivity, S/cm
τ	characteristic damage time, s
τ_E	time constant characterizing the time dependence of E, s
τ_∞	limiting lifetime of a cell, s

Subscripts

d	damaged
e	effective
f	final
i	initial, intact
m	membrane
max	maximal
o	optimal

Notations

B_{PEF}	sample, PEF treated before pressing
D_{PEF}	sample, PEF treated during pressing
M→	constant E model
M↑	exponential E increase model
M↓	exponential E derease model
M↑↑	persistent E change model
M↑↓	anti-persistent E change model
U	untreated sample

Abbreviations

PEF	pulsed electric field

Grimi et al., 2010) or cut slices (Bazhal et al., 2001; Grimi et al., 2007). In particular, the studies have shown that apparent density of slices had an impact on PEF efficiency, and kinetics of damage was more accelerated for denser packing (Mhemdi et al., 2013). In previous studies, the mechanisms of electroporation were mostly studied for constant operation conditions (constant electric field strength E and other parameters of pulse protocol) (Angersbach et al., 2002; Barbosa-Canovas et al., 2000; Donsi et al., 2010; Knorr et al., 2008; Lebovka and Vorobiev, 2010; Vorobiev and Lebovka, 2010). Practical implementations of PEF-assisted technologies often require combination of PEF with other techniques, e.g., pressing (hydraulic, roll or belt pressing (Praporscic et al., 2007; Turk et al., 2012)), when the electric field strength E and electrical conductivity of the sample can change significantly during the operation (Ben Ammar et al., 2011a,b; Grimi et al., 2007; Parniakov et al., 2014; Praporscic et al., 2007).

However, it was still unclear to what extent the PEF treatment with time-variable electric field strength can influence electroporation efficiency. So, it is important to develop the optimal strategies of non-stationary PEF protocols in order to provide minimum power consumption and high degree of material damage.

The aim of this work was to study the impact of PEF on the damage efficiency and power consumption under conditions when the electric field strength, E, was non-steady during the PEF treatment. Development of PEF-induced damage was simulated using different strategies of E value changes. The obtained data were compared with the results for the constant electric field strength (model M→). The potato tissue was chosen as a model food tissue for the experimental part of this work. The PEF treatment was applied to the potato disks and slices. In the latter case, the effects of pressing on the efficiency of juice expression were compared for untreated (U), PEF treated before pressing (B_{PEF}), and PEF treated during pressing (D_{PEF}) samples. The theoretically and experimentally obtained relations between the damage efficiency and power consumption under the PEF treatment with variable electric field strength were compared and discussed.

2. Materials and methods

2.1. Materials

Commercial potatoes (Marabel) of good and uniform quality were purchased at the local supermarket (Compiegne, France) and stored at 4 °C until required. The moisture content, measured by drying 20 g of fresh potato tissue at 105 °C to constant weight, was about 77–79%. The density of potato tissue, ρ, was of 1.08 ± 0.04 g/cm^3.

2.2. Details of the computational model

The Monte Carlo model, similar to that described earlier (Ben Ammar et al., 2011a,b) was used for simulation of the effect of PEF treatment of plant tissues. The plant tissue was simulated by an array of randomly distributed cells with different radii r. At the initial moment of time before PEF treatment, $t_{PEF} = 0$, all cells were assumed to be intact and Gaussian distribution of the cell radii r was assumed as

$$N(r) = N_t \exp(-(r - \langle r \rangle)^2/2\delta^2)/\sqrt{2\pi}\delta, \quad (1)$$