Articles for

ORAL PRESENTATIONS

SESSION 1-2

Innovative Technologies - 2

Theoretical and Experimental Approaches to Improve Performance of UV systems for Liquid Foods and Beverages

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Abstract.

Challenges of ultraviolet (UV-light) processing of liquid foods, drinks and ingredients are due to their broad range of optical and physical properties, diverse chemical compositions that influence UV light transmittance (UVT) and momentum transfer. Transfer and delivery of absorbed UV fluence (product of UV light irradiance and residence time) directly affect microbial inactivation. Tayllor-Couette (T-C) reactor design demonstrated higher inactivation efficiency in comparison to traditional laminar and turbulent flow due to formed rotating vortices that deliver all parts of the treated liquid to UV source. The objective was to evaluate performance of T-C system in terms of microbial inactivation in low UVT liquids.

Inactivation performance of T-C system was experimentally validated through biodosimetry using specially developed model liquid that simulated pH, absorbencies and viscosity of low UVT liquid foods. Bacillus subtilis spores were used as a test microorganism.

CFD simulations were applied to determine optimal design of T-C reactor with single centrally located UV source, gap dimensions, and processing parameters such as rotation speed (0-200 rpm) and flow rate (up to 0.2 l/min). Model liquid recipe was developed to simulate properties of low UVT liquids. Concentrations of malate buffer, molasses and glycerol were determined to vary pH, absorbance and viscosity. UV fluence was calculated for each processing regime and absorbance value of model liquid. Based on experimentally measured numbers of survived B. subtilis spores, dose-response curves were constructed and effects of model properties and flow regimes were studied. In a case of close to opaque model liquid maximum inactivation of spores up to 5-logs was found when laminar vortices were formed.

Optimization of UV-systems design and selection of UV-sources with parameters that match to specific product spectra have a potential to make UV processing of low UVT foods more effective and will serve its further commercialization.

Keywords. UV systems, low UVT food liquids and beverages, Tayllor-Coutte reactor, model

A New Approach For The Optimization Of UV-Reactor Design By Mean Of CFD Simulation

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Abstract. *Ultraviolet (UV) sterilization is an emerging technology for beverages and waste water treatment. It can either be used as disinfection barrier, where the UV light is used to inactivate pathogenic microorganisms, or in combination with hydrogen peroxide as an advanced oxidation process. In this paper, a new simulative approach is presented for both fluid dynamics and optical optimization of UV reactors. The fluid dynamics analysis is carried out with a commercial CFD software (Tdyn Multyphisics), while the optical simulation is done by mean of an original tool, named "UVdose", which was developed in collaboration with the software developer SmartCAE. This software takes into account both physical-chemical parameters of water (i.e., turbidity) and optical effects, such as refraction; as output, it provides the statistical distribution of the dose absorbed by the fluid across the reactor.*

We consider two configurations of the reactor. The first one is a commercial UV reactor with 3 medium-pressure lamps, designed by the Italian company Puro s.r.l.; the second one is a modified configuration of the same reactor, with a different placement of the lamps. These configurations are compared from both the fluid dynamics and optical point of view, in order to identify the configuration which provides the best treatment to the fluid processed. For this latter configuration, we finally develop a framework which correlates the minimum UV dose required with some design parameters of the reactor, and is thus useful during the design stage of UV reactors.

The method we used in this paper can be extended to the optimization of any type of UV reactors, including more operating parameters of the reactor (e.g., type and number of lamps, type and number of baffles, layout etc...).

Keywords. *Ultraviolet, UV reactor design, UV dose, optimization, CFD, sterilization, water treatment.*

Introduction

Ultraviolet treatment is a non-thermal technology that can be used for the treatment of surfaces and liquids such as water, to inactivate many types of organisms, including viruses (Guerrero-Beltrán & Barbosa-Cánovas, 2004); UV radiation was also successfully applied to reduce the microbial load in different fruit juices and nectars (Keyser, Műller, Cilliers, Nel & Gouws, 2008). When designing a UV reactor, the achievement of a defined minimum dosage has to be ensured; in particular, reactors for water treatment have to guarantee a minimum dose of 40 mJ/cm^2. Small and medium enterprises often lack a specific R&D department, which makes particularly difficult to design UV reactor. Consequently, predicting the exact and effective treatment guaranteed by the machine can be difficult, and this is why the reactor is often oversized to ensure that a desired treatment is achieved. In this study, a commercial reactor, designed by Italian company Puro s.r.l., is analyzed and compared with another reactor with the same number of lamps but a different configuration.

Safety Emphasis

A careful and optimized design of UV reactors ensures the achievement of the minimum required dose, as well as allowing the minimization of operation costs. The tool developed in this paper allows to simulate, for example, the performances of the reactor under hard working conditions (e.g., lamp with a low efficiency, maximum turbidity of the water, etc. ..) so as to ensure optimal safety conditions even in these cases.

