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MODELISATION OF PULSED ELECTRIC FIELDS FOR TROPICAL LIQUID FOOD INDUSTRIAL PROCESSING

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ABSTRACT: In order to process food destined to human consumption, most of the methods which have been used industrially till today are various forms of thermal processing, which unfortunately trigger unwanted reactions in foods, altering their qualities by causing extensive loss of flavour, colour, nutrients and vitamins. These qualities are naturally very important to consumers whose demand for fresh-like food products is still increasing. This is why there is a growing interest in non-thermal processes for food quality preservation. Non-thermal processing technologies have are being developed to eliminate, or at least minimise, the resulting degradation of food due to classic methods. Pulsed electric field (PEF) is one of those non-thermal processing technologies. It is still not well known. Many empirical experimental results have already been obtained: PEF should be applied to non-treated liquid food in the form of short-duration high voltages pulses in order to generate inactivation of micro-organisms. Some authors confirm that exposing some microbial cells to pulsed electric fields may result in a dielectric breakdown of cell membrane, and have noticed that the said breakdown can be reversible or not depending on the intensity and the duration of the applied electric field [1, 2]. The aims of the present study are to propose models and solutions that describe quantitatively that phenomenon of sterilisation obtained by PEF. We limit analysis on the specific case of Saccharomyces Cerevisiae which particularly concerns types of tropical liquid food products that are very appreciated in developed countries. The method once mastered could hopefully contribute significantly to industrialize those tropical products. Originality of the method consists of combining electromagnetic studies with mathematical finite elements methods to analyse the mechanism of sterilization, and confirms theoretically empiric experimental results [3]. The study then shows why values of the duration, amplitude and frequency of the applied field are so important. Different models and graphs of values of physical quantities focussing actions of PEF on microbiological cells constitution are also described.

Keywords: high voltage pulsed electric field, industrial food processing.

I. INTRODUCTION

Tropical climate constitutes, due to its temperatures and humidity, a propitious environment to culture of particular types of fruits commonly named tropical fruits. It could be noticed that 98 % of producers of those products are underdeveloped and emerging countries while 80 % of consumers are developed countries. For instance more than 80% of UK consumption of those products comes from tropical countries [4]. In 2004, world production of those products was around 67.7 million of tonnes with nearly 90% of that volume lost, and only 10% used either as exported fresh products or as entrance for juice processing. So there is a realistic problematic of thinking over a simple cost accessible technology that could be used by farmers of those countries to avoid huge postharvest losses.

Traditional technologies that are used to obtain juice from biological fruits or to conserve them, are costly and of difficult access. They are generally based on heating or cooling processing, and by this fact, unfortunately induce nutritional and biochemical changes [5-6], and consequently reduce in a great amount economic values of those products. Manufactured products that are obtained present low nutritional values, bad sensorial qualities (taste, flavour, and color). To come over those problems, non thermal sterilization methods have been expected among different solutions.

It has been proved that these non thermal methods lead to a better conservation of natural properties (nutritional values, flavour...) in obtained results after processing [7]. One of those new interesting non thermal technologies is pulsed electric fields (PEF). Many studies using PEF on bacterial and yeast micro-organisms have been carried out showing sterilization results of 99.9 % [5,8-10], with some of them being applied on apple juice with successful reduction of 4 to 5 logarithmic cycle when applying a PEF of 40 kV/cm at 25°C [11]. Other studies have performed elimination of Saccharomyces Cerevisiae in orange juice also with success, obtaining a reduction of 2.5 logarithmic cycles with an application of a 50 kV/cm PEF at 50°C [12].

So processing some tropical juice by means of PEF could be possible when this method will be mastered. A review of present scientific literature can show that the mechanisms of destroying infected microorganism are still not well known. Many attempt approach exist including breakdown membrane theory [1]. We propose in this study an analysis which combines Maxwell electromagnetic equations of electric quantities like the known applied PEF with a Finite Elements Method, and so helps observing electrical phenomenon inside the microorganism. The calculated electric fields lines inside the studied microorganism can allow us to obtain the voltage drop across membrane cell, the induced physical forces inside the cell, evolution of the voltage inside the cell, and confirm calculated pulsed voltage in different parts of the cell.

