Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2017) 25: 4149 – 4159

doi:10.3906/elk-1611-42

Study and analysis of new pulsed electric field treatment chamber configurations for food extraction

Yassine BELLEBNA[1,*], **Hamza BERMMAKI**[2], **Abdelkader SEMMAK**[2], **Abdelkader CHAKER**[3], **Amar TILMATINE**[2]

[1]Department of Electrical Engineering, National Polytechnic School of Oran, Oran, Algeria
[2]Department of Electrical Engineering, APELEC Laboratory, Djillali Liabes University of Sidi Bel-Abbes, Sidi Bel-Abbes, Algeria
[3]Department of Electrical Engineering, SCAMRE Laboratory, National Polytechnic School of Oran, Oran, Algeria

Received: 04.11.2016 • **Accepted/Published Online:** 23.04.2017 • **Final Version:** 05.10.2017

Abstract: In all treatment chamber (TC) models used in industry and in research laboratories, the product to be treated is placed in one volume unit delimited between two electrodes energized by a pulsed voltage and the electric field lines are monoaxial and perpendicular to the electrodes. The objective of this paper is to perform an experimental analysis, based on the pulsed electric field-treated beet juice extraction efficiency, of two TC new configurations. The first model is constituted of one, two, or three parallel PEF units comprising several alternate ground-HV electrodes. The treatment chambers made of Plexiglas have a square parallelepipedic shape, in which are placed two (TC_1), three (TC_2), or five (TC_3) vertical and parallel stainless steel electrodes. The second biaxial treatment chamber model is constituted of four identical stainless steel electrodes placed on the side walls of a square shape treatment chamber made of Plexiglas of the same dimensions as the first model. For this latter, each pair of adjacent metal plates forms one electrode. The obtained results expressed in terms of extracted juice mass, betanin concentration by measuring the absorbance, and energy consumption have shown that the models TC_3 and TC_4 are much better due to the higher values of the electric field for the same applied voltage.

Key words: Electrode, treatment chamber, pulsed electric field (PEF), membrane, high voltage, cell, electroporation

1. Introduction

Mechanical expression (hydraulic pressing) is widely used in solid–liquid separation processes for extraction of fruit juice and vegetable oils, dewatering of fibrous materials, etc. [1]. The efficiency of such processes can be increased by raw material plasmolysis, cellular damage, or permeabilization prior to its expression [2]. Different methods are usually employed to increase the degree of raw material plasmolysis: heating, osmotic drying, freezing dehydration, alkaline breakage, and enzymatic treatment [3–7].

Pulsed electric field (PEF) treatment was also used for cellular material plasmolysis (known as electroplasmolysis or electroporation). Electroporation has proven useful for juice yield intensification and improving the product quality in juice production [8–11], processing of vegetable and plant raw materials [12], food processing for pasteurization [13], winemaking [14], and sugar extraction [15].

The food product is placed in the treatment chamber, where two electrodes are connected together with

*Correspondence: yassinebellebna@yahoo.fr

a nonconductive material to avoid electrical flow from one to the other. In both static and dynamic chambers, high voltage electrical pulses are applied to the electrodes, which then conduct the high intensity electrical pulse to the product to achieve membrane electroporation [16–18]. Static chambers, where only a given volume can be processed at once, are for experimental applications. However, dynamic chambers enable continuous processing, in accordance with the requirements of industrial applications [19].

Since the parallel plate treatment chamber consists of two stainless steel parallel plate electrodes separated by an insulator, the uniformity of the electric field allows homogeneous treatment. However, for the co-field chambers, although the electric field lines are nonuniform, they are more commonly used due to their better fluid dynamic characteristics [20].

Nowadays, despite the fact that the treatment chambers currently used give good performances, the reduction of electric energy consumption remains a major challenge in PEF technology. The main objective of this work is to show that it is possible to save more energy by using different treatment chambers and also have a significant quantity of beet juice extracted with a good quality of betanin.

For classic parallelepipedic PEF treatment chambers constituted of one treatment unit comprising two parallel metal plates [21,22], the electric field between the electrodes is constituted of monoaxial straight lines perpendicular to electrodes. The objective of the present work is to analyze two new configurations of such a model.

The first configuration comprises two or four parallel units (TC_2, TC_3), consisting of several alternate ground-HV electrodes, in order to increase the processing flow rate and save more energy. The second configuration is constituted of four identical metal plates placed on the side walls of a similar square parallelepipedic treatment chamber (TC_4). For this latter, each pair of adjacent metal plates forms one electrode.

2. Materials and methods

2.1. Materials

Fresh red beets, of average mass 60 g each, were used. After sorting and cleaning operations, a homogeneous mash was obtained using a domestic food processor (Thomson, THMX05736 Model). A beet raw 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, Spain).

The treatment chamber for extraction consisted of an insulated cylinder made of plastic (Teflon, PTFE) of length 140 mm and diameter 70 mm (Figure 1). The electrodes are constituted by a cylindrical plunger and a disc base of the same diameter, 70 mm, having a rigid structure for juice pressing operation, both made of stainless steel. Extracted juice was filtered through a stainless steel sieve placed on top of the perforated plunger. Juice extracted during pressing was collected in a plastic collector placed under the treatment chamber. The volume of the treatment chamber was 192.3 mL. For all experiments, the same treatment chamber was used for both pressing steps.