Materials and methods

Reactor geometry

The different geometries analyzed are depicted in Fig. 1:

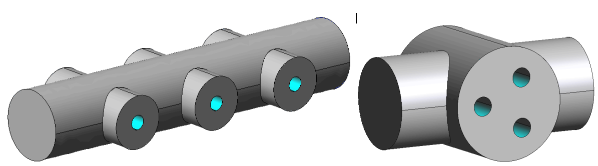

Fig. 1: reactor's configuration designed by Puro (left) and the new one (right)

As can be seen from Fig.1, the new configuration is smaller than that currently marketed by the company, and is therefore characterized by a smaller footprint and lower construction costs. The objective of this study is to determine which one of these two configurations is preferable from the fluid dynamic, optical and microbiological perspectives. The best configuration will be further optimized on the basis of its main design parameters.

Fluid flow analysis

The fluid flow calculation is carried out by means of TDyn Multiphysics. For both configurations, a flow rate of 260 m^3/h is assumed. Spalart-Allmaras turbulence model was used; it is a one equation model for turbulent flows with integration to the wall. It does not require a fine grid resolution in wall-bounded flows as two-equations turbulence models, and it shows good convergence in simpler flows (Tdyn Turbulence Handbook).

Optical analysis

The optical simulation is done by means of an original tool, called “UVdose”, which was developed in collaboration with the software developer SmartCAE. This tool allows calculating not only the UV intensity radiation inside the reactor but also the dose absorbed by the water crossing the reactor. The Beer–Lambert law (Blatchey, 1997) is the main mathematical basis for the computation of UV light intensity distribution. In particular, in this tool, the line source with diffused emission (LSDE) model is used (Quan, Pehkonen, Ray, 2004). This model assumes the lamp to be a linear source of the same length divided into a number of points; the user can arbitrarily choose the number of point sources to take on the axis of the lamp; in this study 100 point sources on each lamp has been taken (Ferretti, Montanari, Rizzo, Solari & Abba, 2010); each point on the line emits radiation in all directions in a diffused way, following the cosine law:

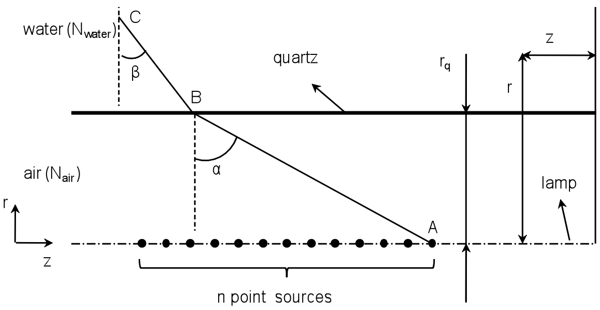

Fig. 2: Geometry of LSDE models with refraction at the interface air/quartz/water

$$I_\lambda(r,z) = \sum_{i=1}^{n} \frac{P_\lambda / n}{4\pi d_i^2} \cdot \cos\alpha \cdot \exp\left[-\left(a_q s_q + a_\lambda \left(r - r_q\right)\right)\right]\frac{l_i}{r}$$ **Equation 1**

In Equation 1, l_i is the distance traveled by the ray of light to get from the point on the axis of the lamp to the point in the water domain; as can be seen from Fig. 2:

$$l_i = \overline{AB} + \overline{BC}$$ **Equation 2**

To take into account the refraction of light at the water/quartz/air interfaces, Snell's law has also been implemented (Bolton, 2000):

$$\sin\beta = \frac{N_{air}}{N_{water}}\sin\alpha$$ **Equation 3**

Since β is independent of the material in the middle (Bolton, 2000) and since the thickness of the quartz is very small (approx 2mm), the presence of the quartz sleeve at the air/water interface can be neglected in calculating the refraction. Also the reflection of light caused by the walls has been neglected as well as the shadow effect caused by the other lamps inside the reactor. The analysis is carried out setting the parameters at the following values:

- Water absorbance: 0.009 cm^{-1}; UV-C lamp power (P_λ): 300 W

Dose calculation

Dose calculation is carried out by integrating UV intensity along the trajectory of each particle:

$$G = \int_{t_0}^{t_f} I\,dt$$ **Equation 4**

For the analysis, 1677 particles distributed uniformly on the input section were taken. Fluid flow analysis allows reconstructing the trajectory of each particle; once the trajectory of each particle is known, as well as the value of UV intensity in each point, the dose absorbed by each particle can be calculated by means of
Equation 4. Also this calculation is done by means of "UVdose".