II. DESCRIPTION OF THE STUDIED SYSTEM AND ITS MODELISATION

II.1 HYPOTHESES OF THE STUDY

In this section, we will first set hypothesis that have guided us during the study. We have supposed that:

-There are only electrostatic forces inside the studied microorganism. So Van der Waals and repulsive double-later forces, Hydration forces, other forces between amphiphilic surfaces, and Inter and Intra membranes forces, are all neglected [13].

-We limit this first study to bi-dimensional cases that study only plant, Saccharomyces Cerevisiae microorganism.

-We do not consider mechanical functions such as motility, food entrapment, and transport, nor biological and biochemical structures and activities of the cell because our main aims are to focus the study on electrical effects due to PEF. So the cell structure used is simple with a biological membrane and cytoplasm all modelled only by their respective permittivity. Different parts like: vesicles, gorgi, mitochondria, nucleus, and endoplasmic reticulum, are not taken into account [13]. The study shows nevertheless that they could be affected by circulating electric field lines in the cell that are due to application of a PEF.

II.2 DESCRIPTION OF THE STUDIED SYSTEM

The studied system is constitutes by a static Saccharomyces Cerevisiae microorganism inside a liquid which here the water, both are placed between two electric plates that receives a Direct Current high voltage of 30 kV that could be timely varied. The used (x,y) geometric system is such that the centre of the cell is at coordinates (0,0). We have focussed the study on the cell, so the distance between the two plates is 2.5 times the radius of the cell (Rc) which is here 5 micro meters, while the length of the plates is set 3 times Rc. Those dimensions as well as other specifications of the system are mentioned in table 1 as follows:

Table1. Specifications of the studied system: Saccharomyces Cerevisiae inside water ($R_c = 5*10^{-6}$ m) – Applied Direct Current Voltage in both cases.

Applied Voltage	Geometric characteristics of studied Saccharomyces Cerevisiae		Length of the plates	Distance of the plates (d)	Cytoplasm radius
(kV)	Cell radius (m)	Width of Membrane cell (m)	(m)	(m)	(m)
30	R_c	R_c /4	3* R_c	2.5* R_c	3* R_c /4

We have then considered four regions as described in figure 2 and according to supposed hypothesis. Electric sources are placed in the air, and constitute one region, while the water, cell membrane, and interior cytoplasm of the cell are respectively region 2, 3 and 4, all those being set to present different electric permittivity (table 2).

Table2. Specifications of different regions ($\varepsilon_o = 8.854*10^{-12}$ F/m) in case 1.

	Air	Water	Cell	Cytoplasm

	Electric source	Outside sources		membrane	
Permittivity(F/m)	ε_o	ε_o	$80*\varepsilon_o$	$10*\varepsilon_o$	$80*\varepsilon_o$
Region names	Region 1	Region1	Region 2	Region 3	Region 4

II.3 MAXWELL EQUATIONS CONSIDERATIONS

Electromagnetic phenomenon in any structure which is submitted to electric voltage is generally studied owing to well known classic Maxwell equations. Those equations could be decoupled and written on simple forms in some cases. In the present study, electric field vector E, and electric induction vector D are the only variables to be considered, while involved materials having being set to have different electric permittivity ε. Electric sources are represented by charges density ρ. We use Cartesian coordinates, and we can write in any medium [14]:

$$\nabla \times E = 0 \quad (1)$$

$$\nabla . D = \rho \quad (2)$$

$$D = \varepsilon E \quad (3)$$

Equation (1) generally leads to consider a scalar function V, which is the here applied electric voltage, such that:

$$E = -\nabla V \quad (4)$$

And finally, the only equation to consider is the following:

$$\nabla .(\varepsilon \nabla V) + \rho = 0 \quad (5)$$

So, the knowledge of V will permit to have quantitatively the other electromagnetic variable at any point of the system.

We should mentioned, that in Eq.5, ρ should be taken equal to zero outside electric sources.

