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EXPERIMENTAL ANALYSIS OF MONOAXIAL AND BIAXIAL PULSED ELECTRIC FIELD TREATMENT CHAMBERS FOR FOOD PROCESSING

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ABSTRACT

Except for the "Co-field" electrodes, the majority of PEF treatment chambers, used in food processing experiments, are constituted of two parallel metal electrodes energized by a pulsed voltage. The electric field lines which are perpendicular to the electrodes are monoaxial and oriented almost in only one direction. The objective of the present work is an experimental comparative analysis between such treatment chamber (TC1) to a similar one but comprising four identical metal plates placed on the side walls of a square treatment chamber (TC2). For this latter, each pair of the adjacent metal plates form one electrode, the electric field lines being biaxial and oriented in two directions. The chamber made of Plexiglas has a square paralelipedic shape of dimensions 6x10x10 cm^3, in which are placed either two (TC1) or four (TC2) vertical stainless steel electrodes, of dimensions 6x10 cm^2. The experimental analysis was made using a classic pulse voltage generator, by measuring the mass of PEF pretreated extracted juice from beet and the amount of betanine using a spectrophotometer. The obtained results, using the methodology of experimental designs, have shown that the TC2 model is more efficient, because higher quantities of juice and betanine were obtained up to 25% more with an energy saving of nearly 90%.

1. Introduction

Pressing and pulsed electric field (PEF) treatments are widely combined for extraction of juice. Several studies confirmed the positive effect of PEF treatment on both juice yield and its quality (Akinlaja, 1998; Bazhal, 2003; Gachovska, 2006; Grishko, 1991; Nabil, 2010). Moreover, inactivation of microorganisms and acceleration of the drying process using PEF technique were demonstrated (Qian, 2015; Raluca, 2010). Furthermore, the extraction rates of many compounds were increased in the food industry (El-Belghiti, 2005).

Food product is placed in the treatment chamber, where two electrodes are connected together with a nonconductive material to avoid electrical flow from one to the other. There are two types of treatment chambers: static and dynamic. In both cases, high voltage electrical pulses are applied to the electrodes, which then conduct the high intensity electrical pulse to the product placed between the two electrodes, to achieve membrane electroporation (Humberto, 2007; Maged, 2012). In the static chambers only a given volume can be processed at once, for experimental applications. A dynamic chamber enables continuous processing, in accordance with the requirements of industrial application (Ratna, 2010).

While the parallel plate treatment chamber consists of two stainless steel plate electrodes and an insulator, the cofield chambers have two stainless steel tubes separated by an insulator, the electric field and the food flow concurrently (Lebovka, 2002). The parallel plate treatment chamber allows the uniformity of the electric field, and thus a homogeneous treatment, while co-field electric chambers which are more commonly used provide better fluid dynamics characteristics. The coaxial chamber is basically composed of an inner cylinder surrounded by an outer annular cylindrical electrode that allows food to flow between them. Although the coaxial treatment chambers are simpler, their cross-section which permits the flow of the food is narrower, and since some foods contain solid particles, this may cause blockage of the flow. This is not the case with co-field chambers which allow a continuous flow without risk of blocking even for foodstuffs with large particles (Kambiz, 2009; Nicolas, 2006).

For classic PEF treatment chambers with two parallel metal electrodes, the electric field lines which are perpendicular to the electrodes are monoaxial and oriented in only one direction. The objective of the present work is an experimental comparative analysis between such treatment chamber to a similar one but comprising four identical metal plates placed on the side walls of a square treatment chamber. For the latter, each pair of the adjacent metal plates forms one electrode.

2. Materials and methods

2.1. Experimental setup

The experimental setup used in the present work is composed of several components, comprising a high DC voltage source, an energy storage capacitor, a spark gap switch and a treatment chamber (Figure 1). A DC high voltage supply (Spellman 40 kV, 9 mA) charges the bank of capacitors until producing the spark gap's breakdown, causing an abrupt voltage (shock) applied to the load (treatment chamber where the sample is disposed). The storage element is composed of three sets of five series capacitors (2 µf, 2 kV), with the possibility to reach a maximum voltage of 10 kV and a total capacitance of 1.2 µF (Figure 2).