Just after PEF treatment, the filled treatment chamber was pressed until a defined pressure of 50 kg/cm^2 and was then held at this pressure for 5 min, which was measured with a chronometer and it was kept constant for all the experiments. The PEF-treated extracted juice was then analyzed by measuring both its mass using an electronic balance of 0.1-mg precision and the betanin concentration by measuring the absorbance of beet juice using a spectrophotometer (Optizen 200 plus, Mecasys Co, Ltd) at $\lambda = 530$ nm.

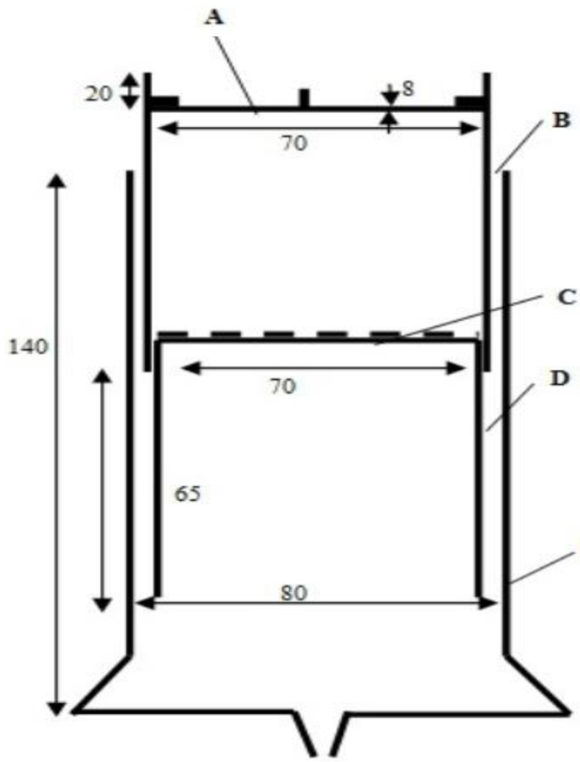


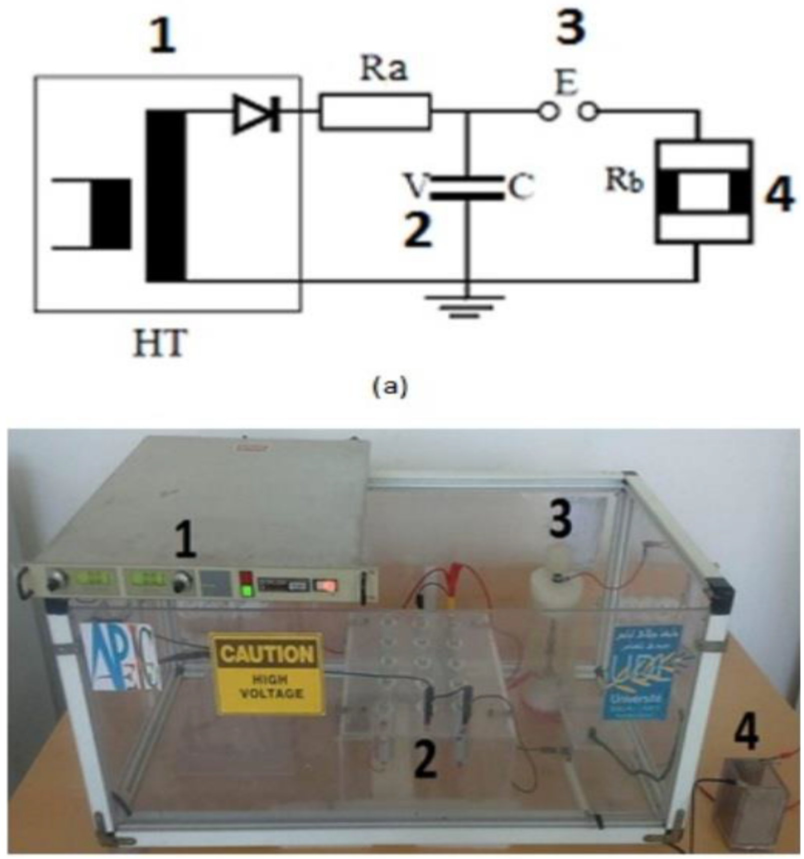
Figure 1. Schematic description of the treatment chamber for extraction step (all dimensions are in mm). A – Stainless steel disk, B – Teflon cylinder, C – Stainless steel sieve, D – Perforated stainless steel plunger, E – Plastic container for the collection of extracted juice.

2.2. Methods

All experiments were performed while maintaining the following factors at constant values: pulse repetition frequency (f) = 1 Hz, extraction pressure (P) = 50 kg/cm^2, total pressing duration (t) = 5 min, and the interelectrode gap (d) = 60 mm.

The experimental setup for the PEF treatment used in the present work is composed of a couple of components, comprising a high DC voltage source, an energy storage capacitor, a spark gap switch, and a treatment chamber (Figure 2). A DC high voltage supply (Spellman 40 kV, 9 mA, Spellman High Voltage Electronics Corporation) 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.