It should be reminded also that solutions V of Eq.5 are unique only when boundary conditions, and specific equations when going from one medium to next, are taken into account when solving Eq.5. It should be also known that Eq.5, do not have easy solutions when the geometry of the studied system is complex. This is why we have been obliged to write some software codes, on PDE Solutions environment that uses Finite Element Method. In the case, we would like to take into account electric conductivity σ of one part for instance the one of the membrane cell we will have to consider that part as an electric conductor on which a voltage is applied. We will then have an electro kinetic model that would be described by the following equation:

$$\nabla.(\sigma\nabla V)+\rho=0 \tag{6}$$

So no matter the studied case, by knowing the voltage V at any physical point of the system, including the cell, we will be able to deduce other quantities like the electric field, the pressure that appears...and so on.

II.4 MODELISATION OF THE STUDIED SYSTEM OWING TO A F.E.M. CODE

It should be reminded also that solutions V of Eq.5 are unique only when boundary conditions, and specific equations when going from one medium to next, are taken into account when solving Eq.5. It should be also known that Eq.5, do not have easy solutions when the geometry of the studied system is complex. This is why we have been obliged to write some software codes, on PDE Solutions environment that uses Finite Element Method like it is shown on Figure 1 where could be distinguished the study cell membrane in green, the interior cytoplasm in orange, the surrounding water in blue, electric plates in white, and the air outside the system in yellow, finite element meshes are also represented, dimensions are set according to table 1 since it is known that current dimensions of Saccharomyces Cerevisiae microorganisms are between 7 and 13.4 µm, those microorganisms having generally round shapes [15].

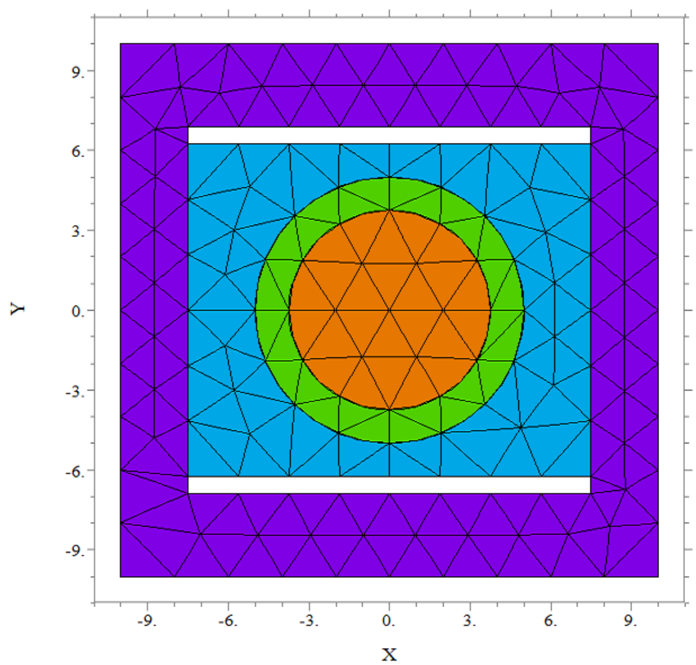


Figure.1 Modelisation of the studied system owing to PDE Solution. Units (X,Y) in µm

We know that Saccharomyces Cerevisiae microorganisms have a complex structure that includes other biological components apart from the cell membrane and interior liquid cytoplasm. We can also find in the cytoplasm: vesicles, gorgi, mitochondria, nucleus, and endoplasmic reticulum. In order to approach this reality, we propose some other regions inside the cytoplasm as it can be seen on figure.2. Characteristics of those new introduced elements (number, dimensions, geometries, permittivity, conductivity...etc) can also be varied at ease. We wanted to prove that such study can be done. So we chose four elements of the size that have been placed on X and Y axis and have been given permittivity: $60.\varepsilon_o$, $30.\varepsilon_o$, and $10.\varepsilon_o$.

