Comparison between monopolar and bipolar µs range pulsed electric fields in enhancement of apple juice extraction

P. S. Brito, H. Canacsinh, J. Mendes, L. M. Redondo, and M. T. Pereira

***Abstract*—The effect of monopolar and bipolar shaped pulses in additional yield of apple juice extraction is evaluated. Applied electric field, pulse width and number of pulses are assessed for each pulse type and divergences are analyzed. Variation of electric field is ranged from 100 V/cm to 1000 V/cm, pulse width from 20 µs to 300 µs and number of pulses from 10 to 275, at frequency of 200Hz. Two trains separated by 1 second are applied to apple cubes. Results are plotted against reference untreated samples for all assays. Energy consumption is calculated for each experiment as well as qualitative indicators for apple juice of total soluble dry matter and absorbance at 390 nanometers wavelength. Bipolar pulses demonstrated higher efficiency and energetic consumption has a threshold where higher inputs of energy do not result in higher juice extraction. Total soluble dry matter and absorbance results do not illustrate significant differences between application of monopolar and bipolar pulses but all values are inside the limits proposed for apple juice intended for human consumption. A pilot scale treatment chamber with 503 cm^3 is used and associated errors due to the small scale are considered.**

***Index Terms*— Bipolar pulses, Juice Extraction, Monopolar pulses, Pulsed Electric Fields.**

I. Introduction

The exposure of a living cell to short high intensity pulsed electric fields (PEF), in the range of ns to ms, can cause the disruption of the cell membrane which is composed of a lipid bilayer. This phenomenon is called electroporation and its exploitation in the food and drug industry has been largely researched. Applied pulse electric fields, PEF, into a cell cause the charging of the lipid bilayer membrane that rapidly rearranges its structure as a response to the electric field. A great increase in ionic and molecular transport takes place causing a transition to a localized water filled structure also called "aqueous pathways" or "pores" [1]. Every living cell has a local transmembrane voltage at each point of its membrane, and for a specific pulse duration and applied external field, there is a threshold for the electroporation phenomenon be able to take place [2]. It is generally accepted that for an average cell size of 100 µm, field strengths of 100 V/cm to 1000 V/cm together with pulse widths of 10 µs to 100 µs trigger a reversible electroporation effect (where the pores are able to reclose and the cell life is not compromised) if the pores electric charge is smaller than the critical membrane surface charge. Similarly, if the value is higher than the critical value the cell apoptosis occurs [3].

Continuous technological research has been carried out through the last decades in developing flexible solid-state pulsed power modulators [4], [5]. In fact, the ability to control the pulse width, electric field amplitude, number of pulses, frequency and polarity of the applied field associated with solid-sate based modulators is of main importance regarding the success of food and drug treatments and today this technology has proven to be surpassing numerous traditional methods of fruit juice extraction [6]-[8], fruit juice quality [9]-[11], food non-thermal sterilization [12]-[15] and medical treatments [16]-[19].

Apples are a rich source of antioxidant compounds and fibers. Apple polyphenol extracts can lead to reduction in LDL and total cholesterol and their fiber content is particularly important in prevention of heart disease through healthy regulation of blood fat levels. The Apple juice industry produces over 1.5 million tons per year [20], making the optimization of its production an attractive field.

Application of PEF for the enhancement of apple juice extraction has obtained good results with effective increases in yield from applying electric field in 100 V/cm to 520 V/cm range, 100 µs pulse duration, 50 pulses with 100 Hz repetition rate, the pulse shape was rectangular and monopolar [7].

Another experiment was carried out varying electric fields from 100 V/cm to 1000 V/cm, pulse width from 10 µs to 100 µs, number of pulses from 100 to 1000 with 100 Hz repetition rate, the pulse shape was, also, rectangular and monopolar [8].

However, very few studies have been done using bipolar pulses. Pasteurization of Apple juice using PEF with bipolar pulses was compared to the traditional method [21], [22], sugar beet tissue damage degree was studied with PEF application (though together with thermal treatment) [23], a comparative study between the effect of monopolar and bipolar pulses on the contamination of metallic ions in a cell suspension during electroporation [24] and a study of electroporation of muscle fibers cells showed interesting results [25]. The hypothesis behind these results lies in the fact that living cells are not perfectly spherical and the position of the cell membrane with respect to the direction

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of the applied electric field causes the critical membrane surface charge to change [26]-[28], if the interior of a cell has a negative potential, concerning its exterior, its transmembrane potential will be higher at the pole facing the positive electrode and vice-versa. Fig. 1 and Fig. 2 are a microscope image of apple cells and a schematic of the concept above described respectively.