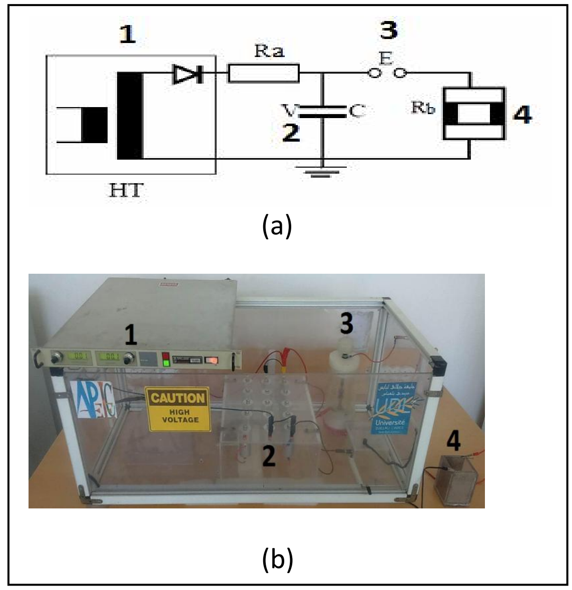


Figure 1. The pulse generator.
a) Descriptive schematic of the setup;
b) The photography of the setup
1- HV DC power supply, 2-Set of capacitors,
3- Spark gap switch, 4-Treatment chamber

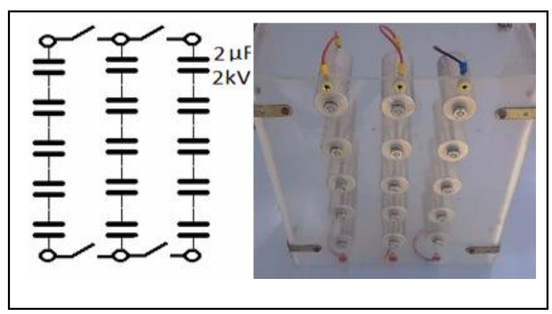


Figure 2. The bank of capacitors.
a) Descriptive schematic,
b) The photography of the capacitors bank

Two square parallelipedic treatment chambers made of Plexiglas, of dimensions 6x6x10 cm^3, in which are placed vertical stainless steel electrodes, were used in this work. The model TC1 comprises two parallel and opposite electrodes of dimensions 6x10 cm^2, while the model TC2 is constituted of four electrodes (Figure 3). For this latter, each pair of the adjacent metal plates form one electrode.

The volume of both treatment chambers is 192.3 ml.

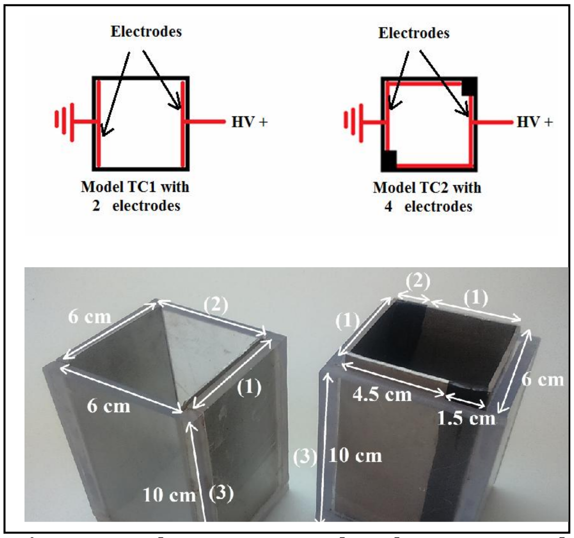


Figure 3. The treatment chambers TC1 and TC2; 1: Electrode 2: Insulating 3: Plexiglas