Results and discussion

Fig. 3 shows the pressure drops inside the two different configurations considered:

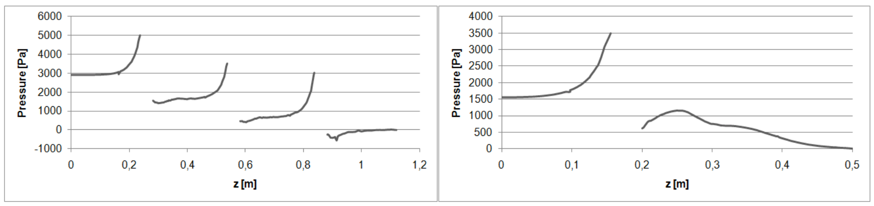

Fig. 3: pressure drop in the two configurations along the reactor's axis

As can be seen, in the compact reactor configuration (Fig. 3, graph on the right), less pressure drops is observed, which involves lower operating costs. Moreover, since the second layout is much more compact, the water flow turns out to be much more concentrated in regions close to the lamp (Fig. 6); then, the resulting treatment will be much more uniform. The results are summarized in Table 1: the new configuration turns out to be preferable from both the fluid dynamics (lower losses) and microbiological (higher absorbed dose) points of view.

Table 1: results summary

Configuration	Q	Pressure drop	Absorbance	Minimum absorbed dose
Marketed	260000 l/h	2930 Pa	0.009 cm^{-1}	46.4 mJ/cm^2
New	260000 l/h	1580 Pa	0.009 cm^{-1}	61.5 mJ/cm^2

Reactor optimization

The compact reactor configuration was found to be preferable from both the fluid dynamic and microbiological points of view. This configuration could be further improved by changing some of the geometric parameters of the reactor and assessing how these changes affect its performance. The diameter of the circle on which the axes of the lamps (D) lie and the rotation angle of the lamps (α) were chosen as optimization parameters (Fig. 4).

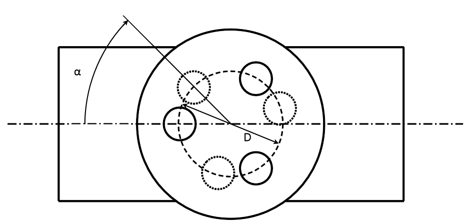

Fig. 4: Optimization parameters

Table 2 lists the parameter values for which the simulations were carried out. 7 different values of α and 10 different values of D were chosen, for a total of 70 different configurations.

Table 2: numerical values of the parameters for which the simulations were carried out

α [°]	0	10	20	30	40	50	60

D [mm]	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5	92.5

Because of the reactor's symmetry, and of the negligible effect of gravity, the configurations where α ranges between 0° and 60° can be considered as equivalent to those where α ranges between -60° and 0°. Graphs in Fig. 5 shows the minimum absorbed doses as a function of the two parameters selected for optimization:

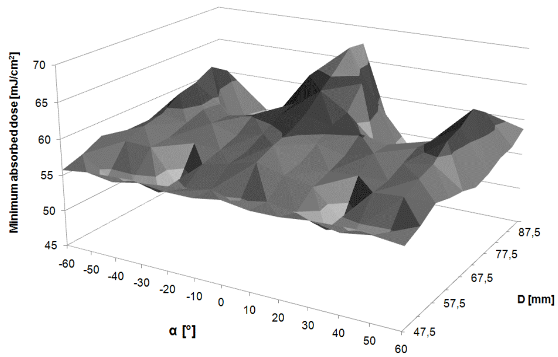

Fig. 5: minimum absorbed dose as a function of the two optimization parameters (α and D)

The configuration characterized by α=0° and D=87.5 mm turns out to be the most performing one: such a configuration ensures a minimum dose of 67.85 mJ/cm^2. Moreover, in this configuration a better uniformity of treatment compared to the other configurations can be observed; in particular, more than 90 percent of the particles are treated in a small interval of dose [67.85 mJ/cm^2 ÷150 mJ/cm^2] (Fig. 6).

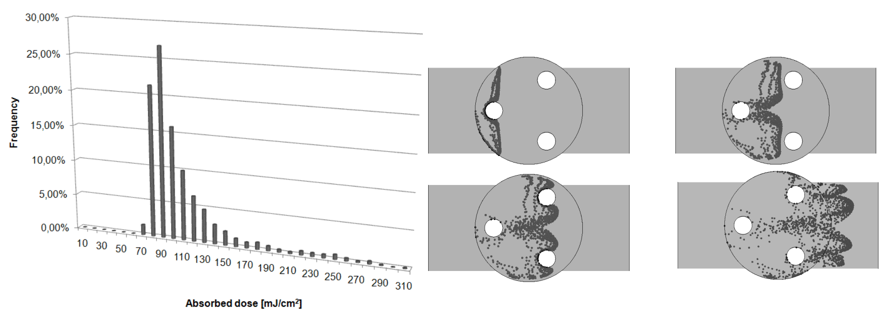

Fig. 6: dose distribution and trajectories of particles in the most performing configuration