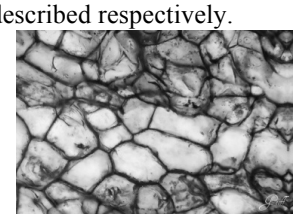

Fig. 1. Microscope image of apple cells. Courtesy of Geoff Whiteway, teacher at the Marine Institute, Canada.

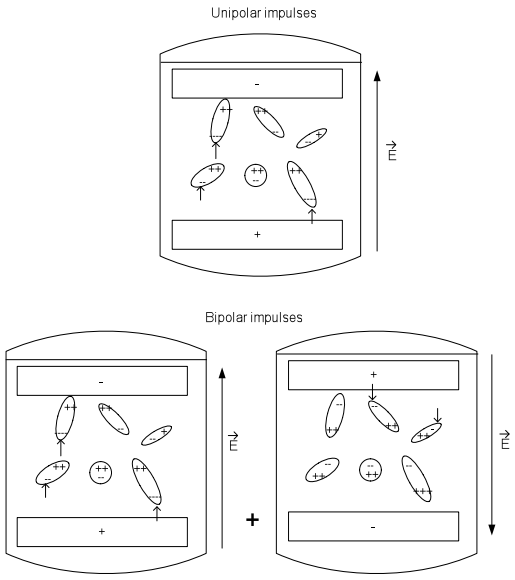

Fig. 2. Electric field effects on the differently shaped and directed apple cells. Transmembrane induced voltage is higher on sharper points and electroporation occurs if the threshold value of membrane surface charge is surpassed. Bipolar pulses seem to increase the number of cells affected by the high electric field, increasing the amount of disrupted membranes. Arrows represent the points where electroporation may take place.

Apple juice PEF assisted enhanced extraction with separate bipolar rectangular pulses in comparison to monopolar rectangular pulses of equal amplitude and duration is described in this paper, using a solid-state modulator capable of deliver either pulses. The aim of this work is to conjecture about the efficiency of monopolar and bipolar pulses, comparing the yield of apple juice extraction with both pulse types towards reference blank samples as well as the measurement of the absorvance and total solids content. This is critical as bipolar generators are more complex and expensive than monopolar ones, since in average twice the switches are used. Pulse width, number of pulses and electric field applied are also studied with both pulse types, in order to evaluate the mechanisms of electroporation and to improve the performance of PEF application.

II. Experimental Procedures

Fig. 3 shows the simplified schematic of the experimental procedure used for the apple juice PEF assisted extraction.

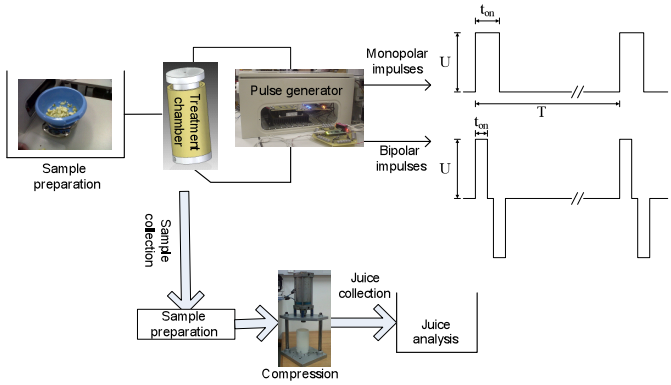

Fig. 3. Schematic of the process with application of monopolar and bipolar impulses in apple samples for juice extraction.

Golden type apples caliber 60/65 mm were cut in cubes (1 to 1.5 cm side) at room temperature and immediately placed inside a cylindrical treatment chamber, 9 cm diameter and 1 to 5 cm height, maximum 300 cm^3. In order to suppress yield differences, due to different fruits and ages, every assay had a reference blank sample collected and analyzed. Both blank and tested samples were equivalent; half the weight of the sample belonged to one fruit and the other half to another for the blank assays and remain two halves were used as the tested material.

