Modelling of static electric field

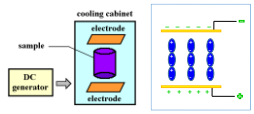
Pr Michel HAVET
In collaboration with Pr Olivier ROUAUD and Pr. Alain LE BAIL

November 5th 2018

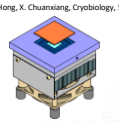
Introduction

Static electric field applied between:

- 2 plane electrodes (Electrofreezing)

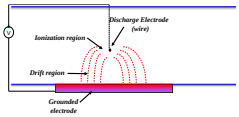


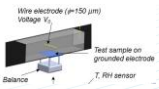
S. Wei, X. Xiaobin, Z. Hong, X. Chuanxiang, Cryobiology, 56, pp 93-99, 2008.



M. Orlowska, M. Havet, A. Le Bail , *Food Research International*, 42, 879–884, 2009.

- Electrodes with different radius of curvature (HMT enhancement)





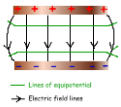
S. A. Ould Ahmedou, O. Rouaud, M. Havet, *Food and Bioprocess Technology*, 2, 240-247, 2009.

2

2 plane electrodes

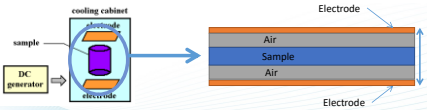
Electric field strength inside the product ?

- Uniform field strength



$$E = \frac{V}{d}$$

- Non uniform field strength (Electrofreezing)



$E = \frac{V}{d}$ ✗

➔ Modelling of the system to determine E inside the sample

3

2 plane electrodes

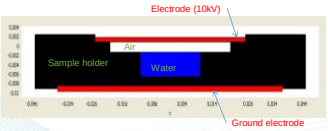
Numerical model (Comsol®)

- Equations of Electrostatic

$$-\nabla \bullet \varepsilon_0 \varepsilon_r \nabla V = 0$$

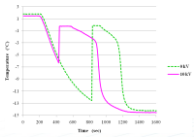
$$\vec{E} = -\nabla V$$

- System: Electrofreezing of distilled water



ε_r= 1 (air), 3.6 (sample holder) and 80 (water)

M. Orlowska, M. Havet, A. Le Bail , *Food Research International*, 42, 879–884, 2009.



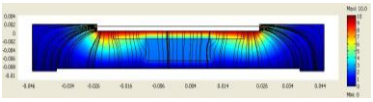
Influence of applied voltage on temperature

4

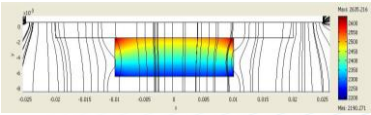
2 plane electrodes

Numerical model (Comsol®)

- Potential in the system (kV) – Streamlines of field strength



- Potential in the sample (V) – Streamlines of field strength



➔ Great impact of air gap !!

5

2 plane electrodes

Numerical model (Comsol®)

- 'Real values' of E in the sample:

	V/d [V/m]	E_{mean} [V/m]
Orlowska *et al.* 2009	~~1.1x10^6~~	5.5×10^4
Wei *et al.* 2008	~~1.1x10^6~~	5.4×10^3

S. Wei, X. Xiaobin, Z. Hong, X. Chuanxiang, Cryobiology, 56, pp 93-99, 2008.

6

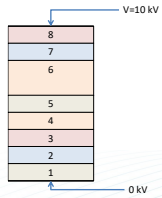
2 plane electrodes

Simplified model (Excel®)

- Objective: 1 D model for helping in system and experimental designs
- System: multiple layers (samples, air…)
- Inputs of the model:
  - Applied potential V
  - Number of layers (materials)
  - For each layer i : δx_i , ε_i
- Equations:

$$\delta V_i = \frac{V \times \frac{\delta x_i}{\epsilon_i}}{\sum_{j=1}^{n} \frac{\delta x_j}{\epsilon_j}}$$

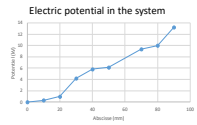
- Outputs:
  - Voltage distribution
  - Electric field distribution

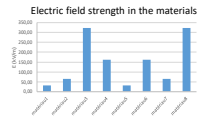


2 plane electrodes

Simplified model (Excel®)

- Objective: 1 D model for helping in system and experimental designs





- Validation against Comsol®

	E_{mean} [V/m] Comsol®	E_{mean} [V/m] Simple model
#1	2.02×10^4	1.96×10^4
#2	3.46×10^3	2.85×10^3

➔ Very satisfactory results with small efforts ☺

2 plane electrodes

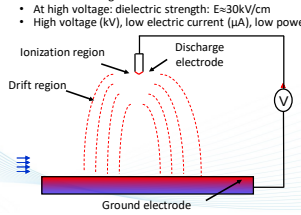
Conclusion on Modelling

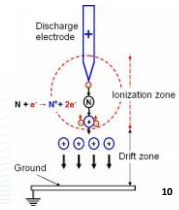
- Modelling is required to
  - 'Get an idea' of electric field strength inside the products
  - Analyse influence of process parameters (V, geometry, materials) on product qualities (ice crystals size …)
- 2 approaches can be performed
  - Model based on Finite elements methods for complex geometries (3D) and for couplings with heat and mass transfer, phase change
  - Simple 1D model for quickly determine E and optimize a system
- Main challenges in the future:
  - Determination of dielectric properties of materials and food products
    - Evolution of properties with temperature
    - Case of heterogeneous products
  - Relationship between modelling and product quality