The uniformity of treatment is due to the particular configuration of the reactor, which influences the flow of water and directs it near the lamps. Such a particular flow configuration ensures that all particles pass close to one (and only one) UV lamp, so that the doses absorbed by all particles are very similar. This result can be inferred by observing the sequence in Fig. 6. This reactor turns out to be oversized since the minimum dose guaranteed is greater than 40 mJ/cm^2; thus, with this kind of reactor it would be appropriate to treat a greater flow of water or, with the same water flow, it would be possible to treat water with higher turbidity. To optimize this configuration as a function of these two parameters a series of simulations with different values of flow and turbidity of water have to be made in order to obtain a design diagram; with this diagram will then be possible to choose one parameter as a function of the other one, in order to ensure the minimum required dose without over sizing of the machine (Ferretti, Montanari, Rizzo, Solari & Abba, 2010).

Conclusions

In this paper, an innovative simulative approach for the optimization of UV-reactor design by means of CFD simulation has been presented. For this purpose, a new tool (called "UVdose"), properly developed in collaboration with SmartCAE, was used; thanks to this tool, both fluid dynamics and optical (absorbed dose) performance of two different reactor configurations were compared; then, the best reactor configuration was further optimized by varying some of its geometrical parameters. The approach proposed in this paper can be used to optimize any type of UV reactor, since the software allows investigating, for instance, the optimal number and placement of lamps, the optimal shape and arrangement of diaphragms and all other parameters that may be of interest for UV reactor designers.

Acknowledgements

The authors acknowledge SmartCAE for the support and the collaboration in the software development and utilization.

Nomenclature

a	=	absorbance (cm^{-1})
I	=	light intensity (mW/cm^2)
N	=	refractive index
P	=	lamp power (mW)
Q	=	flow rate (l/h)
s	=	thickness (cm)
t	=	time (s)
Greek symbols		
λ	=	sterilizing wavelength
Subscripts		
0	=	initial
f	=	final
q	=	quartz sleeve

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Combined Inactivation Model and Shelf Life of Fruit Juices Treated by Pulsed Electric Field

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Abstract. *The shelf life of a food product can be defined as the period during which the product is still acceptable for human consumption. The shelf life is determined by microbial, chemical and physical aspects, which is in most cases a consequence of raw material quality, product formulation, processing, packaging and storage conditions. The combination of processing and storage conditions (package and temperature) determines what enzymes can be regarded as shelf life limiting. Enzyme activity in food may result in a change of the chemical composition of the product, resulting in changes in flavour, odour, colour and texture. Pulsed electric field (PEF) is considered as non-thermal technology, which could improve the juice quality while increasing or maintaining the period of shelf life. However, PEF treatment can affect the structure and activity of proteins. Also changes in structures and activities of bioactive compounds, vitamins and nutrients have been reported in literature. In this work, experimental models were developed to predict the microbial and enzymatic inactivation and the shelf life after continuous PEF treatments. The influence of the storage temperature on the shelf life was also considered and included within the model. A combination of models was used to predict the shelf life of PEF treated fruit juices based upon microbial and enzymatic spoilage. Vitamins and bio-active compounds were also analysed during the shelf life and included into the model. Furthermore, these models were compared with theoretical assumptions such as microbial growing kinetics and vitamins degradation during storage. As a result, the shelf life of PEF treated fruit juice was always determined by microbial spoilage for all process conditions and storage temperatures. Vitamins were minimal affected by the treatment and degradation was determined according packaging conditions. Furthermore, an overview will be given of the literature available on the influence of refrigerated storage on the microbial and quality of fruit juices treated by PEF.*

Keywords. Fruit juice, shelf life, pulsed electric field, microbial inactivation, enzyme inactivation, kinetic model.

Processing of Native Phosphocasein Micelles by Ultra-High Pressure Homogenisation

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Abstract. *Ultra-high pressure homogenisation (UHPH) is a physical technology with a low environmental impact and an innovative character. It is based on dynamic pressure effects on biological components (pressure increase in the high-pressure intensifier and pressure drop passing through the HP-valve, elongational shear stress in the HP-valve gap plus turbulence, cavitation and impact phenomena at the HP-gap outlet). The short-life heating phenomena that take place when the fluid is processed through the HP-valve seem to be an important processing parameter to control. UHPH is able to produce submicron particles (fragmented particles, submicron emulsion droplets or protein aggregates) that are interesting for the food, cosmetic and pharmaceutical domains. Previous studies indicated that dissociation/re-association phenomena in native phosphocasein micelles (PCN) are induced by isostatic high-pressure treatment at ambient or cold temperatures (Regnault et al.,2004). Structural changes induced by dynamic high-pressure (or (ultra)-high pressure homogenisation) could also modify casein micelle organisation with some incidence on the binding of hydrophobic ligand to the newly UHPH-formed neo-micelles.*