2.2. Materials and method

Beets were crushed with a household robot to obtain a homogeneous leg. The sample was held in a closed container to prevent evaporation before use. A beet paw sample of mass 80 g was used for each experiment. After PEF treatment, an extraction step was achieved using an extraction chamber and a hydraulic pressing machine (Mega, 15 tons). The PEF treated extracted juice was then analyzed by measuring both its mass using an electronic balance of 0.1 mg precision and the betanine amount using a spectrophotometer (Optizen *200 plus*) for λ= 530 nm.

All experiments were performed while maintaining following factors at constant values: pulse repetition frequency f = 1 Hz, extraction pressure P = 50 kg/cm^2, total pressing duration t = 300 s and the inter-electrodes gap d= 60 mm.

The methodology of the experimental designs makes it possible to determine the number of experiments to be achieved according to a well-defined objective, to analyze several factors simultaneously, to reduce dispersion related to measurements, to appreciate the effects of coupling between factors and finally to evaluate the respective influence of the factors and their interactions (Frigon, 1996; Taguchi, 1987). Before starting the experiments, we need to opt for the most suitable design which can model the process with maximum precision. The Composite Centered Faces design (CCF), which gives quadratic models, was adopted in the present work.

3. Results and discussions

The three following factors were considered in this work: the applied voltage V (kV), the number of pulses (n) and the pulse duration T (µs). The pulse duration is determined by the corresponding value of the capacitance, as shown in Table 1. The pulse duration was deduced from the corresponding oscillogram for a determined value of the capacitance, as shown for example in Figure 4 for C= 0.8 µF. The three following factors were considered in this work: the applied voltage V (kV), the number of pulses (n) and the pulse duration T (µs). The pulse duration is determined by the corresponding value of the capacitance, as shown in Table 1. The pulse duration is calculated at 37% of the amplitude of the electric field and deduced from the corresponding oscillogram for a determined value of the capacitance, as shown for example in Fig.4 for C= 0.8 µF.

Table 1: Values of the pulse duration according to corresponding capacitance

C (µF)	0.2	0.4	0.5	0.8	1.2
T (µs)	8	20	24	40	60

Moreover, the mass of extracted juice m (g), the amount of betanine expressed in terms of absorbance and the energy (W = ½ n C V^2) were considered significant to be considered as the response of the model. Absorbance (Abs) is the measurement of the amount of light absorbed by a given material for a determined wavelength using a spectrophotometer which is proportional to the coloration rate. Higher is the absorbance greater is the concentration of betanine substance.

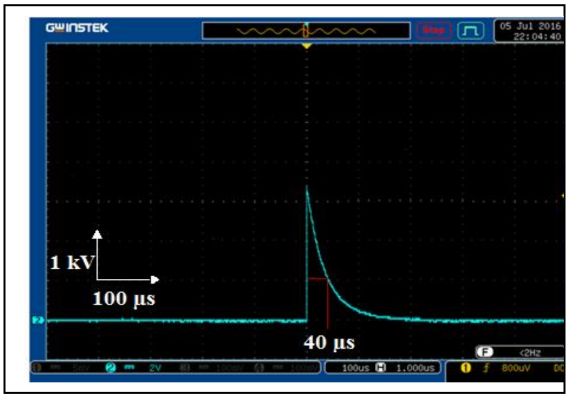


Figure 4. Pulse shape of duration T= 40 µs obtained for C=0.8 µF

A set of three preliminary experiments was performed. For each experiment, a factor was varied while the others were kept constant. The purpose of these preliminary experiments is to determine the variation domain for each factor in view of the following step by performing a CCF experimental design, which should enable the modeling and optimization of the PEF treated extraction process.