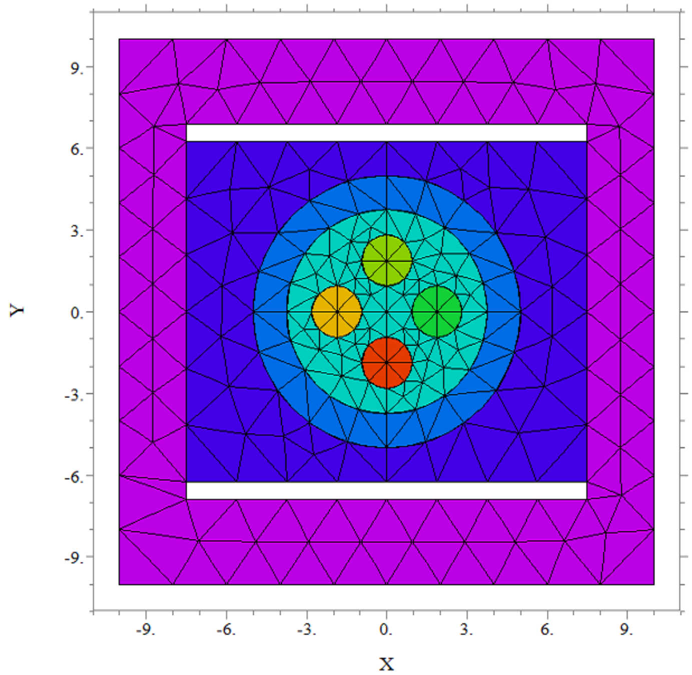


Figure.2 Modelisation of a case with 4 elements inside the cytoplasm. Units (X,Y) are in µm

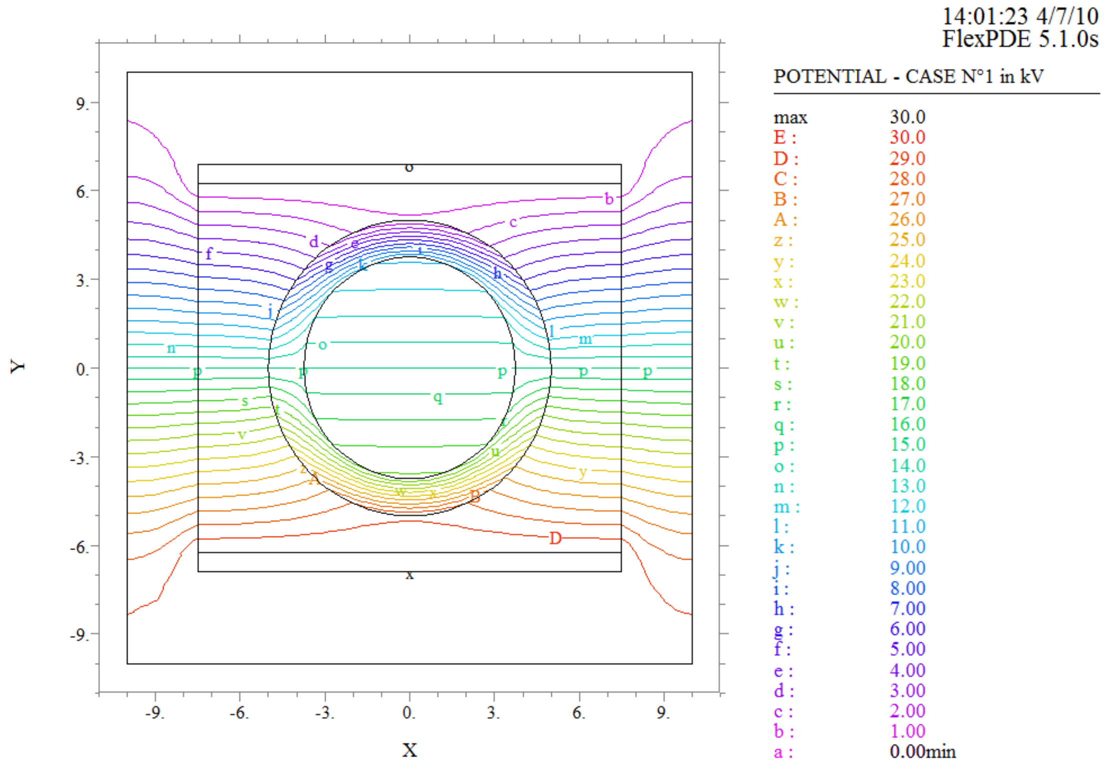
III. RESULTS AND COMMENTS

III.1 VOLTAGE LINES IN THE WHOLE SYSTEM.