Two configurations of the square parallelepipedic treatment chamber model were developed and compared with the classic chamber TC_1 comprising two parallel metal electrodes (Figure 3). The models TC_2 and TC_3 comprise two and four parallel units, consisting of three and five alternate ground-HV electrodes, respectively (Figure 4). The model TC_2 is constituted of two units comprising three electrodes: one central HV electrode and two outside ground electrodes, while the model TC_3 is constituted of four units comprising five alternate HV-ground electrodes: two HV electrodes and three ground electrodes. The second new configuration (model TC_4) is constituted of four identical metal plates placed on the side walls of a similar square parallelepipedic treatment chamber. For the latter, each pair of adjacent metal plates forms one electrode (Figure 5).



(a)

(b)

Figure 2. 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.

All the models are parallelepipedic treatment chambers made of Plexiglas, with the dimensions of 6 × 6 × 10 cm^3, in which are placed vertical stainless steel electrodes with the same dimensions of 6 × 10 cm^2. The volume of all the treatment chambers is 360 mL.

2.3. Measurement

An experimental investigation was performed to compare PEF treatment efficiency between all the models. For each model, the influence of the applied voltage (V, kV), the pulses number (n), and the pulse duration (T, μs) was analyzed. The pulse duration was determined by the corresponding value of the capacitance C as follows:

For C = 0.2 μF, T = 8 μs, for C = 0.4 μF, T = 20 μs, for C = 0.8 μF, T = 40 μs, and for C = 1.2 μF, T = 60 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 6 for C = 0.8 μF.

Moreover, the mass of extracted juice (m) (in g), the amount of betanin expressed in terms of absorbance (A), and the energy $(W) = \frac{1}{2} n C V^2$ were considered significant to be considered as the responses of the process.

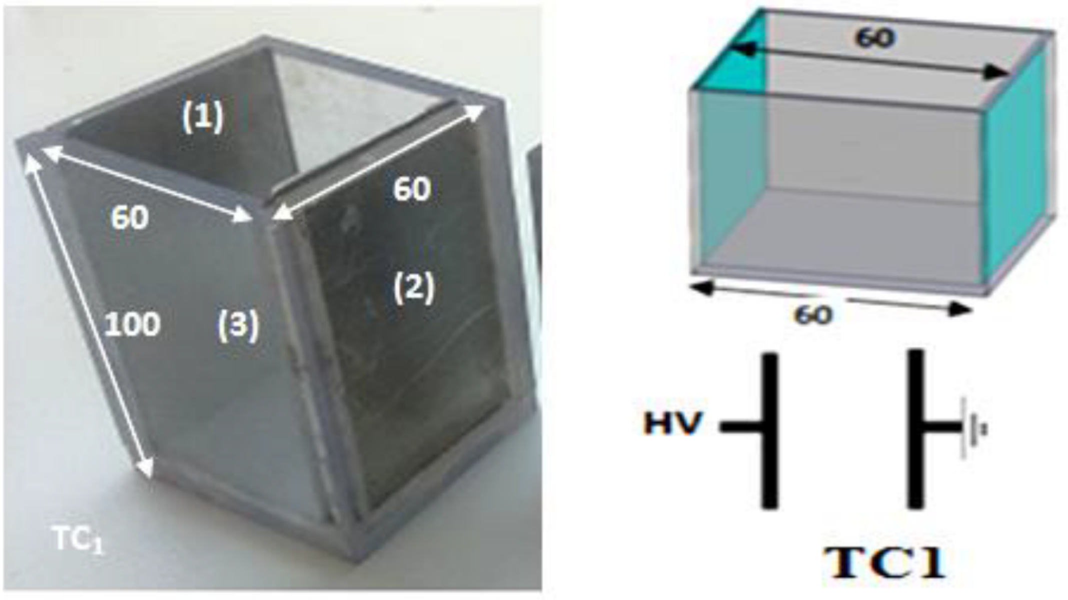


Figure 3. The treatment chamber TC_1 model (dimensions in mm). 1: HV electrode. 2: Ground electrode. 3: Plexiglas wall.

