Evaluating the heating capacity of NutriPulse® E-Cooker® in liquid food products

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INTRODUCTION

Pulsed Electric Fields (PEF) can cause cell electroporation and accelerate diffusion processes in foods [1], but at the same time, the electrical energy delivered during the PEF treatment can cause food heating. This is based on the PEF induced ohmic heating and the electroporation effect which can increase the electrical conductivity of the solid product during the treatment improving the heating uniformity [2]. Depending on the pulse width and frequency of pulses, the heating velocity can also be modified. This has motivated the development of domestic appliances based on PEF like the NutriPulse® E-Cooker® to be used in cooking operations [3]. However, there is hardly any literature of the heating capability of the system in different products.

OBJECTIVE

- **To investigate the heating capacity of NutriPulse® E-Cooker® in different liquid food products and to compare it with other domestic heating systems such as an induction cooktop.**

MATERIAL and METHODS

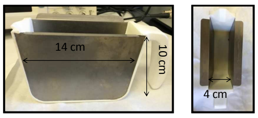
NutriPulse® E-Cooker ®

Voltage: 100 - 600 V
Electric field: 25 - 150 V/cm
Max. Power: 3000 W
Square-wave pulses

Selectable parameters:

- Pulse width: 10 - 60 µs
- Number of pulses: 5,000 - 80,000 pulses
- Final temperature: 20 - 100 °C

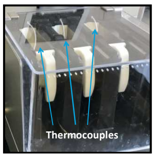
3 parallel electrode treatment chambers (300 mL):



TEMPERATURE EVOLUTION STUDIES

- A **thermocouple** in each treatment chamber enables to monitor and control the temperature of the treated product.

- **Data logger** integrated in the system.
- **Wi-Fi connection** to download time/number of pulses/temperature profiles.



STUDIED PARAMETERS:

- Pulse width: 10 to 60 µs
- Number of pulses
- Temperature range: 20 to 60ºC
- Electrical conductivity: NaCl solutions of 2.0, 7.5, and 13 mS/cm

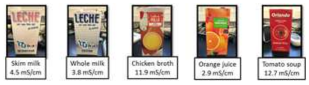
ANALYSES OF RESULTS

1. DESCRIPTION OF TEMPERATURE EVOLUTION CURVES BY MULTIPLE REGRESSION:

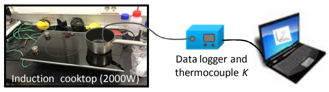
$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i>j}^{k} \beta_{ij} X_i X_j$$

X_i: number of pulses or time (s); X_j electrical conductivity; X_k pulse width

2. VALIDATION OF THE MATHEMATICAL EQUATION in LIQUID FOOD PRODUCTS:



3. COMPARISON WITH OTHER HEATING SYSTEMS:



RESULTS and DISCUSSION

Firstly, heating curves of different NaCl water solutions of different electrical conductivity were obtained applying different PEF protocols.

Figure 1 shows the temperature evolution of three solutions of different conductivity when using pulses of distinct width (10, 40 and 60 µs). As observed, temperature increased with processing time at all the investigated conditions, being slower at the beginning and then becoming linear. The heating was faster with larger pulse widths and higher electrical conductivities of the treatment medium.

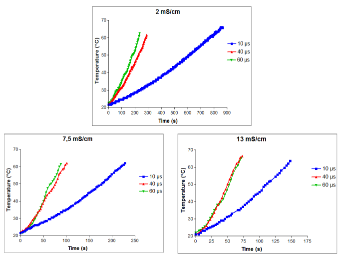


Figure 1. Heating curves of different NaCl water solutions of 2.0, 7.5 and 13.0 mS/cm applying PEF pulses of different width.

Table 1 summarizes the obtained results from Figure 1. It is indicated the number of pulses and the time required to heat the solutions from 20° to 60°C with PEF at the different investigated conditions. From these data, the temperature increase applied per pulse and per second (heating rate), and the frequency of pulses were calculated.

Heating-up rates ranging from 0.052 to 0.678 ºC/s were obtained in water of conductivities of 2 to 13 mS/cm, respectively. Higher rates were obtained the longer the pulse width and the higher the electrical conductivity. Pulse frequency was constant (around 345 Hz) at all treatment conditions.

Table 1. Heating rates for different PEF treatment conditions applied in media of distinct electrical conductivities with NutriPulse E-Cooker.

