PULSED ELECTRIC FIELD PROCESSING OF FOODS

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OUTLINE

- Background
- PEF Overview
- Microbial inactivation case studies
- Biofilm control
- Quality aspects
- Safety monitoring
- Concluding remarks
BACKGROUND

FOOD PROCESSING OBJECTIVES

• maintain safety and quality of food products for as long as possible

• impact unique attributes to products
THERMAL TREATMENT
preferred method used by the food industry to inactivate pathogenic microorganisms and enzymes

PROBLEMS
• high temperatures and overcooking result in quality deterioration affecting sensory and nutritive attributives
• energy requirements
NON THERMAL PROCESSES

being explored to address the adverse effects of thermal processing.

- high pressure processing
- ultrasound
- ultraviolet light pulses
- magnetic fields
- pulsed electric fields (PEF)
PEF SYSTEMS: PRINCIPLES

PULSED ELECTRIC FIELD PROCESSING involves the application of pulses of high electric voltage (in the range of 20 to 80 kV/cm) across food contained between 2 electrodes.

ELECTRIC FIELD results in inactivation of microorganisms suspended in the food medium without significantly increasing the temperature of the food product.
electropermeabilization = electroporation = electroplasmolysis


\[ u_m - \text{transmembrane potential} \]

increase in cell walls permeabilization
Inactivation par CEP

Electroporation

Cell membrane

Cytoplasm

Medium

a) $E=0$: Absence of EF

b) $E < E_R$: Presence of EF

c) $E > E_R$: Reversible breakdown

d) $E >> E_R$: Irreversible breakdown
ELECTROMECHANICAL MODEL OF CELL RUPTURE

For spherical cells:

$$V_i = 1.5mrE_o \cos(\theta) \left[ -e^{-t/t_r} \right]$$

$$V_R = 1.5rE_R \cos(\theta)$$

where:
- $V_i$ = induced potential
- $V_R$ = rupture electric field
- $r$ = cell radius (m)
- $E_o$ = applied electric field (V/m)
- $E_R$ = rupture electric field (V/m)

$\theta$ = angle (rad) between the vector of the cell radius and the vector of the electric field at a point on the membrane
$\tau$ = duration of application of $E_o$ (s)
$t_r$ = relaxation time between electric field application and the moment when the membrane acquires a stable electric potential
$m$ = term related to surface conductance and cell resistivity
FOOD ENGINEERING

- liquid food pasteurization
- mass transfer process enhancement: dehydration, pressing, diffusion, drying

MEDICINE, BIOLOGY
Genes and drugs transfer into the cells

Electropermeabilization

| Cell suspension in liquid medium | Biological tissues |
**PEF SYSTEMS: COMPONENTS**

**HV Power Supply**

**Charging Resistor**

**Energy storage capacitor, Co**

**Discharge Switch**

**Treatment Chamber**

**Food**

**E = V/d**

where V = voltage across the electrodes and
d = gap between electrodes.

\[ V = \frac{Q}{C} - Ri - L \frac{di}{dt} \]

\[ V_C = \text{voltage across a capacitor} \]
\[ V_R = \text{voltage across a resistance} \]
\[ V_L = \text{voltage across an inductance} \]

**The resistance (in ohms) of a treatment**

\[ R = \frac{d}{A \sigma} = \frac{d^2}{V \sigma} \]

A = cross sectional area of active electrode (m²)
\[ \sigma = \text{conductivity of medium (S/m)} \]
SYSTEM CHARACTERISTICS

Energy per pulse:

\[ E = \int_{0}^{t} V_p(t)I(t)\,dt \]

For square wave pulse

\[ E = P_{\text{peak}}t = V_{\text{max}}I_{\text{max}}t = \frac{V_{\text{max}}^2}{R_a} \]

Capacitance of the capacitor

\[ C_o = \frac{\tau}{R} = \frac{\tau \sigma A}{d} \]

Energy stored in a capacitor

\[ Q = \frac{1}{2} C_o V_o^2 \]

Energy density

\[ Q_s = \frac{VI}{R} = \frac{V^2}{R} = n \sigma \tau E^2 \]