When applying a static DC voltage on one face of the plaque, the whole system will subject of electric and potential lines. Those two types of lines are perpendicular. We have chosen to present only one (Figs.3 and 4) in the two studied cases. It can be noticed that parts of the cell near the high voltage plaque receive higher voltage lines, while particles inside the cytoplasm will also be circulated by electric field lines, and could so for instance be applied a physical force if they are polarized, and be moving.

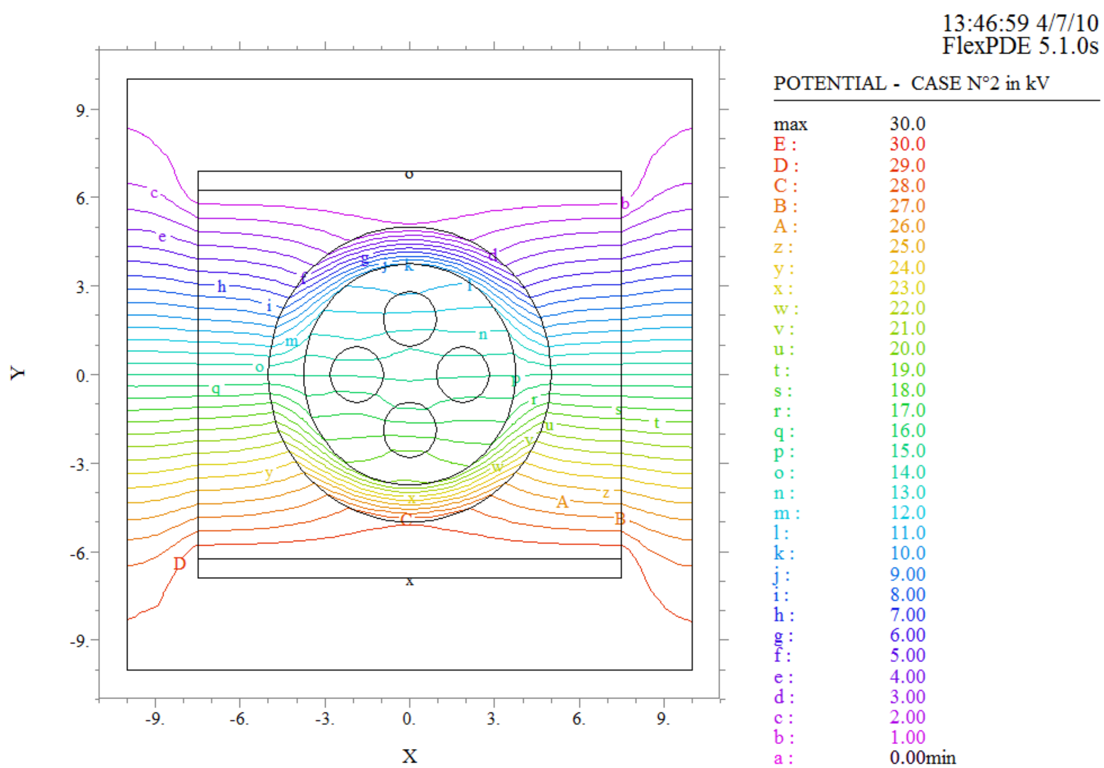
III.2 INDUCED VOLTAGE ALONG THE CELL INTERIOR MEMBRANE FACE.

We can also notice that different points, here points 1, 2, 3 and 4, of the cytoplasm-membrane boundary are not submitted to the same voltage (Fig.5). This means that, if that surface present conductivity, surface micro electric currents will circulate and probably cause some heat effects. It can also be deduced that two different surfaces, for instance, interior and exterior surfaces of the cell will be applied a voltage drop like it had be foreseen in breakdown theory [1]. That voltage drop can here be calculated as it is done in the next sections.