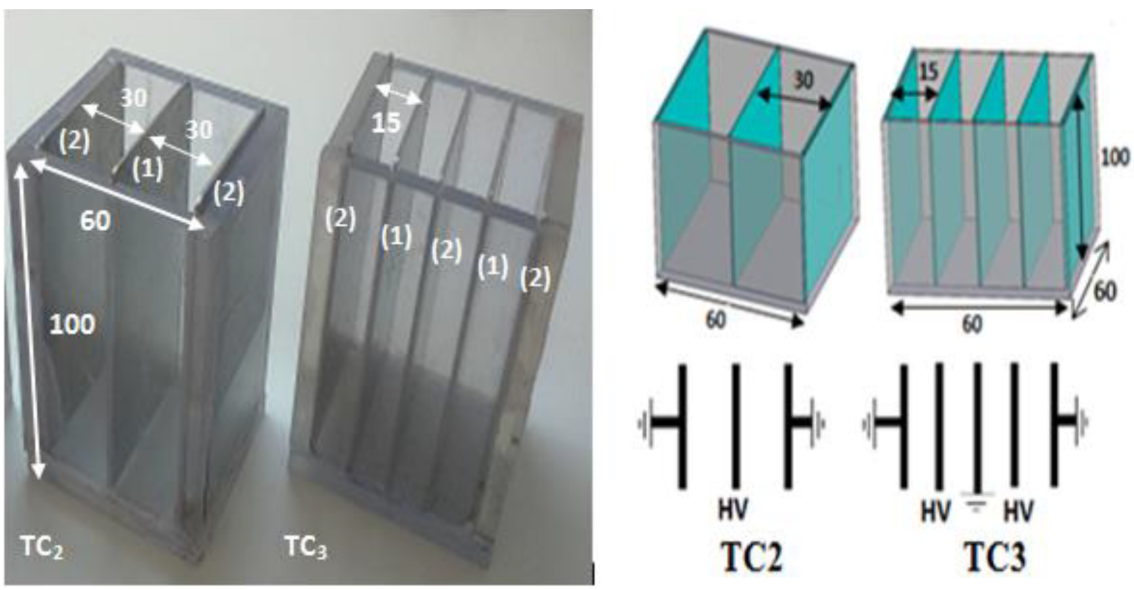


Figure 4. The treatment chambers TC_2 and TC_3 model (dimensions in mm). 1: HV electrode. 2: Ground electrode. 3: Plexiglas wall.

In addition to the extraction efficiency, the comparison between the four models should be performed in terms of energy consumption, by evaluation of energy saving using the following relation:

$$W_{Saving} = \frac{W_{TC1} - W_{TCi}}{W_{TC1}}$$

W_{TC1}: Energy of TC_1.
W_{TCi}: Energy of TC_2, TC_3 or TC_4.

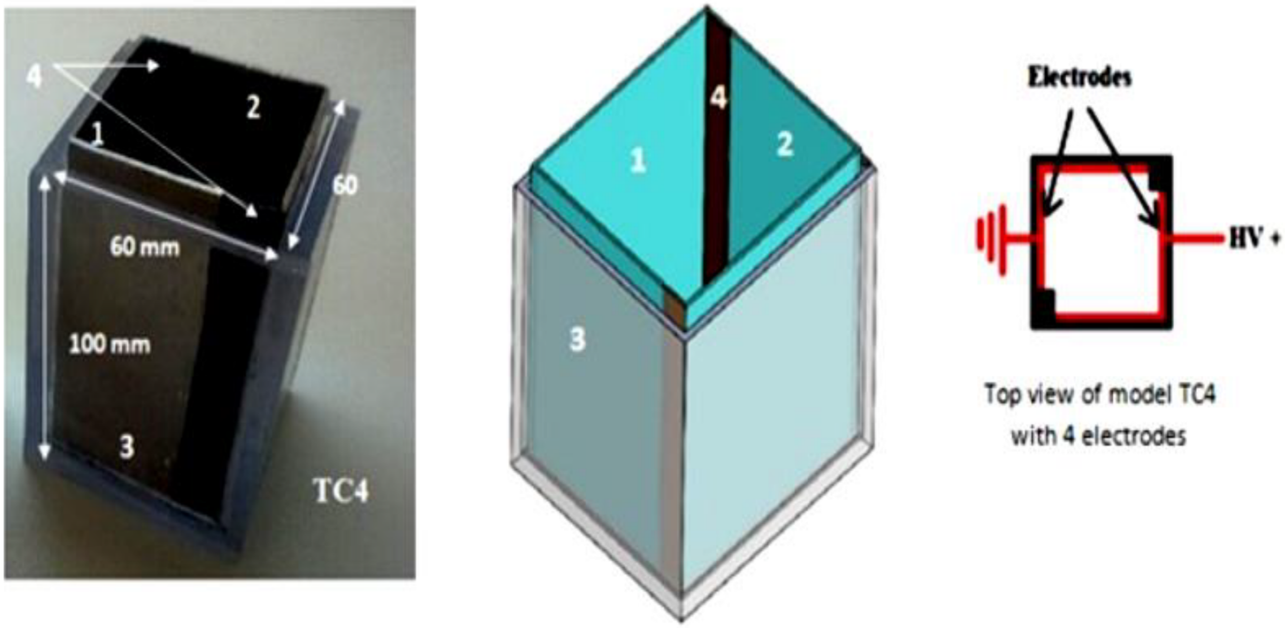


Figure 5. The treatment chamber TC_4 model (dimensions in mm). 1: HV electrode. 2: Ground electrode. 3: Plexiglas wall. 4: Insulating separator between electrodes.