Electrodes with ≠ radii of curvature

ElectroHydroDynamic (EHD) enhancement of Heat and Mass transfer (HMT)

- Context
  - Most of heat treatments of foods are performed by convection with air (drying, chilling…).
  - → High energy consumption due to high airflow rates and air treatment in AHU
  - Improvement of energy efficiency by an alternative process: EHD enhancement of HMT
- Mechanisms
  - Corona discharge at the electrode with the lower radius of curvature
  - At high voltage: dielectric strength: E≈30kV/cm
  - High voltage (kV), low electric current (µA), low power (W)

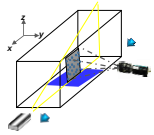


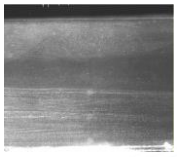


Electrodes with ≠ radii of curvature

Modification of the airflow

- Effect of ionic wind on the airflow
- Enhancement of convection at the surface





Laser tomography

V = 16 kV

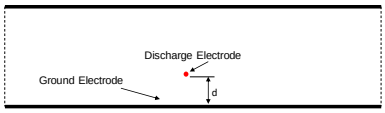
Instantaneous velocity

➔ Modelling of the system to determine influence of process parameters

Electrodes with ≠ radii of curvature

Complex phenomena: modelling approach by CFD

- Governing equations for a single wire electrode (2D)



Poisson's equation	$\nabla \cdot E = \frac{\rho_c}{\varepsilon_0}$ avec $E = -\nabla V$	1
Current conservation	$\nabla \cdot J = \nabla \cdot \left[\rho_c (U + bE) - D\nabla\rho_c\right] = 0$	2
Momentum conservation	$\rho(U \cdot \nabla)U = -\nabla p + (\mu + \mu_t)\nabla^2 U + \rho_c E$	3
Energy conservation	$U \cdot \nabla T = \nabla \cdot ((\alpha + \alpha_t)\nabla T)$	4

Electrodes with ≠ radii of curvature

Complex phenomena: modelling approach by CFD

- Equations and couplings

$$U\cdot\nabla T=\nabla\cdot\left((\alpha+\alpha_t)\nabla T\right)$$

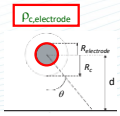
$$\rho\left(U\cdot\nabla\right)U=-\nabla p+\left(\mu+\mu_t\right)\nabla^2U+\rho_c E$$

$$\nabla\cdot J=\nabla\cdot\left[\rho_c\left(U+bE\right)-D\nabla\rho_c\right]=0$$

$$\nabla\cdot E=\frac{\rho_c}{\varepsilon_0}$$

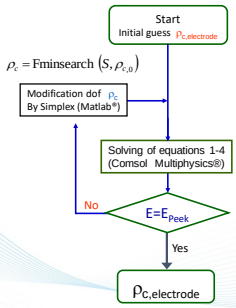
- Boundary conditions for V and ρ_c
  - At the ground electrode: V=0
    $\partial\rho_c/\partial n=0$
  - At the discharge electrode: $V=V_0$
    ρ_c: Peek's law

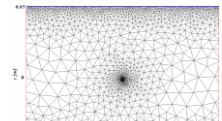
$$E_i=3\times10^6 m\left(\delta+0.0308\sqrt{\frac{\delta}{R_{electrode}}}\right)$$

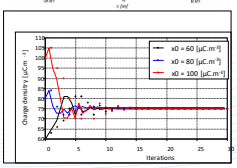


Electrodes with ≠ radii of curvature

Numerical procedure





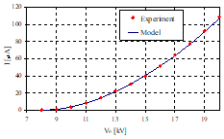


Electrodes with ≠ radii of curvature

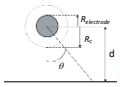
Prediction of the electric variables

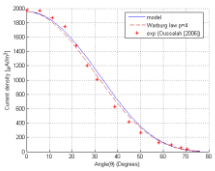
- Current-voltage characteristics

d=3 cm



- Current density on the grounded electrode



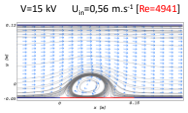


Electrodes with ≠ radii of curvature

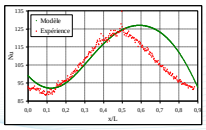
Prediction of the airflow and heat transfer

- Flow field in the channel

V=15 kV U_{in}=0,56 m.s^{-1} [Re=4941]



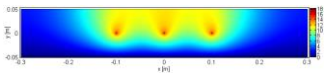
- Nusselt number along the plate



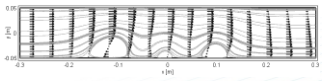
Electrodes with ≠ radii of curvature

Design of process with multiple electrodes

- Voltage [kV]



- Velocity vectors, streamlines



Electrodes with ≠ radii of curvature

Conclusion on modeling

- Modelling is required to
  - Get information on convective transfer at the surface of the products
  - Well design system (geometry, range of acceptable potential)
- Only 1 approach can be performed
  - CFD model to solve coupled equations
  - Optimization procedure do deal with electric field at the corona electrode
- Main challenges in the future:
  - Improvement of numerical model
    - Turbulence has to be better taken into account
    - Computational time has to be reduced
  - Complete design of an EHD process with multiple electrodes (>10)

Thank you for attention