Considering the relative low voltages involved in the laboratory experiments, an H-bridge topology was used, capable of deliver monopolar and bipolar into the load, v_0, where the S_i switches hold-off the voltage of the power supply U_{dc}, as shown in Fig. 4. Relaxation time between bipolar pulses was fixed at 100 µs.

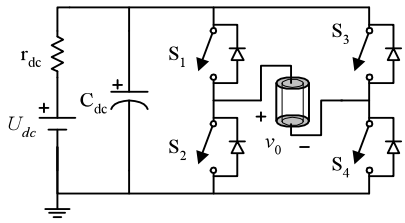

Fig. 4. H-bridge generator topology used in experiments.

Each tested sample was submitted to the exact same variation of studied parameters. First, electric field E was changed from 100 V/cm to 1000 V/cm, with constant pulse width t_{on}=100 µs, frequency f=200 Hz, for N_i= 75 pulses (pulse train). Second, E was fixed at 600 V/cm, N_i was maintained at 75, frequency kept at 200 Hz and t_{on} was studied with a variation from 20 µs to 300 µs. Finally, the number of pulses per train was changed from 10 to 275, keeping constant: f (200 Hz), E (600V/cm) and t_{on} (100 µs). For all assay two pulse trains were applied with 1 s separation. Energy delivered per pulse train, E_c (J/Kg) can be calculated according to

$$E_c = \frac{N_i v_0 i_0 t_{on}}{M}, \quad (1)$$

where M (Kg) is the initial apple mass, v_0 the applied voltage and i_0 the current across.

The PEF treatment was applied and the apple cubes were collected. The same treatment chamber was used for the compression stage and the filter cloth was placed inside it before the compressing of the apple treated cubes for the juice collection. A 4 bar pressure was applied for 5 minutes and the juice was instantly collected and weighted.

It is important to consider the associated error of measurement in all assays. Used treatment and compression chamber has a small volume making all the assays pilot experiments. Therefore, the mass of juice collected is affected by significant deviations which are considered in all plots with associated error bars. Table I show the mass and the considered error (in percentage) used in this work.

Table I
Apple masses and associated errors for juice extraction

Tested parameter	Electrode distance (cm)	mass (g)	Error (%)
E (V/cm)	2.5	65	15
t_{on} (µs)	4	100	10
Ni	4	100	10

Sigma Aldrich filter cloth with permeability factor of 25 cfm (cubic feet per minute) was used to collect the juice during the compression stage. All absorbance measurements were made in a UNICAM UV2 UV/Vis spectrophotometer in plastic cuvettes at room temperature and at 390 nanometers wavelength. Dissolved total solids content (ºBrix) were measured in a Refractometer ATAGO 3T; samples were kept at a constant temperature of 23ºC with a water bath incorporated in the refractometer. All samples were stored in the fridge at 5ºC for no more than 24 hours before their chemical analysis.

III. Results and Discussion

A. *Effect of applied Electric field on additional juice yield*

Comparison between the effects of applying different electric fields with pulse shape is shown in Fig. 5. Values in percentage correspond to the difference between the treated apple cubes and reference samples (without any PEF treatment), i.e. plots are based in additional yield percentage towards the untreated apples and not the total yield of treated samples. Negative values mean a decrease in yield.

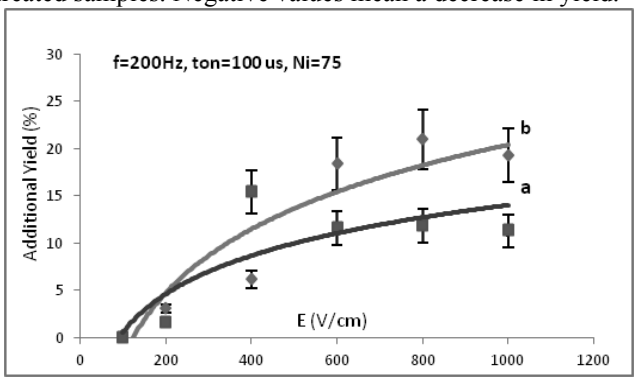

Fig. 5. Additional juice yield versus applied electric field for monopolar (a) and bipolar (b) shaped pulses.

For an applied electric field of 200 V/cm and onwards it is clear the positive effect of the application of PEF in apple samples for both pulse shapes. In the two pulse shape studied, higher electric fields applied result in more additional extracted juice being in agreement with other studies with apples [8], [11] and electroporation general theory. Bipolar pulses seem to be more effective than monopolar with a tendency for higher extraction of juice under the same conditions.