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

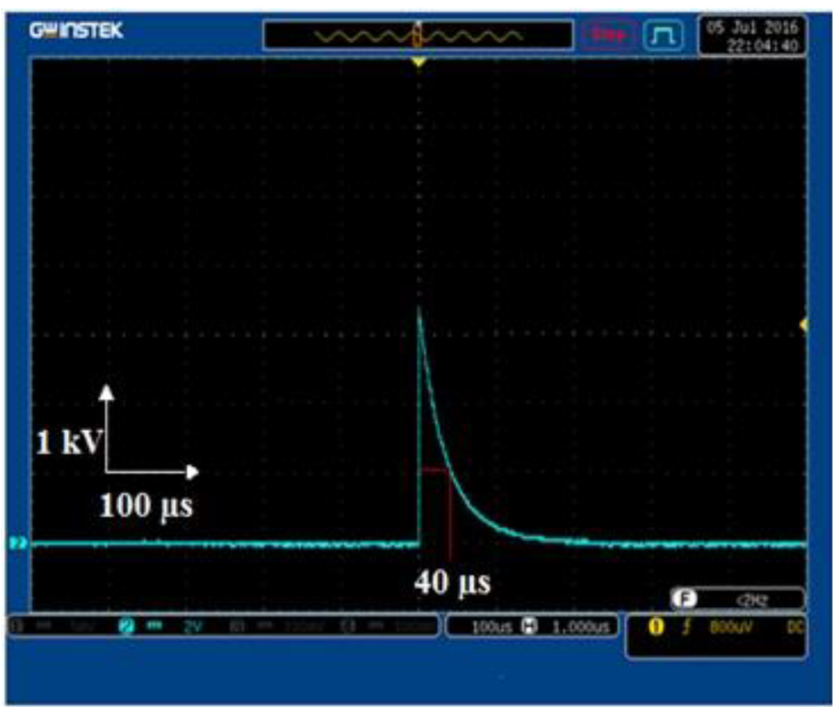


Figure 6. Pulse shape of duration T= 40 μs obtained for C = 0.8 μF.

For all the experiments described in this paper, PEF pretreatment of beet tissue using any of the TC models is followed by the application of a pressure of 50 kg/cm^2, at ambient temperature, for a total duration of 5 min. All experiments were repeated twice and the average value was considered for plotting.

3. Results and discussion

PEF treatment resulted in a significant increase in the yield of juice extraction. The obtained results showed that PEF treatment increased the quantity of extracted beet juice up to more than 90% compared with untreated one. The increase in the extracted juice was due to the new cellular structure of the plant as a result of the electroporation of the cell membrane because of an interaction with the PEF.

For all the experiments carried out in this section, for each TC model, one factor was varied while the two other factors were kept at constant values. Thus, Figure 7 represents the variation in PEF treatment efficiency, in terms of extracted juice mass (m), according to the voltage V, the pulses number n, and the pulse duration T, respectively. In the same way, in Figure 8 is represented the evolution of the absorbance (A) as function of V, n, and T, respectively.

As expected, the mass of extracted juice and the quantity of betanin obtained with a PEF-treated sample increases according to the applied voltage (Figures 7a and Figure 8a), for the four chambers. Beyond a determined value of the voltage, the effect of the PEF treatment is inversed due to "oxidation" of the product, which causes the opposite effect. However, the treatment is more efficient for models TC_2, TC_3, and TC_4 compared with the classic chamber TC_1 comprising only two electrodes. While for the model TC_1 the optimal treatment was obtained for V = 7 kV (m = 32.7 g & A = 0.384), for the other chambers greater values of m and A were obtained with lower voltage (Table 2).

Table 2. The maximal values of both the mass *m* and the absorbance *A* and the corresponding energy W obtained with each TC.

	TC_1	TC_2	TC_3	TC_4
Mass (g)	32.7	34.2	38.2	36.4
Abs (%)	0.384	0.450	0.486	0.470
W (J)	360	288	216	216

However, when comparing the models TC_2, TC_3, and TC_4, the best results of juice yield and betanin concentration were obtained with TC_3. High values of energy saving were achieved for TC_2 and TC_3. The advantage of the multiunit chambers is that for the same voltage the electric field is increased compared to the "one-unit" chamber comprising two electrodes. For example, when a voltage of 6 kV is applied, the electric field of the models TC_1, TC_2 and TC_3 is equal to 1, 2, and 4 kV/cm, respectively.

Thus, for the TC_3 and TC_4 models, the optimal treatment was obtained for V = 5 kV (m = 38.2 g & A = 0.486) and V = 5 kV (m = 36.4 g & A = 0.470), respectively.

As seen in Figures 7b and 8b, the mass of extracted juice and the quantity of betanin obtained with a PEF-treated sample increase with pulse number for the four chambers. However, the treatment was more efficient for models TC_2, TC_3, and TC_4 compared with the classic chamber TC_1. When comparing the new configuration models TC_2, TC_3, and TC_4, note that for the model TC_3 the optimal treatment was obtained for n = 60 pulses (m = 38.5 g & A = 0.606), while for the other treatment chambers smaller values of m and A were obtained.