The obtained results of the preliminary experiments are plotted in Figs.5-7, representing the variation of the extracted juice mass *m* as function of the voltage *V*, the pulses number *n* and the pulse duration *T* respectively. Moreover, the variation of the absorbance is shown in Figs.8-10 for both treatment chambers.

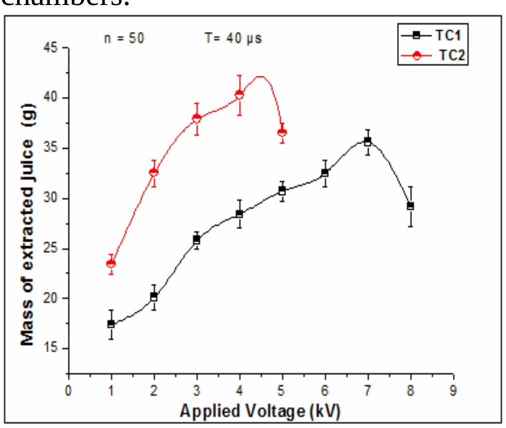


Figure 5. Evolution of the extracted beet juice mass according to the voltage (n=50, T=40µs)

According to the obtained results, following variation domains of each factor were selected, corresponding to the best limits giving maximum outcome:

Model TC1: V_{min}= 6 kV &V_{max}= 8 kV; n_{min}= 80 & n_{max}= 120; T_{min}= 20 µs & T_{max}= 60 µs

Model TC2: V_{min}= 3 kV &V_{max}= 5 kV; n_{min}= 60 & n_{max}= 100; T_{min}= 8 µs & T_{max}= 40 µs

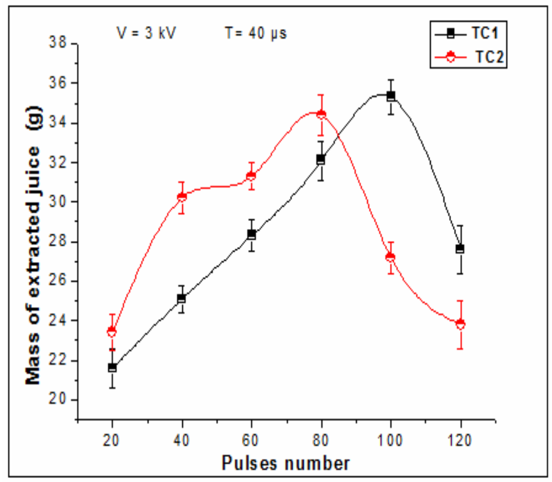


Figure 6. Evolution of extracted beet juice mass according to the pulses number (V=3kV, T= 40 µs)

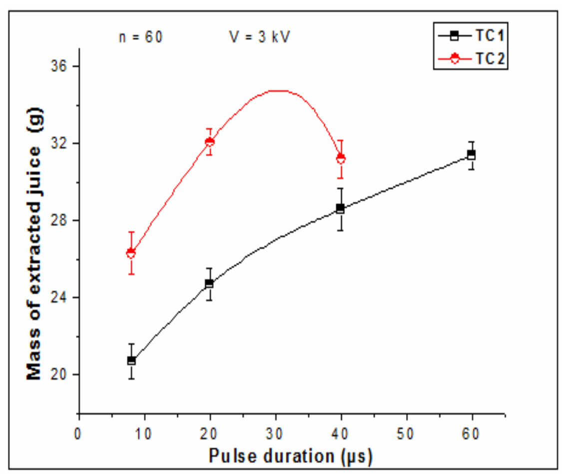


Figure 7. Evolution of extracted beet juice mass according to the pulse duration (V=3kV, n=60)

The following step is the modeling of the process using the design of experiments methodology, by performing two CCF designs for both TC1 and TC2 chambers (Tables 2 and 3).

Predictive and descriptive quality of the models are satisfactory since values of criteria $Q^2$and R^2 are close to the unit, leading to validated mathematical models for both chambers.