In the present study, PCN dispersed in simulated milk ultrafiltrate was UHPH-processed in the presence of α-tocopherol acetate (α-TA) at 100-300 MPa and various initial fluid temperature (T_{in}). The size distribution of PCN micelles, the viscosity and turbidity of PCN dispersions were determined to evaluate UHPH-induced effects on PCN physico-chemical characteristics. The ability of PCN to incorporate α-TA was investigated. Preliminary results indicated that processing parameters could influence both the size reduction of casein micelles and the content of entrapped α-TC. UHPH could thus offer the possibility of incorporating hydrophobic ligands in casein micelles while inducing some notable microbial inactivation.

Regnault, S., Thiebaud, M., Dumay, E. & Cheftel, J.C. (2004). Pressurisation of raw skim milk and of a dispersion of phosphocaseinate at 9°C or 20°C: effects on casein micelle size distribution. International Dairy Journal, 14, 55-68.

Keywords. Ultra-high pressure homogenisation, dynamic high pressure, casein micelles, α-tocopherol acetate, submicron particles.

Freezing and Freeze-Drying of Vegetables: Benefits of a Pulsed Electric Fields Pre-Treatment

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Abstract.

Pulsed Electric Fields (PEF) can provoke selective permeabilization of the cell membranes without causing any serious damage to the cell walls, which is favorable to the preservation for texture preservation in the case of vegetable tissues. The electroporation of multicellular tissues results in better connections between intra- and extracellular contents allowing increased probability of ice nucleation and faster ice propagation on freezing and, correspondingly, reduction of the freezing time.

This work mainly presents the effects of PEF pre-treatment (400-600 V/cm) on the freezing and freeze-drying kinetics of the various types of vegetables. The PEF treatment impact on the quality of the products in terms of their structure and texture is also discussed. In this study, PEF pretreated potato, green bean; spinach and onion were frozen in a rapid air-blast freezer (-80°C). A more or less significant (-3% to - 30% depending on the vegetable type) decrease of the effective freezing time was observed. The freezing of PEF pre-treated onion was also studied at the cell scale using an optical microscope and a special cooling plate (cooling rate: 1°C/min). Darkening of the cytoplasm, which appeared at temperatures less than -10°C, was attributed to the water phase change. All the cells in the image were frozen within few seconds in the case of PEF pre-treated onion, while it took about 1 minute in the case of untreated onion. Freeze-drying of PEF pre-treated potato was investigated too. The PEF pre-treatment induced 18% reduction of the time constant of mass loss kinetics. PEF-treated allowed improvement of shape and noticeable preservation of color of freeze-dried potatoes.
Keywords: freezing, freeze-drying, pulsed electric fields, electroporation, potato, onion, spinach, green bean, texture.

Introduction

The quality of frozen food is considered inversely related to the size of the ice crystals and their location inside the food (Delgado and Sun, 2001). The existing freezing preservation technologies tend to avoid formation of large ice crystals inside the food by regulation of heat removal. Pulsed electric field technology implies application of very short electric field pulses with intensities ranging from 0.5 - 1 kV/cm to a food product held between two electrodes, inside a chamber, usually at room temperature. Such treatment allows selective electroporation of the cell membranes without causing any serious deterioration of the semi-rigid cell walls nor significant temperature increase (Fincan and Dejmek 2002; Lebovka, Bazhal and Vorobiev, 2002; El-belghiti and Vorobiev 2005). The positive effects of a pulsed electric field pre-treatment on drying, extraction, and diffusion processes have been demonstrated (Raso and Heinz, 2006; Vorobiev and Lebovka, 2010). The effects of such pre-treatment on freezing of plants have not been investigated yet in details.

The aim of this study was to evaluate and characterize the effect of a PEF pre-treatment on the freezing kinetics and freeze-drying of some vegetables from different families: potato, green bean, spinach and onion tissues.

Materials and methods

Raw materials

Cylindrical samples (diameter = 26 mm, thickness = 10 mm) were taken with a punch from potatoes and onions. Spinach leaves were cut into 26 mm diameter disks and assembled into 10 mm thick stacks. Green beans (8-9 mm diameter) were lined up and then cut with a punch in cylindrical form of 26 mm in diameter. Juice from each of the four vegetables was prepared with a food liquidizer (AV6, Moulinex, France). Onion upper epidermis tissue was manually stripped from the concave surface of the bulb. Debris of onion flesh on the upper surface of epidermis was partially removed by washing with deionized water. Small sections (5 mm × 5 mm) were cut out using a sharp blade on cover glass.