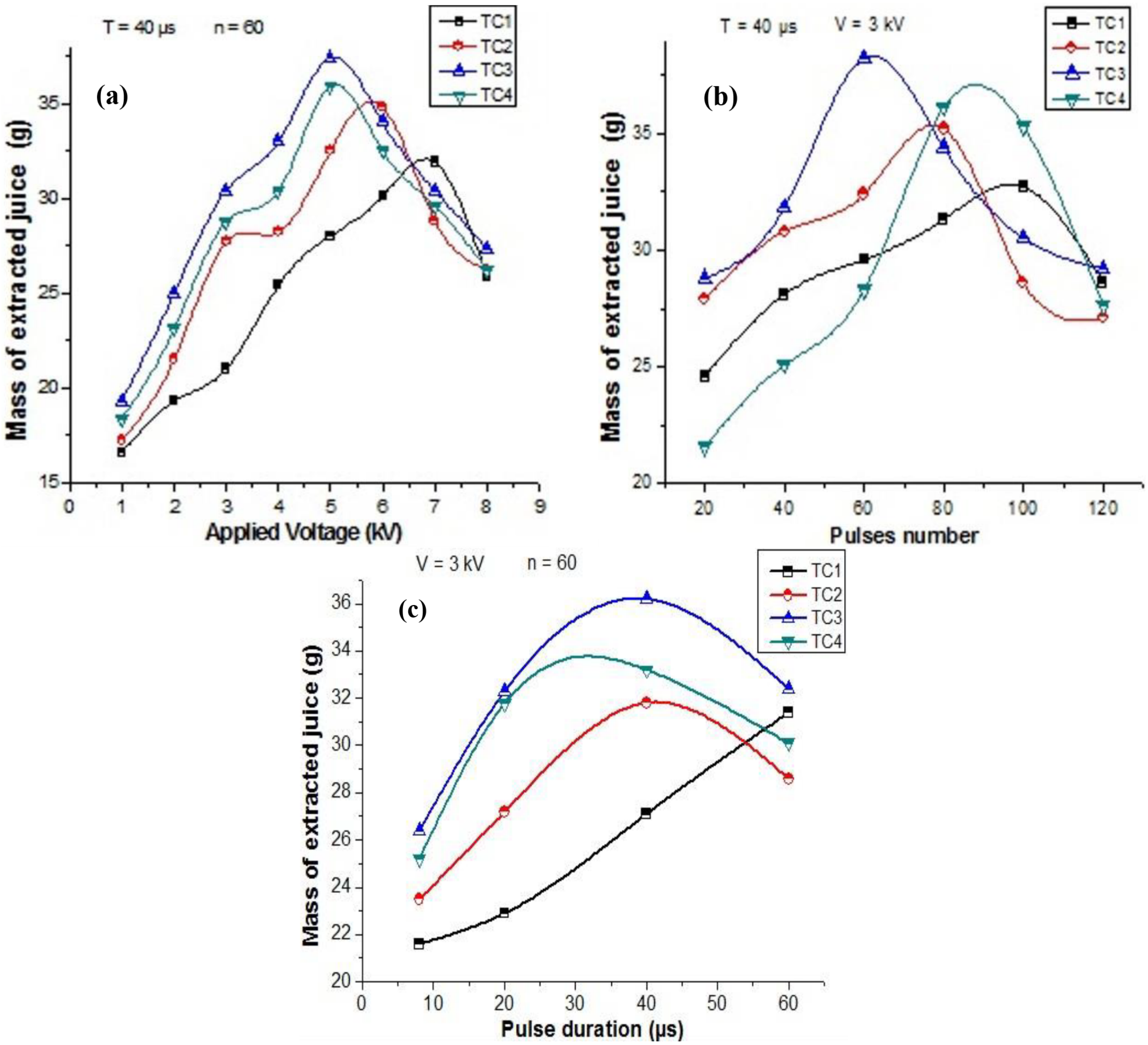


Figure 7. Evolution of the extracted juice mass according to (a) the voltage V, (b) the pulses number n, and (c) the pulse duration T for the different TC models.

On the other hand, the mass (m) and the absorbance (A) obtained with a PEF-treated sample increased with the pulse duration T for all the chambers up to a determined value (40 μs) and then decreased. As for the previous factors, the treatment was more efficient for TC_2, TC_3, and TC_4 models compared with the classic chamber (Figures 7c and 8c). In contrast to the model TC_1 for which the optimal treatment was achieved for $T = 60$ μs ($m = 31.4$ g & $A = 0.292$), greater values of treated juice extracted were obtained with smaller pulse duration for the models TC_2, TC_3, and TC_4 as shown in Table 3, showing that the superiority of the model TC_3 is definitely confirmed in comparison with the other models.

Energy saving of 20%, 40%, and 40% was achieved for models TC_2, TC_3, and TC_4, respectively, with respect to the energy of the classic model TC_1 (Figure 9).