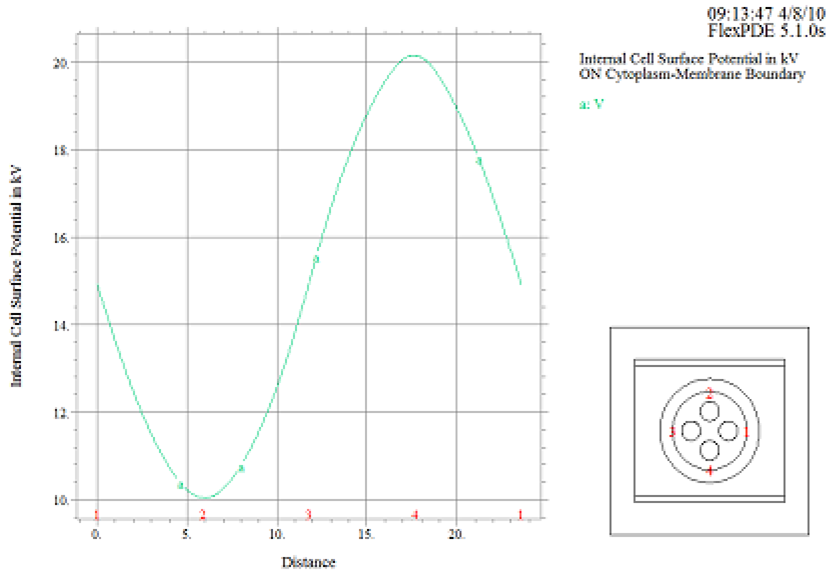
Model-PEF-CiGr2010: Grid#1 p2 Nodes=595 Cells=260 RMS Err= 0.0016

Figure.3 Equipotential Lines - Case N°1



Model-PEF-5-2-CiGr2010: Grid#1 p2 Nodes=895 Cells=410 RMS Err= 0.0014

Figure.4 Equipotential Lines - Case N°2

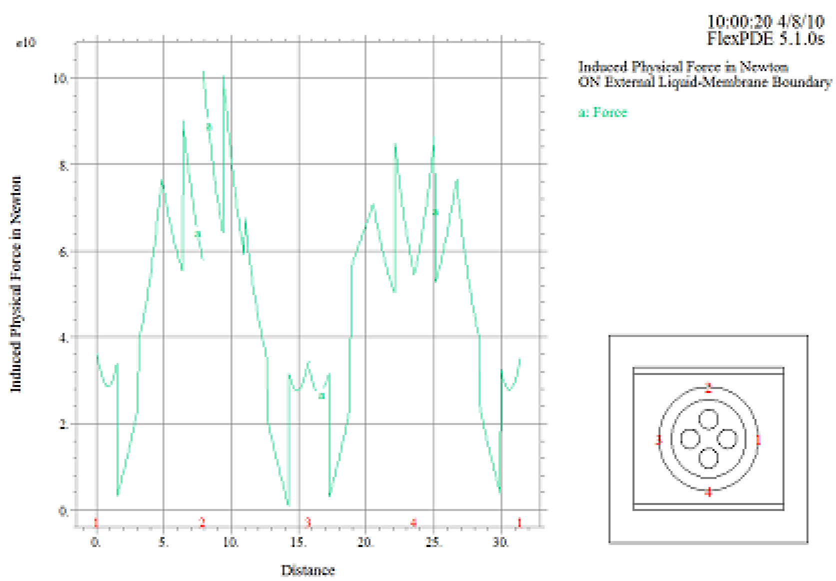


Model-PEF-5-2-CiGr2010: Grid#1 p2 Nodes=895 Cells=410 RMS Err= 0.0014

Figure.5 Voltage along cytoplasm-membrane boundary

III.3 INDUCED PHYSICAL FORCE IN THE CELL.

It is known that electric energy brought to the plaques are transformed into electromagnetic energy carried by the electric field inside the system. The variation of that energy results then according to virtual work theorem into a field of physical forces that could bring an electric, for instance a polarized particle, to move. Figure 6 shows an evolution of that force along the exterior surface of the cell membrane. We can here deduce that the cell will increase in volume exteriorly in the direction of points 2, and 3 of our study case when the applied voltage will reach a certain amount depending on the cell constitution.