PEF-treatment

PEF-treatment cell consisted of a polypropylene cylindrical tube with a 26 mm with inner diameter with an electrode at the bottom of the tube, one below the sample and the other above the sample. The electrodes (stainless steel) were connected to a PEF generator (400 V - 38 A). The generator provided bipolar pulses of a near-rectangular shape, which allowed avoiding the asymmetric electroporation. *N* series of pulses, called a train, were applied. Each train consisted of *n* pulses with pulse duration, t_i, pulse period, Δt , and a pause after each train, Δt_t . Current, voltage, electrical conductivity, and temperature, were collected using a data logger and relevant software. The electrical conductivity was measured during the inter-series periods, Δt_t, at a frequency of 0.5 kHz.

Table1. Parameters of PEF treatments

	Potato	Green Beans	Spinach	Onion
Number of pulses, *n*	5	2	2	5
Voltage (V/cm)	400	500	580	400
Pulse duration, t_i (μs)	1000	1000	500	1000
Number of trains, *N*	100	1000	600	500
Total time of PEF treatment (s)	0.5	2	0.6	0.5

The degree of tissue damage was estimated from the electrical conductivity disintegration index, Z (Lebovka, 2002):

$$Z = (\sigma - \sigma_u) / (\sigma_d - \sigma_u)$$

where σ (S/m) is the measured electrical conductivity and the subscripts u and d refer to the conductivities of untreated (intact) and completely damaged tissues, respectively. The value of σ_d was determined from the measurements of electrical conductivity of a raw tissue slowly frozen in a cold store (-25°C) and then thawed.

Freezing experiments

Rapid freezing of cylindrical samples was achieved in an ultra-low temperature freezer MDF-U2086S (Sanyo, Gunma, Japan). The temperature was set at -80°C. A modular-type temperature controller SR Mini SYSTEM (TC Ltd, France) and the Specview Plus software (SpecView Corporation, Gig Harbor, USA) were used to measure temperature. A type T thermocouple of 0.5 mm diameter with an accuracy of ±0.1°C (TC Ltd, Dardilly, France) was introduced into the geometrical centre of a sample. The effective freezing time, t_f, was used to characterize the freezing kinetics of cylindrical samples. It was defined as the time required for the temperature to decrease by 10°C from the initial freezing temperature T_f in the centre of the sample. The freezing rate was defined as the ratio of the effective freezing time and the distance between the outer surface and the centre of the product.

The freezing was observed at the cellular scale in the onion upper epidermis tissue using an optical microscope (Nikon, Japan) connected to a special heating cooling stage (Linkam THMS600, UK). The temperature was decreased from room temperature to -20°C at a rate of 1°C / min, then to -40°C at a rate of 2°C / min thanks to liquid nitrogen flowing into the stage and a temperature control system. The microscope images were converted to digital images through a SSC-DC58AP color video camera (Sony, Japan), captured and processed with image analysis software (Windows Movies Maker).

Freeze Drying experiments

Potato cylindrical samples were initially frozen in the air-blast freezer at -80°C and held there for 20 min. They were then loaded onto a shelf pre-cooled to ≈ 0°C in a SMH 15 freeze-drier (Usifroid, Maurepas, France). Freeze drying was performed at the shelf temperature (platinum temperature probes immerged into the shelf) of 0°C for 48 h. The chamber pressure was maintained at $4 \cdot 10^{-2}$ mbar throughout the drying process.

Results and discussion

Evolution of Z during a PEF pre-treatment

As shown in Figure 1, the electrical conductivity disintegration index, Z, versus time of PEF treatment strongly depended on the nature of the product. The tissues of spinach and green bean required more intensive PEF treatment than potato and onion tissues. These results were related to the wide diversity in cells geometry and size of the studied tissues (Ben Ammar, Lanoisellé, Lebovka, van Hecke, Vorobiev, 2010).

Effect of PEF pretreatment on freezing kinetics

Macroscopic scale

The cooling-freezing kinetics of untreated and PEF pre-treated cylindrical samples are shown on Figure 2. The time-temperature dependencies were quite typical for freezing of biological tissues, with a plateaus corresponding to the ice crystallisation zone. No significant difference in plateaus temperature was observed for untreated and PEF pretreated samples: for all of them it was around -1°C. The PEF pretreatment essentially reduced the plateau length. The effective freezing times and freezing rates were calculated as described previously. They are plotted on figures 4 and 5 respectively.