The mathematical model of the responses considered for optimization, which are the mass of extracted juice, the absorbance and the consumed energy were obtained with MODDE 5.0 (MODDE. 1999), as shown in Table 4.

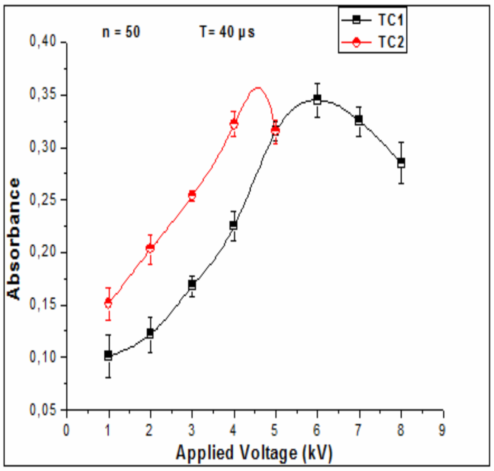


Figure 8. Evolution of the juice absorbance according to the voltage (n=50, T= 40 µs)

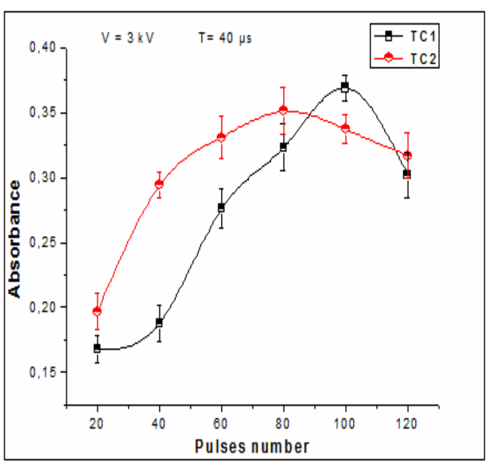


Figure 9. Evolution of the juice absorbance according to the pulses number (V=3kV, T= 40 µs)

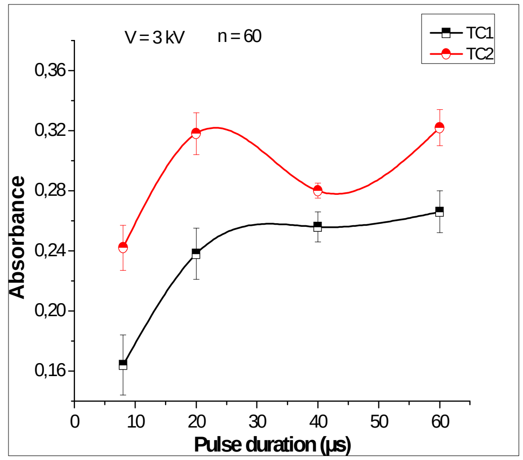


Figure 10. Evolution of the juice absorbance according to the pulse duration (V=3kV, n=60)

Table 2. Results of the CCF design experiment (TC1)

Exp N°	V (kV)	n	T (µs)	m (g)	Abs	W (J)
01	6	80	20	21.3	0.317	576
02	8	80	20	29.3	0.384	1024
03	6	120	20	24.7	0.364	864
04	8	120	20	30.3	0.395	1536
05	6	80	60	27.4	0.389	1728
06	8	80	60	32.7	0.457	3072
07	6	120	60	28.5	0.377	2592
08	8	120	60	32.8	0.383	4608
09	6	100	40	25.2	0.386	1440
10	8	100	40	32.8	0.415	2560
11	7	80	40	31.3	0.371	1568
12	7	120	40	31.4	0.373	2352
13	7	100	20	26.6	0.355	980
14	7	100	60	29.9	0.388	2940
15	7	100	40	30.5	0.385	1960
16	7	100	40	30.5	0.382	1960
17	7	100	40	30.5	0.384	1960

Table 3. Results of the CCF design experiment (TC2)