Temperature increase

\[ \Delta T = \frac{nE}{mc_p} \]
PEF WAVEFORMS

Monopolar  Electric fields  Bipolar

- Rectangular
- Exponential decay
- Continuous rectangular
- Rectangular

Long tail of low voltage
Maximal use of high energy
PULSE CHARACTERISTICS
PEF SYSTEMS: TREATMENT CELL
COAXIAL CHAMBER
HIGH VOLTAGE SWITCHES

Spark Gaps

Solid State
## Microbial Inactivation by PEF

<table>
<thead>
<tr>
<th>Electric field strength</th>
<th>Type of microorganism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment time</td>
<td>Microbial growth stage</td>
</tr>
<tr>
<td>Number of pulses</td>
<td>Ionic strength of medium</td>
</tr>
<tr>
<td>Pulse wave shape</td>
<td>Other medium characteristics</td>
</tr>
<tr>
<td>Processing temperature</td>
<td></td>
</tr>
</tbody>
</table>
MATERIALS AND METHODS

Untreated milk samples

High Voltage DC Pulse Generator

High Voltage DC Pulse Generator

Peristaltic Pump

Water bath

Thermocouple

Treatment chamber

HV probe

HC probe

Oscilloscope

GND

Treated milk samples

Untreated milk samples

Schematic of experimental setup
PEF GENERATOR @McGILL

Generator

PFN

30 kV, 100 Ω, 9 MW, 18J/p
TYPICAL WAVEFORMS
Inactivation of *E. coli* O157:H7 in whole milk using electric field strength of 30 kV/cm
Inactivation of *E. coli* O157:H7 in whole milk using electric field strength of 20 kV/cm
Kinetic rate constants for inactivation of *E. coli* O157:H7 in whole milk.
\[ \Delta s = \log(N_{TE}) - \log(N_T) = \log\left(\frac{N_{TE}}{N_T}\right) \]

Additional inactivation
Additional inactivation

- Additional log reduction
- Initial temperature (°C)
- Voltage (kV/cm)

- E=15 kV/cm
- E=6 kV/cm
- E=3 kV/cm

n=300
Log reduction

$E = 15 \text{kV/cm}$

$E = 0 \text{kV/cm}$

$\Delta T$ due to PEF heating

additional thermal

synergy
Initial temperature (°C)

Additional log reduction

Synergistic effect

Thermal inactivation

$E = 15 \text{ kV/cm}$

$\Delta T = 0$

$\Delta T = 4$
Increase in the rate of inactivation with temperature is attributed to reduced trans-membrane breakdown potentials at higher temperatures.

Phospholipids molecules in cell membrane undergo temperature-related transitions, changing from a firm gel-like structure to a less ordered liquid crystal phase at higher temperature, thus reducing the mechanical resistance of the cell membrane.
<table>
<thead>
<tr>
<th>Source</th>
<th>Milk type</th>
<th>Process conditions</th>
<th>Log reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunn et al. 1987</td>
<td>Pasteurized milk</td>
<td>Batch, 43°C, 43 kV/cm, 23 pulses</td>
<td>3</td>
</tr>
<tr>
<td>Zhang et al. 1995</td>
<td>SMUF</td>
<td>Batch, 33°C, 70 kV/cm, 80 pulses</td>
<td>9</td>
</tr>
<tr>
<td>Grahl et al. 1996</td>
<td>UHT milk (1.5% fat)</td>
<td>Batch, &lt; 45°C, 20 kV/cm, 20 pulses</td>
<td>4</td>
</tr>
<tr>
<td>Dutreux et al. 2000</td>
<td>Fat free milk</td>
<td>Continuous, 17°C, 41kV/cm, 63 pulses</td>
<td>4</td>
</tr>
<tr>
<td>Evrendilek et al. 2005</td>
<td>Skim milk</td>
<td>Continuous, 24 kV/cm, 50 pulses</td>
<td>1.96</td>
</tr>
</tbody>
</table>
Biofilm: biologically active matrix of cells and extracellular substances in association with a solid surface.

Food-borne pathogens and spoilage microorganisms accumulate as biofilm on stainless steel, aluminium, glass, Buna-N, teflon steel and nylon materials typically found in food-processing.
MECHANISM OF BIOFILM FORMATION

• Conditioning of a surface – the accumulation of macromolecules at the solid-liquid interface on food-contact surface.

• Adhesion of cells – attachment of microorganisms to the conditioned surface.

• Formation of microcolony – layer of cells covering the surface.