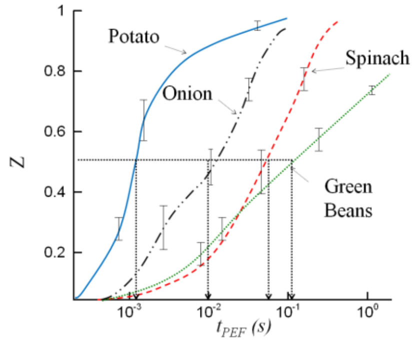


Figure 1. Evolution of electrical conductivity disintegration index, Z during PEF treatment

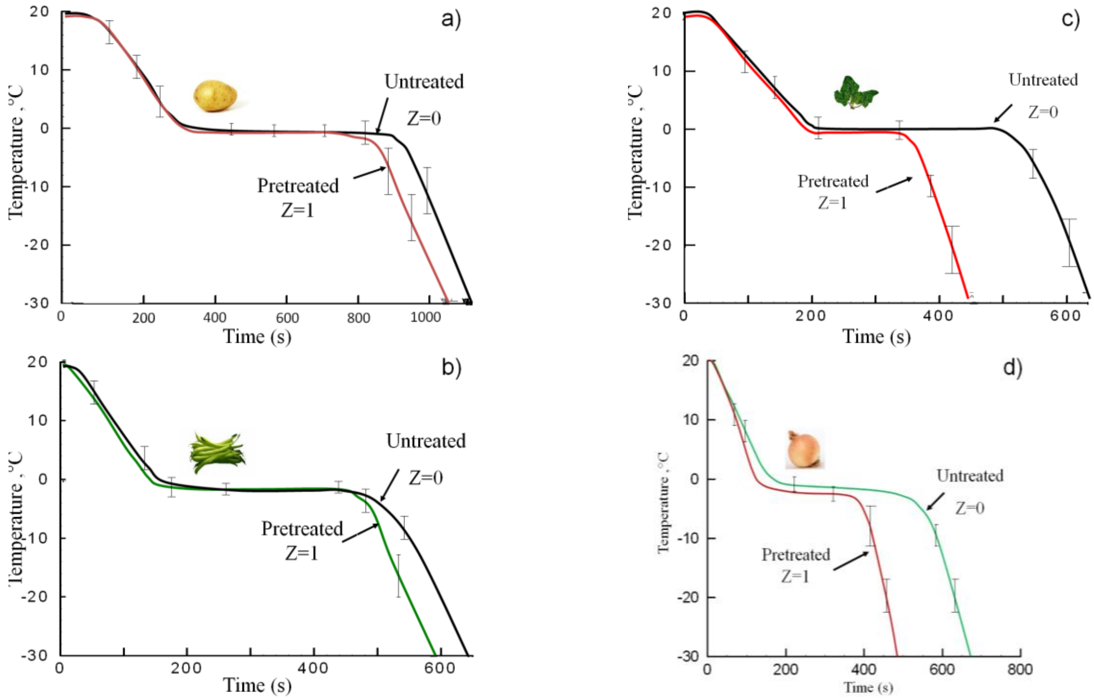


Figure 2. Temperature inside geometrical centre of the sample versus cooling time during the air-blast freezing for the untreated and PEF pretreated samples:
a) Potato; b)Green beans; c) Spinaches; d) Onion.

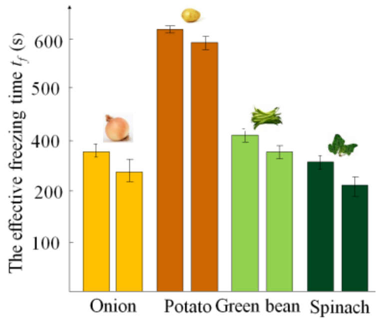


Figure 3. The effective freezing time, t_f, for PEF pretreated and untreated samples

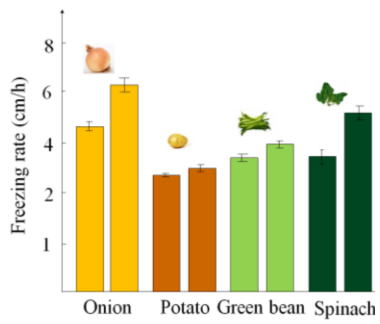
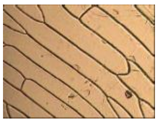
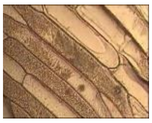
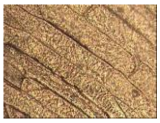


Figure 4. The freezing rate for PEF pretreated and untreated samples (3 replicates)

A PEF pre-treatment decreased the effective freezing time and consequently increased the freezing rate. The gain obtained from PEF treatment was depended on the vegetable nature. It was the most significant in the case of spinach and onion, which have the lamellar type structure. Obtaining of the best results for spinach can be partially explained by significant leaf thickness reduction during the PEF treatment. The freezing rate of bulk vegetables like potato or green bean was increasing to the less extent after PEF pretreatment

Microscopic scale

The effects of PEF pre-treatment on freezing of vegetables were studied at the cellular scale by observation of the onion upper epidermis tissue during its freezing. Figure 5 presents some typical images captured during freezing of untreated (a) and PEF-treated (b) samples.