Conductivity (mS/cm)	Width (µs)	Nº pulse (20-60ºC)	Time (s) (20-60ºC)	ΔT/1000pulse (°C)	Heating rate (ºC/s)
2.0	10	265,000	766	$0.145\pm5.509\cdot10^{-3}$	0.052
2.0	40	97,000	284	$0.392\pm3.010\cdot10^{-2}$	0.141
2.0	60	77,000	227	$0.474\pm1.896\cdot10^{-2}$	0.176
7.5	10	77,000	221	$0.500\pm1.896\cdot10^{-2}$	0.181
7.5	40	35,000	101	1.100 ± 0.209	0.396
7.5	40	35,000	101	$1.100\pm4.171\cdot10^{-2}$	0.396
7.5	60	29,000	85	$1.328\pm5.034\cdot10^{-2}$	0.471
13.0	10	47,000	135	$0.819\pm3.106\cdot10^{-2}$	0.296
13.0	40	22,000	63	$1.795\pm6.636\cdot10^{-2}$	0.635
13.0	60	20,000	59	1.925 ± 0.219	0.678

To determine the influence of the studied parameters and to estimate the temperature increment after treatments applied with NutriPulse E-Cooker, a mathematical equation (**Eq. 1**) was obtained using multiple regression tools:

$$\Delta T = -2.35 + 3.70\cdot10^{-5}C*P + 2.47\cdot10^{-6}P*W + 2.52\cdot10^{-6}C*P*W - 2.01\cdot10^{-4}C*W^2 \quad \text{(Eq. 1)}$$

where *C* was the electrical conductivity, *P* was the number of applied pulses, and *W* was the pulse width. In order to show the goodness of the fit of the equation, values of 0.980, 0.980, and 1.797 were obtained for R^2, R^2-adj and RMSE, respectively.

The developed equation enabled to predict the temperature increase of different liquid food products when applying PEF treatments. **Table 2** shows the goodness of the predictions when comparing predicted and experimental values.

Table 2. R^2, RMSE, A_f and B_f values obtained when comparing experimental and predicted values with Eq. 1 when applying PEF treatments in different food products.

Food	R^2	RMSE	B_f	A_f
Skim Milk	0.942	3.962	0.987	1.076
Whole Milk	0.972	7.541	0.878	1.166
Chicken broth	0.889	6.003	0.955	1.129
Orange juice	0.958	9.258	0.860	1.199
Tomato soup	0.921	10.849	0.827	1.242

In a second step, the heating uniformity throughout the volume of different treated products was investigated when applying PEF treatments of different pulse width. Heating curves were obtained by measuring the temperature in the bottom (1 cm), middle and upper (1 cm from the top) area of the treatment chamber (**Figure 2**).

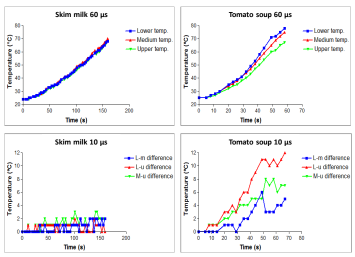


Figure 2. Evolution of the temperature in different zones of the treatment chamber when applying PEF treatments of distinct pulse width.

As observed, heating was more uniform when longer pulses were applied. The largest differences in temperature were observed in tomato soup probably due to its high viscosity. However in this case, the maximum variation in temperature was only of 6ºC.

Finally, heating curves for different food products were compared with the ones obtained with an induction cooktop. **Table 3** shows the RMSE of the temperature differences between two points of the treated liquid when heated with an induction cooktop at the maximum power and with NutriPulse (60 µs). As observed, RMSE were lower with NutriPulse mainly for high viscosity products like tomato soup (temperature differences of 6ºC and 14-50ºC were measured, respectively), indicating higher heating uniformity. Also in these products, heating rate was faster when PEF were applied (**Figure 3**).

Table 3. Root Mean Square Error (RMSE) between measured values in two different points of the heated product with NutriPulse E-Cooker and in an induction cooktop (2000W).

Product	Heating system	RMSE
Skim milk	Induction cooktop	35,42
	NutriPulse	4,04
Chicken broth	Induction cooktop	11,46
	NutriPulse	7,86
Tomato soup	Induction cooktop	739,17
	NutriPulse	82,67

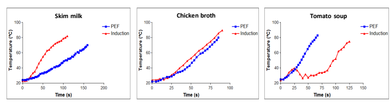


Figure 3. Temperature evolution of different food products heated with NutriPulse E-cooker or with an induction cooktop at maximum power.

CONCLUSIONS

- **Results indicated that NutriPulse® E-Cooker® could be interesting for a fast and uniform heating when cooking, mainly in products of high viscosity and electrical conductivity.**
- **The highest heating rates were obtained when wider pulses were applied, in media of high electrical conductivity.**
- **A mathematical equation to predict the temperature of the treated product with NutriPulse® E-Cooker® in terms of electrical conductivity, number of pulses and pulse width was developed and validated in different liquid food products.**

ACKNOWLEDGEMENTS:

RTC-2014-1847-6. MINECO.

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