Model-PEF-5-2-CiGr2010: Grid#1 p2 Nodes=895 Cells=410 RMS Err= 0.0014

Figure.6 Physical Force applied on cell external membrane surface

III.4 CASE OF A PULSED ELECTRIC FIELDS

III.4.1 VOLTAGE ALONG AN AXIS OF THE CELL

The study proposed in this paper allows to fixe different forms with respect to time of the applied voltage. We have chosen the pulsed formed shown on Figure.8, curve a. The value of the applied voltage will vary with time, so electromagnetic behaviour of the system will follow. Electric and potential lines, instantaneous voltage at any physical point of the system, and other quantity like applied force, or induced pressure, will also vary accordingly. Figure.7 shows at a fixed time, how the value of the voltage varies along an axis of the system going from points in red 1 to 2.(Fig.7). The voltage drop across the cell membrane can also be read on that figure 7, the centre of the cell being placed at 0 on X axis.

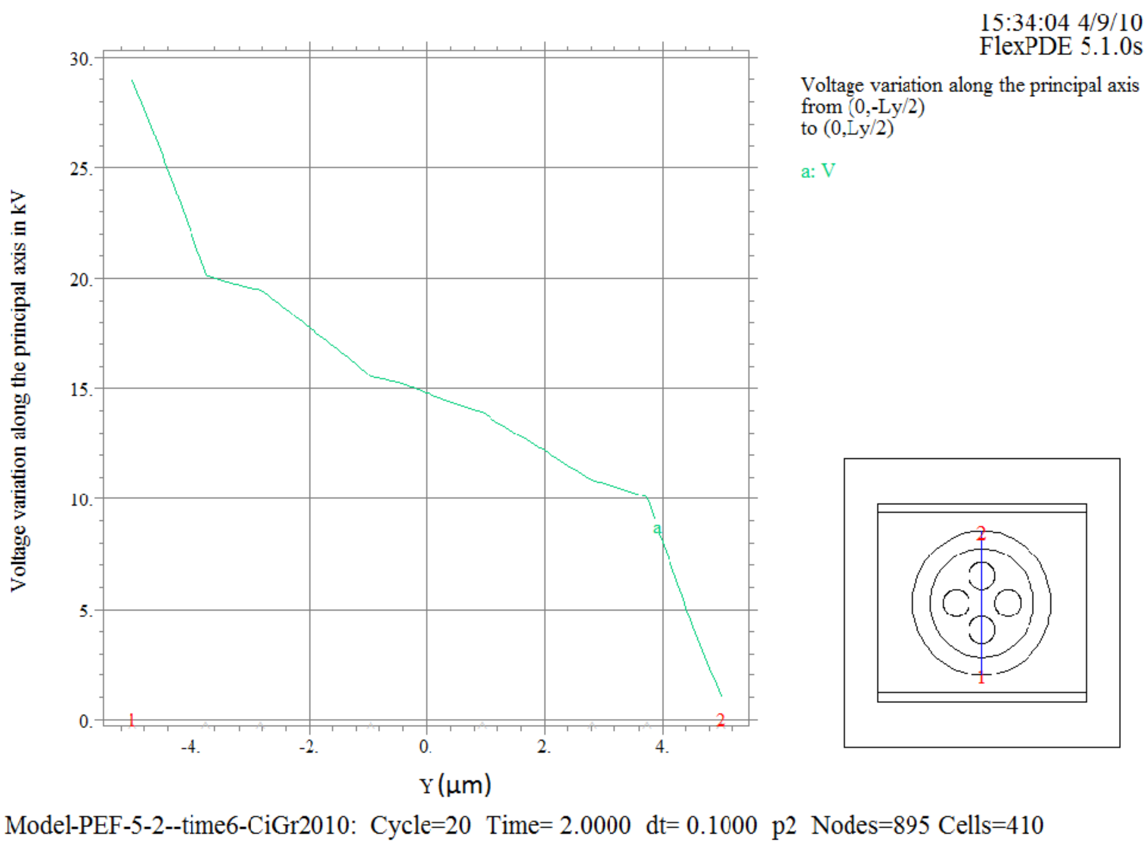


Figure.7 Voltage Evolution inside the cell at 2 µs (Case of an applied PEF)

III.4.2 ALLPIED P.E.F. AND INDUCED PULSED ELECTRIC VOLTAGE INSIDE THE CELL

We can also observe on figure.8 the variations with time of the voltage at different points inside the cell. We so noticed as it was expected, that those voltages, here at points a, b, c, d, on the cell interior membrane surface, behave like the applied voltage, but different amplitudes depending on their position with respect to the source which is here the plaque carrying point e (Fig.8).