B. *Effect of pulse width on additional juice yield*

Pulse width is one important factor that can determine the irreversibility of the pore formation in cells and, generally, when PEF is applied for pasteurization purposes, the pulse width is proportional to the number of bacterial and microbial cell's death [30]. Similarly, for juice extraction functions it is expected to achieve the same tendency. Pulse width influence on additional juice yield is shown in Fig. 6, for the two pulse shapes considered.

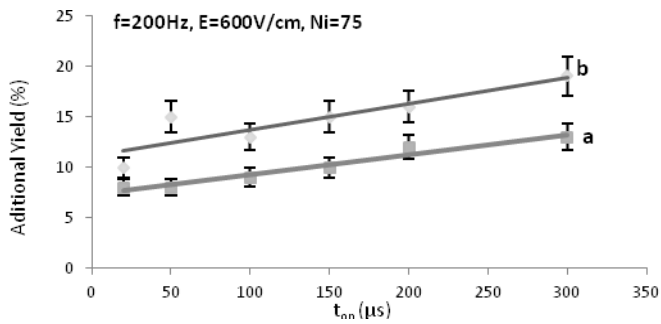

Fig. 6. Additional juice yield versus pulse width for monopolar (a) and bipolar (b) shaped impulses.

For each pulse shape and pulse width the increase in juice yield regarding untreated samples is clear. Both pulse types present the same behavior reaching a maximum efficiency in the range of 200 µs and 300 µs. Bipolar pulses reveal higher additional yields in the juice extraction at all studied pulse widths.

C. *Effect of number of pulses on additional juice yield*

Together with the pulse width, the number of applied pulses in the PEF treatment is directly related to the energy consumption of the system. Fig. 7 shows the comparison of monopolar and bipolar pulses additional yields when the number of pulses is changed.

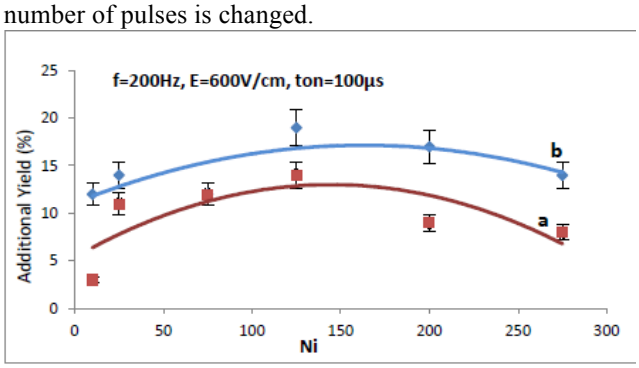

Fig. 7. Additional juice yield versus number of pulses for monopolar (a) and bipolar (b) shaped impulses.

With variation of pulse number there is a tendency for achieving better performances for increasing number of pulses. However, due to the stored energy limitation in the C_{dc} capacitor, for the parameters used, there was a decrease in the applied voltage with the number of pulses higher than 150. Nevertheless, additional yield in the juice extraction is higher when bipolar shaped pulses are applied being this a common tendency with all tested PEF parameters in this work.

D. Energy consumptions of monopolar and bipolar impulses

Duration of PEF treatment is one of the main parameters that determine the amount of consumed energy in the process. For juice extraction application in industry it is worth to deepen the effect of pulse width and number of pulses and find optimal points between energy consumption and additional yields. For PEF successful industrial applications it is essential to understand and find the balance between energy consumption and additional product achieved. As concluded in the previous section, bipolar shaped pulses are able to deliver higher additional apple juice yields. Nonetheless, pulse generators able to produce bipolar pulses are more expensive to manufacture and food industry investments for higher productions must take into account all these combined aspects.

Fig. 8, Fig. 9 and Fig. 10 represent the energy consumed during application of PEF for both shape type pulses towards the variation of electric field, pulse width and number of pulses and additional juice yield.

Observation of Fig. 8, Fig. 9 and Fig. 10 shows that no significant differences of energy consumptions are found between the use of monopolar and bipolar shaped impulses. However, it is possible to determine a threshold where further energy inputs (consequence of higher number of pulses, larger pulses and stronger electric fields) do not influence the additional juice extraction.