Exp N°	V (kV)	n	T (µs)	m (g)	Abs	W (J)
01	3	60	8	34.3	0.376	54
02	5	60	8	39.1	0.482	150
03	3	100	8	36.2	0.456	90
04	5	100	8	39.5	0.515	250
05	3	60	40	38.4	0.488	216
06	5	60	40	40.1	0.522	600
07	3	100	40	39.2	0.492	360

08	5	100	40	39.5	0.495	1000
09	3	80	24	37.7	0.474	180
10	5	80	24	41.5	0.543	500
11	4	60	24	35.9	0.404	240
12	4	100	24	36.8	0.422	400
13	4	80	8	37.7	0.53	128
14	4	80	40	39.8	0.577	512
15	4	80	24	37.6	0.449	320
16	4	80	24	37.2	0.471	320
17	4	80	24	37.4	0.459	320

Table 4. Mathematical model of the responses

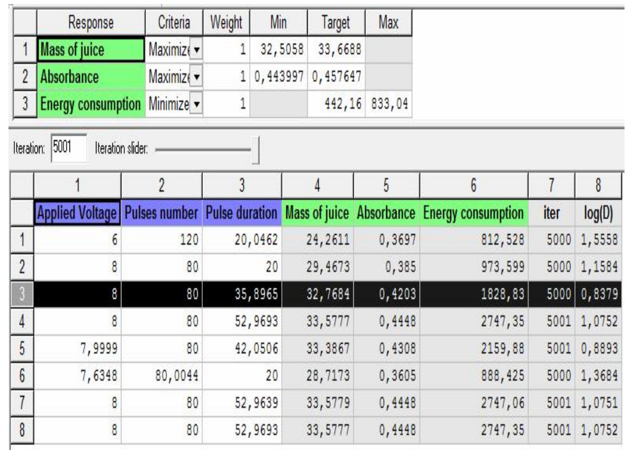
	TC1			TC2		
	Mass (g)	**Abs**	**W (J)**	**Mass (g)**	**Abs**	**W (J)**
Constant	30.3	0.382	1960	37.76	0.47	320
V	3.08	0.020	560	1.39	0.02	160
n	0.56	-0.00	398.4	0.34	0.01	84
T	1.91	0.01	996	1.02	0.02	201.6
V*V	-1.19	0.02	40	1.56	0.01	20
n*n	1.15	-0.01	0	-1.68	-0.07	0
T*T	-1.94	-0.01	0	0.71	0.06	0
V*n	-0.42	-0.01	112	-0.36	-0.01	40
V*T	-0.49	-0.09	280	-0.76	-0.01	96
n*T	-0.4	-0.01	200	-0.26	-0.01	51

The software offers the possibility to identify the optimal values of the factors which should give the highest amount of extracted juice m and Absorbance Abs for the smallest power consumption. It contains an optimization routine that is capable of simultaneously processing several responses, affected by different weighting coefficients. MODDE.05 has an optimizer tool, which proposes the optimal values of factors by maximizing both m and Abs and minimizing the energy.

According to this model, the optimum of the process (i.e., maximizing the mass m and the absorbance Abs and minimizing the energy) should be obtained:

For model TC1: V= 8 kV, n = 80 and T = 35.9 µs corresponding to m = 32.7 g, Abs= 0.48 and P =1828.8 J (Figure 11).

For Model TC2: V = 5 kV, n = 70 and T = 8 µs corresponding to m = 40.68 g, Abs= 0.5 and P =167.9 J (Figure 12).