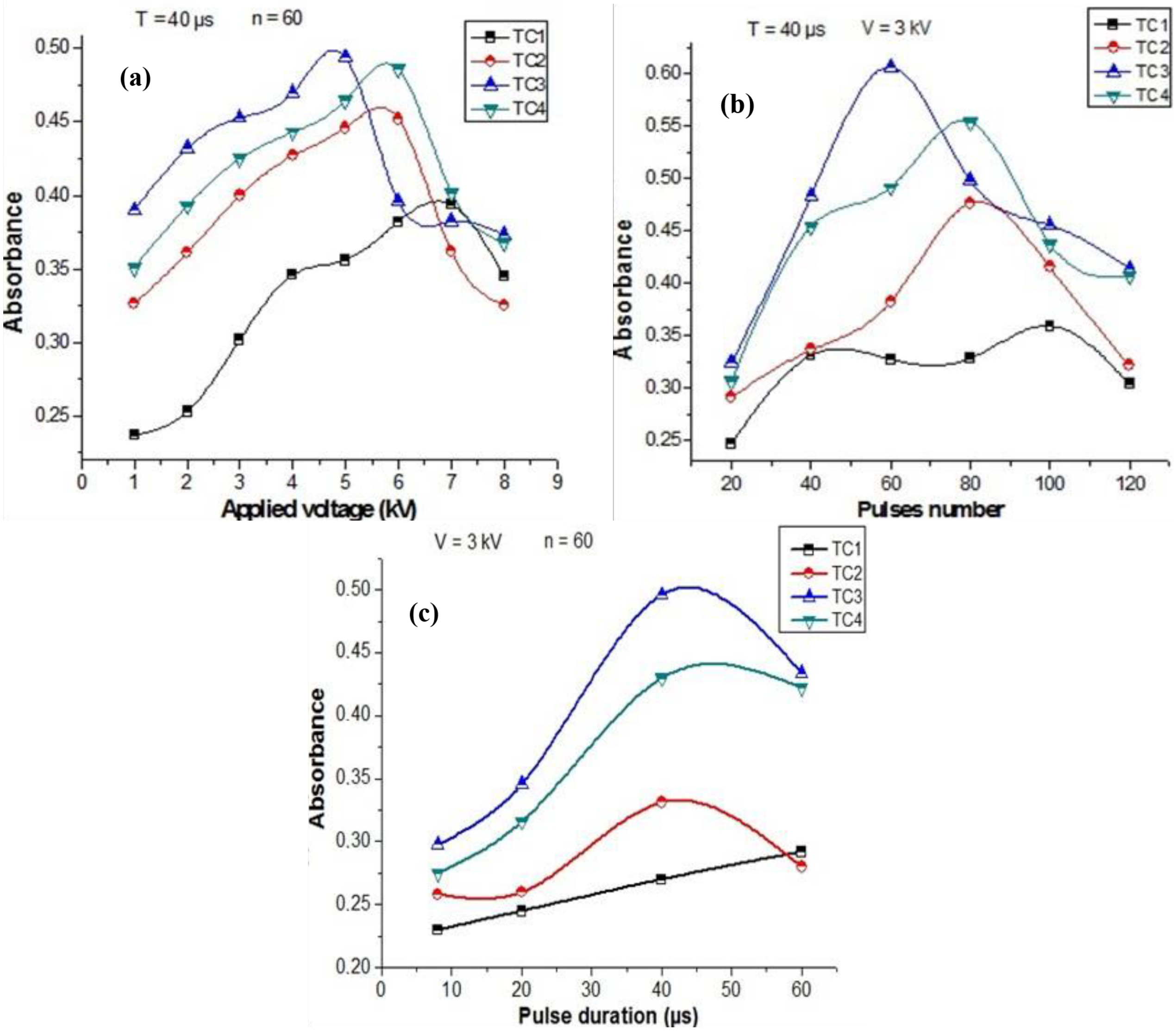


Figure 8. Evolution of the absorbance A according to (a) the voltage V, (b) the pulses number n, and (c) the pulse duration T for the different TC models.

Table 3. The maximal values of both the mass m and the absorbance A and the corresponding energy W obtained with each TC according the pulse duration.

	TC_1	TC_2	TC_3	TC_4
Mass (g)	31.4	31.8	36.2	33.2
Abs (%)	0.292	0.331	0.496	0.430
W (J)	324	259.2	259.2	259.2

4. Conclusion

The present paper describes an experimental comparative analysis between new configuration square treatment chambers of the same dimensions but having two, three, four, or five metal electrodes placed inside the chamber. The comparative experimental analysis was performed by measuring the mass of the PEF-pretreated extracted

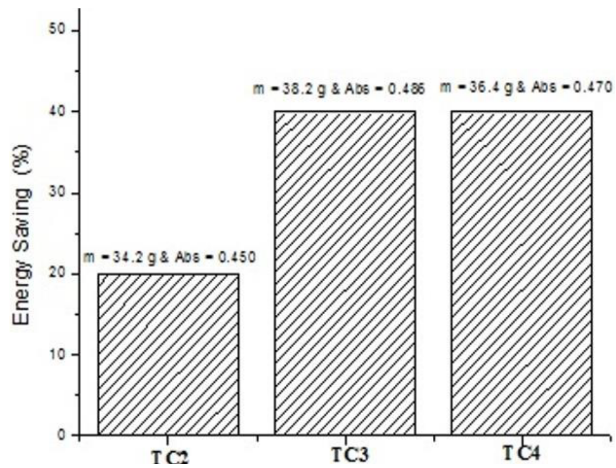


Figure 9. Energy saving corresponding to the optimal values for the new configuration TC models (T = 40 μs, n = 60).

juice mass from red beet and the amount of betanin concentration. The advantage of the chambers used is that for the same voltage the electric field is increased compared to the classic chamber comprising only two electrodes. The obtained results have shown that:

- The combination of pressing and PEF treatment enables higher extraction efficiency to enhance significantly the liquid yield in comparison with untreated samples, whatever is the treatment chamber configuration.
- Among the four configurations, the model TC_4 comprising four electrodes placed on the side wall of the square chamber and the three-unit model TC_3 with five electrodes are more efficient, because higher quantities of juice and betanin were obtained with less energy consumption.
- The three-unit model TC_3 is better than the model TC4 in terms of extracted juice mass and energy consumption.