As explained in section III.C, in the experiment with increasing number of pulses, there was a decrease in the applied voltage above 150 pulses due to the energy store limitation in the system, as seen also in Fig. 10 energy lines.

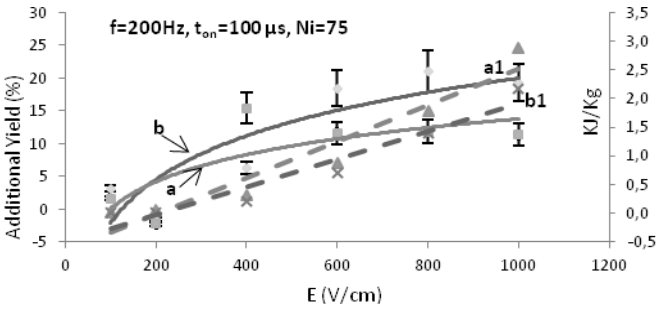

Fig. 8. Consumed energy for monopolar pulses (dashed line a1) and bipolar pulses (dashed line b1) versus additional yield for monopolar pulses (a) and bipolar pulses (b) with electric field variation.

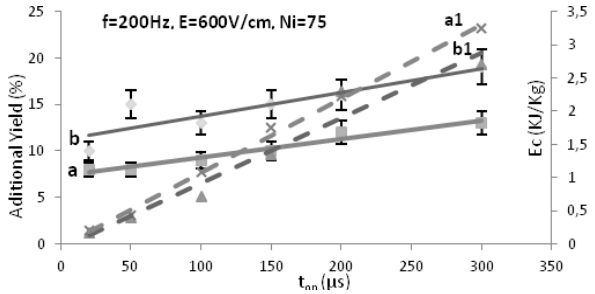

Fig. 9. Consumed energy for monopolar pulses (dashed line a1) and bipolar pulses (dashed line b1) versus additional yield for monopolar pulses (a) and bipolar pulses (b) with pulse width variation.

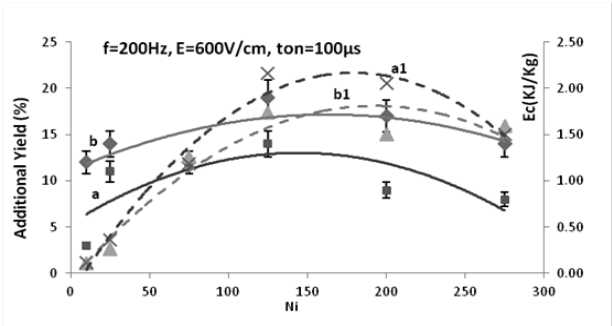

Fig. 10. Consumed energy for monopolar pulses (dashed line a1) and bipolar pulses (dashed line b1) versus additional yield for monopolar pulses (a) and bipolar pulses (b) with number of pulses variation.

The last is valid for both pulse shapes and is directly related to the fact that plotting of additional juice yields versus the three studied parameters has a clear tendency to reach a saturation point. Energy consumptions are as low as, for example, 0.7 KJ/Kg for additional yield of 18 % when bipolar pulses are applied at a 600 V/cm electric field, with pulse width of 100 µs and 75 impulses. These results confirm the strong applicability of PEF in the food industry with great increase in the process efficiency.

E. Juice quality evaluation

PEF application can change the composition of the extracted apple juice and coloration and concentration of soluble dry maters. These parameters affect important visual and qualitative perceptions of the final consumers, and their study is shown in Fig. 11, Fig. 12 and Fig. 13.

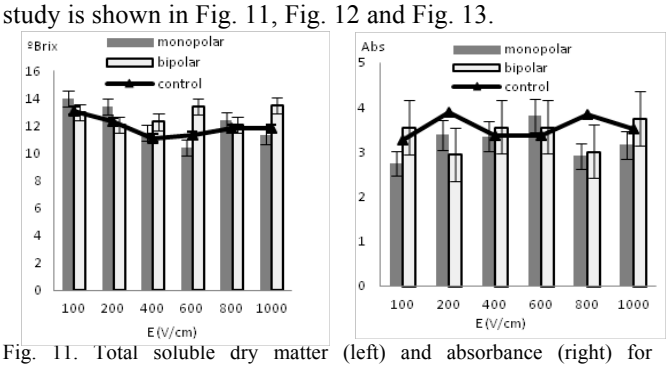

Fig. 11. Total soluble dry matter (left) and absorbance (right) for monopolar and bipolar pulses and control samples versus applied electric field (E), with 75 pulses of 100 µs width and 200Hz frequency. Error bars represent standard deviations in the data.