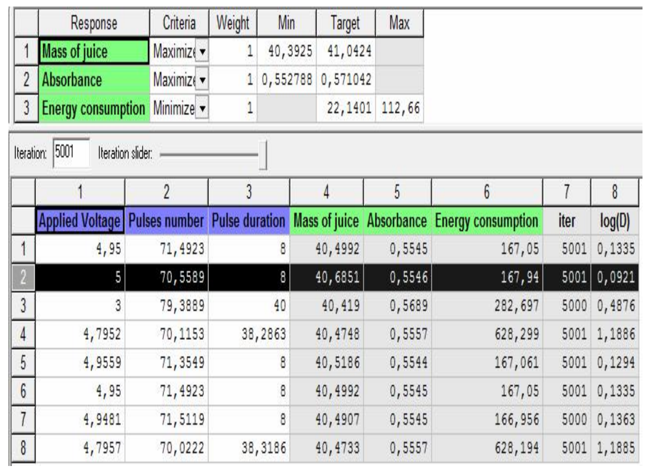


	Response	Criteria	Weight	Min	Target	Max
1	Mass of juice	Maximize	1	32,5058	33,6688	
2	Absorbance	Maximize	1	0,443997	0,457647	
3	Energy consumption	Minimize	1		442,16	833,04

Iteration: 5001 Iteration slider:

	1	2	3	4	5	6	7	8
	Applied Voltage	Pulses number	Pulse duration	Mass of juice	Absorbance	Energy consumption	iter	log(D)
1	6	120	20,0462	24,2611	0,3697	812,528	5000	1,5558
2	8	80	20	29,4673	0,385	973,599	5000	1,1584
3	8	80	35,8965	32,7684	0,4203	1828,83	5000	0,8379
4	8	80	52,9693	33,5777	0,4448	2747,35	5001	1,0752
5	7,9999	80	42,0506	33,3867	0,4308	2159,88	5001	0,8893
6	7,6348	80,0044	20	28,7173	0,3605	888,425	5000	1,3684
7	8	80	52,9639	33,5779	0,4448	2747,06	5001	1,0751
8	8	80	52,9693	33,5777	0,4448	2747,35	5001	1,0752

Figure 11. Optimal values of the factors proposed by MODDE 5.0 for model



	Response	Criteria	Weight	Min	Target	Max
1	Mass of juice	Maximize	1	40,3925	41,0424	
2	Absorbance	Maximize	1	0,552788	0,571042	
3	Energy consumption	Minimize	1		22,1401	112,66

Iteration: 5001 Iteration slider:

	1	2	3	4	5	6	7	8
	Applied Voltage	Pulses number	Pulse duration	Mass of juice	Absorbance	Energy consumption	iter	log(D)
1	4,95	71,4923	8	40,4992	0,5545	167,05	5001	0,1335
2	5	70,5589	8	40,6851	0,5546	167,94	5001	0,0921
3	3	79,3889	40	40,419	0,5689	282,697	5000	0,4876
4	4,7952	70,1153	38,2863	40,4748	0,5557	628,299	5001	1,1886
5	4,9559	71,3549	8	40,5186	0,5544	167,061	5001	0,1294
6	4,95	71,4923	8	40,4992	0,5545	167,05	5001	0,1335
7	4,9481	71,5119	8	40,4907	0,5545	166,956	5000	0,1363
8	4,7957	70,0222	38,3186	40,4733	0,5557	628,194	5001	1,1885

Figure 12. Optimal values of the factors proposed by MODDE 5.0 for model TC2

The obtained results show that the second model with four electrodes is more efficient, because better results in terms of juice mass and absorbance were obtained with less energy. This is explained by the increase of the number of field lines for the model TC2, thus the food product is exposed to more electric field lines than the simple configuration of the model TC1. However, simulation and electric field calculation for the two configurations should be useful for understanding the difference between the two models.

4. Conclusions

The present paper describes an experimental comparative analysis between two square treatment chambers of same dimensions but having either two or four metal electrodes placed on the side walls. For this latter, each pair of the adjacent metal plates form one electrode. The experimental analysis was made by measuring the mass of PEF pretreated extracted juice from beet and the amount of betanine using a spectrophotometer. The obtained results, using the methodology of experimental designs, have shown that the second model with four electrodes is more efficient, because higher quantities of juice and betanine were obtained up to 25% more with an energy saving of nearly 90%.

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