Time	t = 0 s	t = 1 s	t = 2 s	t = 60 s
a) Untreated onion upper epidermis of tissue (Z = 0)				
b) PEF pre-treated onion upper epidermis tissue (Z = 1)				

c) Unfrozen, frozen, partially frozen cells and freezing nuclei

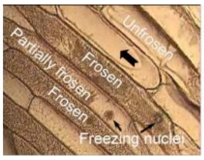


Figure 5. Optical microscopic images of onion upper epidermis tissue captured during freezing at T ≈−12°C. The cell size is about 400 μm x 45 μm.

During cooling in the temperature range between -10°C and -15°C the cytoplasm became turbid and opacity appeared which reflects commencement of freezing. The dark spots are first visible signs of ice crystallization, or freezing nuclei (Fig. 5c). As a result of freezing, the cytoplasm darkness gradually increases. The cells of untreated tissue were freezing progressively, i.e. one after another (Fig. 5a). The process of freezing was lasting approximately 60 s. In contrast, the cells of PEF-treated tissue got frozen practically instantly, in 2-3 s (Fig. 5b). To quantify the effect of PEF pre-treatment on the kinetics of freezing, changes in number of frozen cells as a function of time was counted (Fig. 6).

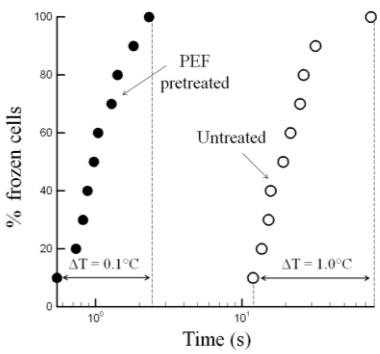


Figure 6. Percentage of frozen cells versus time (logarithmic scale), in a sample of onion upper epidermis.

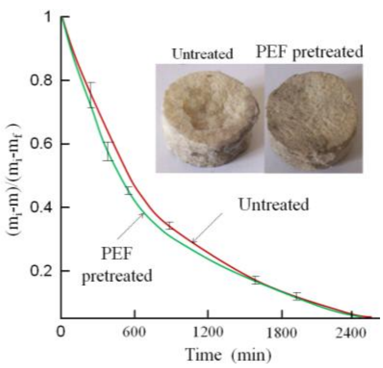


Figure 7. Reduced mass of the untreated and PEF pretreated potato tissue versus the freeze-drying time. The insert shows the shape of samples at t = 48 h.

From figure 6, we can conclude that pretreated upper epidermis froze much faster than the untreated one. In fact all the visible cells of the tissue pretreated by PEF were frozen within an average of 2 s (compared to 60 s for untreated cells).

Effect of PEF pretreatment on freeze drying of potato

Figure 8 presents the reduced mass of the sample $m^* = (m - m_f) / (m_i - m_f)$ (where m_i and m_f are the initial and final masses of the sample measured respectively at t = 0 and t = 48 h) versus the freeze-drying time for the untreated and PEF-pre-treated potato tissues. The PEF pretreatment of the potato resulted in a noticeable acceleration of the freeze-drying process in the first 24 h. In addition, such pretreatment improved the shape of the dried samples and resulted in more clear colours, smaller browning level and visually better quality of these samples (see insert in Figure 8). The similar effect was previously reported for PEF pretreatment (Jalté, Lanoisellé, Lebovka and Vorobiev, 2009).

Conclusion

Experiments showed that vegetables can be more or less rapidly damaged by a PEF treatment. Consequently, a variable but significant effect of a PEF pre-treatment on the freezing kinetics of potato, spinach, green bean and onion tissue was found. The electroporation of cell membranes was correlated to a noticeable decrease of the freezing time. Moreover, the PEF pre-treatment improved the rate of freeze-drying and resulted in more uniform shape, clearer color, less shrinkage and visually better quality of the freeze-dried potato. The PEF process uses ordinary electricity. The facility meets electrical safety standards and no harmful environmental by-products are produced. However, the most disputable issue is the risk of food contamination by products of electrochemical reactions on metallic electrodes. That is why the composition of electrodes and treatment device design are very important. So PEF-assisted freezing may be rather attractive in future for food preservation. Yet, further investigations are needed to characterize the quality of the frozen product. Another investigation deals with the modeling of the freezing kinetics for better understanding the PEF induced effects.

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