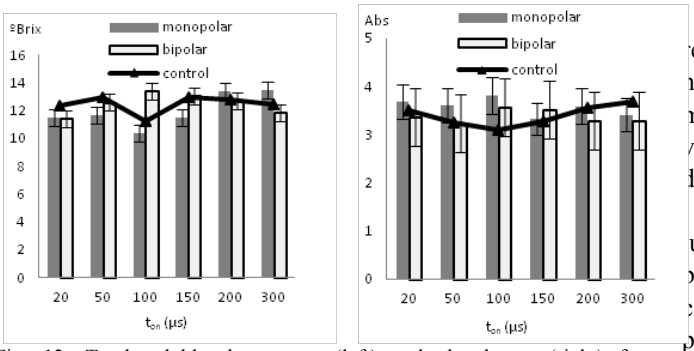

Fig. 12. Total soluble dry matter (left) and absorbance (right) for monopolar and bipolar pulses and control samples versus pulse width (t_{on}), at 600 V/cm, with 75 pulses and 200Hz frequency. Error bars represent standard deviations in the data.

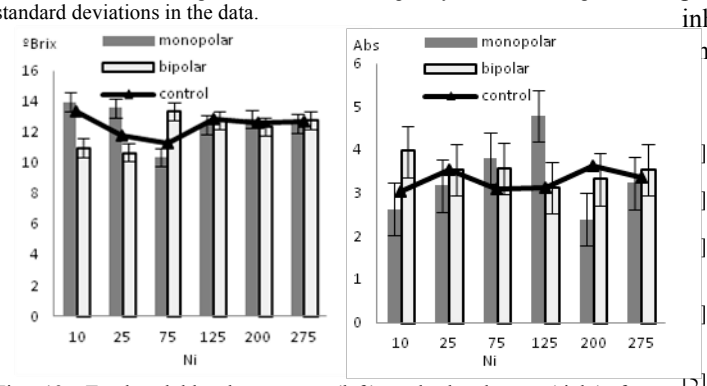

Fig. 13. Total soluble dry matter (left) and absorbance (right) for monopolar and bipolar pulses and control samples versus number of pulses (Ni), at 600V/cm electric field, 100 µs pulse width and 200Hz frequency. Error bars represent standard deviations in the data.

Evaluation of both qualitative parameters suggests that shape of applied pulses in PEF treatment does not have a significant influence on the release of soluble dry matter and coloration of extracted juice. Bipolar pulses may influence the number of electroporated cells but, in fact, pore size and selective permeability of the membranes after being submitted to reversible or irreversible electroporation does not change with the amount of electroporated cells. Nevertheless, conclusions are that minimum quality parameters required by European Union directives [31] are kept and it is possible to establish that, for all the studied parameters in this work, the application of PEF in the extraction of apple juice is in conditions to be widely applied in the food industry.

IV. CONCLUSIONS

Differences on apple juice extraction additional yield and qualitative parameters were analyzed. Application of PEF on apple pre-cutted cubes was investigated with monopolar and bipolar shaped impulses with variation of pulse width, number of pulses and electric field.

Bipolar pulses revealed higher additional yields for all studied parameters. Increasing electric fields, pulse widths and number of impulses leads to higher additional yields but results suggest that there is a tendency for reaching a saturation point;

Disregarding the pulse shape, all studied electric parameters have a threshold where increased energy inputs do not imply increased additional yields; considerably low energetic consumptions (0.7 KJ/kg) are able to produce over 18% more juice than their correspondent untreated samples.

Evaluation of qualitative parameters and comparison of results between monopolar and bipolar shaped pulses does not return significant differences between total soluble matter and absorbance values of treated apples, but all values achieved are in conformity with European Union directives for apple juice for human consumption.

Bipolar impulses demonstrated better performances in juice extractions yields but pulse generators able to deliver bipolar shaped impulses are more complex and, consequently, their economic viability for large scale juice production is dependent on the additional production in respect to more simple pulse generators. This work presented a pilot scale study and the associated error inherent to this has been taken into account for a better implementation in the real-scale industry processes.

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