Nomenclature

PEF	pulsed electric field
TC	square parallelepipedic treatment chamber
TC_1	square parallelepipedic monoaxial classical treatment chamber
TC_2	square parallelepipedic monoaxial treatment chamber of two parallel units
TC_3	square parallelepipedic monoaxial treatment chamber of four parallel units
TC_4	square parallelepipedic treatment chamber biaxial.
λ	wavelength, nm
f	pulse repetition frequency, Hz
p	extraction pressure, kg/cm^2
t	total pressing duration, minute
d	interelectrode gap, mm.
V	applied voltage, kV.
n	pulses number
T	pulse duration, μs.
m	mass of extracted juice, g.
A	absorbance of extracted juice
W	energy consumption, Joule.

References

[1] Bazhal MI, Lebovka NI, Vorobieva E. Damage of cellular material under simultaneous application of pressure and pulsed electric field. J Biophys Biol Phys 2000; 3: 1-10.

[2] Heinz V, Angersbach A, Knorr D. High electric field pulses and membrane permeabilization. The European Conference on Emerging Food Science and Technology; 22–24 November 1999; Tampere. Finland. pp. 78-89.

[3] Ling B, Tang J, Kong F, Mitcham EJ, Wang S. Kinetics of food quality changes during thermal processing. Food Bioprocess Technol 2015; 8: 343-358.

[4] Gonzalez ME, Barrett DM. Thermal, high pressure, and electric field processing effects on plant cell membrane integrity and relevance to fruit and vegetable quality. J Food Sci 2010; 75: 121-130.

[5] Grzegory P, Piotrowski D, BargiełK. Influence of freezing treatment, osmotic dehydration and storage time on the rehydration of vacuum dried strawberries. J Agric Eng 2013; 4: 39-47.

[6] Orue A, Jauregi A, Unsuain U, Labidi J, Eceiza A, Arbelaiz A. The effect of alkaline and silane treatments on mechanical properties and breakage of sisal fibers and poly(lactic acid)/sisal fiber composites. Compos Part A: Appl Sci Manuf 2016; 84: 186-195.

[7] Kaur M, Sharma HK. Effect of enzymatic treatment on carrot cell wall for increased juice yield and effect on physicochemical parameters. Afr J Plant Sci 2013; 7: 234-243.

[8] Vega-Mercado H, Gongora-Nieto MM, Barbosa-Cánovas GV. Advances in dehydration of foods. J Food Eng 2001; 49: 271-289.

[9] Buckow R, Sieh Ng, Toepfl S. Pulsed electric field processing of orange juice: a review on microbial, enzymatic, nutritional, and sensory quality and stability. Compr Rev Food Sci Food Saf 2013; 455-465.

[10] McLellan MR, Kime RL, Lind LR. Electroplasmolysis and other treatments to improve apple juice yield. J Sci Food Agric 1991; 57: 303-306.

[11] Bazhal MI, Vorobiev EI. Electric treatment of apple slices for intensifying juice pressing. J Sci Food Agric 2000, 80: 1668-1674.

[12] Galindo FG. Reversible electroporation of vegetable tissues—metabolic consequences and applications. Bolivian J Chem 2008; 25: 30-35.

[13] Aguilar-Rosas SF, Ballinas-Casarrubias ML, Nevarez-Moorillon GV, Martin-Belloso O, Ortega-Rivas E. Thermal and pulsed electric fields pasteurization of apple juice: effects on physicochemical properties and flavour compounds. J Food Eng 2007; 83: 41-46.

[14] Bobinaitė R, Gianpiero P, Nerijus L, Šatkauskas S, Viškelis P, Ferrari G. Application of pulsed electric field in the production of juice and extraction of bioactive compounds from blueberry fruits and their by-products. J Food Sci Technol 2015; 52: 5898-5905.

[15] Lebovka NI, Shynkaryk MV, El-Belghiti K, Benjelloun H, Vorobiev E. Plasmolysis of sugarbeet: pulsed electric fields and thermal treatment. J Food Eng 2007; 80: 639-644.

[16] Maged EAM, Ayman HAE. Pulsed electric fields for food processing technology. In: Ayman AE. editor. Structure and Function of Food Engineering, Chapter 11. Croatia, European Union: Intech open, 2012. pp. 356-414.

[17] Vega-Mercado H, Gongora-Nieto MM, Barbosa-Canovas GV, Swanson BG. Pulsed Electric Fields in Food Preservation. In: Shafiur R, editor. Handbook of Food Preservation, Second Edition. Boca Raton, FL, USA: CRC Press, 2007. pp. 783-813.

[18] Ratna IP, Syamsiana IN, Choviya H. Design of high voltage pulse generator for pasteurization by pulse electric field (PEF). Int J Comput Electr Eng 2010; 2: 916-923.

[19] Jeyamkondan S, Jayas DS, Holley RA. Pulsed electric field processing of foods. J Food Prot 1999; 62: 1088-1096.

[20] Buckow R, Baumann P, Schroeder S, Knoerzer K. Effect of dimensions and geometry of co-field and co-linear pulsed electric field treatment chambers on electric field strength and energy utilisation. J Food Eng 2011; 105: 545-556.

[21] De-Vito F. Application of Pulsed Electric Field (PEF) Techniques in Food Processing. University of Salerno, Italy, 2006.

[22] Kambiz S, Frank S. Application of pulsed electric field in non-thermal processing of milk. Asian J Food Agro-Ind 2009; 2: 219-244.