• Biofilm formation – continuous attachment of the bacterial cells with associated EPS production.
Biofilm formation:

Attachment | Colonization | Growth

Planktonic cells

Sessile cells

Bulk Fluid

Surface

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P. Dirckx
### Quality Aspects of PEF

Qualitative Parameters of Apple Juice from Control and PEF-Treated Samples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Apple Juice</th>
<th></th>
<th>Sugar Beet Juice</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PEF</td>
<td>Control</td>
<td>PEF</td>
<td>Control</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1059.4</td>
<td>1057.7</td>
<td>1.0392</td>
<td>1.038</td>
</tr>
<tr>
<td>Brix</td>
<td>13.8</td>
<td>13.1</td>
<td>9.8</td>
<td>9.5</td>
</tr>
<tr>
<td>pH</td>
<td>3.91</td>
<td>3.84</td>
<td>5.6</td>
<td>5.65</td>
</tr>
<tr>
<td>Pectin (mg/L)</td>
<td>290</td>
<td>517</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematic viscosity (10⁻⁶ m²/s)</td>
<td>5.917</td>
<td>6.747</td>
<td>2.284</td>
<td>2.595</td>
</tr>
<tr>
<td>Absorbance (wavelength of 520nm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtered</td>
<td>0.02</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonfiltered</td>
<td>0.03</td>
<td>1.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmittance</td>
<td>0.67</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Proteolysis in Cheddar-type Cheese made from Pulsed Electric Field Treated Milk

Major biochemical changes during cheese ripening include proteolysis, glycolysis and lipolysis

Proteolysis is considered the most important issue in terms of flavor and texture development
RESULTS AND DISCUSSION

Typical HPLC profile of the water soluble peptides in Cheddar cheese curd slurry
The ratio of hydrophobic to hydrophilic peptides in cheese slurries

RM: raw milk
PM: Heat pasteurized milk
PEF80: PEF treated milk with 80 pulses
PEF120: PEF treated milk with 120 pulses
PEF treated milk had the similar hydrophobic to hydrophilic proportion as raw milk.

PEF treated milk could give similar flavor to Cheddar cheese as raw milk.
Influence of PEF on drying kinetics

PEF significantly increased drying rate of carrot pieces

Electric field strength, capacitance and number of pulses significantly affected the drying rate
Slicing into cylindrical samples: diameter of 57 mm, thickness 15 mm

Control

PEF treatment

Compression test
Typical stress-strain curves from the compression test on apple samples treated by different number $n$ of electric field pulses ($E=1000$ V/cm, $t_{p}=300$ $\mu$s, $f=1$ Hz); curve with $n=0$ corresponds to untreated sample.
Alfalfa Juice

(a) alfalfa mash before pressing, (b) untreated mash residue after pressing, and (c) treated mash residue after pressing.

Relative quantities of juice extracted from alfalfa mash: (a) juice from PEF treated alfalfa mash and (b) juice from untreated alfalfa mash.

PEF treatment: 1.25 kV/cm; 200 pulses at 1 Hz in two successions. Each PEF treatment was followed by pressure application at 2 and 4 MPa, respectively.
Average yield of pressed alfalfa mash at two pressures. Moisture content of fresh alfalfa was 68% wb.

<table>
<thead>
<tr>
<th></th>
<th>Juice extracted (%) by mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 MPa</td>
</tr>
<tr>
<td>Untreated alfalfa</td>
<td>18.8</td>
</tr>
<tr>
<td>PEF Treated alfalfa</td>
<td>27.5</td>
</tr>
</tbody>
</table>

PEF treatment: 1.25 kV/cm; 200 pulses at 1 Hz in two successions. Each PEF treatment was followed by pressure application at 2 and 4 MPa, respectively.
Combined treatment allows for homogenized tissue structure, intensified plasmolysis of the cells and increased juice yield.
FOOD SAFETY MONITORING: HYPERSPECTRAL IMAGING

CONCLUDING REMARKS

There is excellent potentials for application of PEF to ensure safety of processed high quality foods.

Major efforts are being made to define inactivation kinetics, processing conditions that allow a more reliable comparison among different systems, impact of food additives and the use of hurdle technology, and effects of the process on specific food components, as well as modeling the electric and flow fields and their interaction, developing monitoring and control systems that assure adequate treatment, and developing new products.
Thank You