It should be mentioned that the study opens the possibility of applying periodic voltages of different frequencies and durations, and even allow to calculate the capacitance of each element when its permittivity is know.

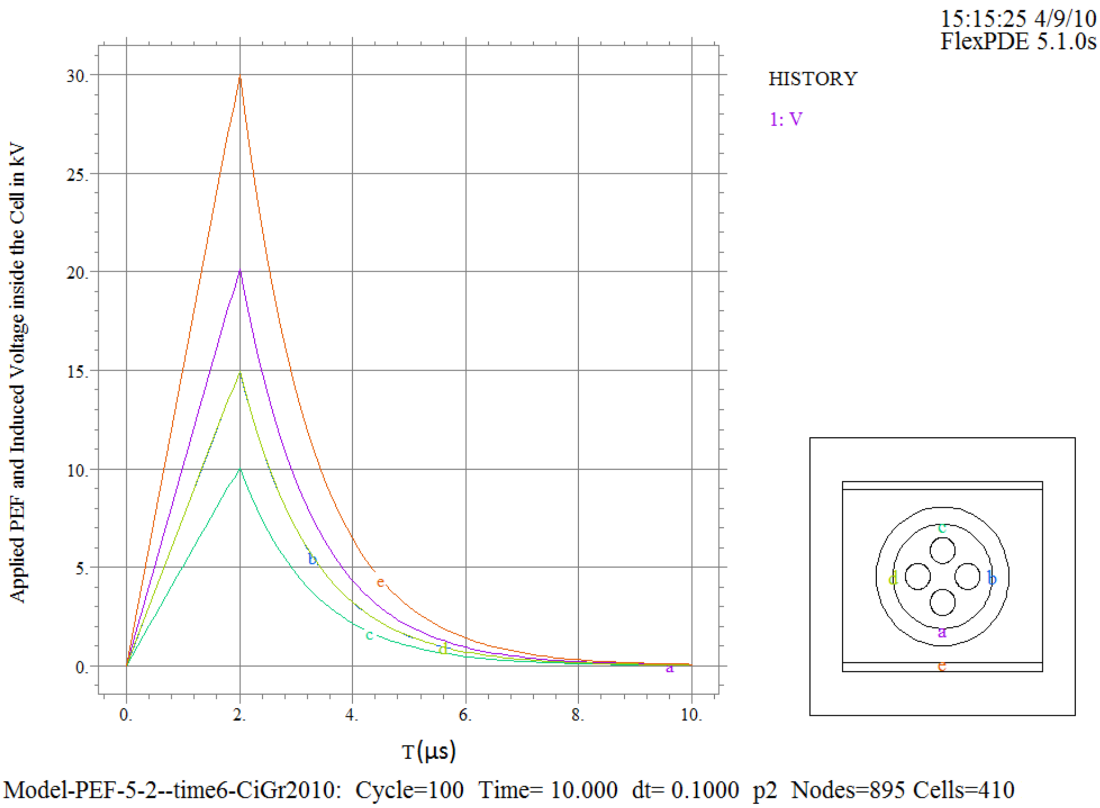


Figure.8 Applied PEF (e) and induced pulsed voltage inside the cell at points: a, b, c and d

IV. CONCLUSION

We have presented a study that brings some lights on the treatments of liquids foods infected by Saccharomyces Cerevisiae microorganisms. The study has supposed some hypothesis, and brought the calculations owing to Maxwell equations and some written Finite Elements Codes, of electric phenomenon that appeared inside the cell placed in a liquid and submitted to high pulsated fields. So the behaviours of different quantities like the voltage have been made possible to be observed. The study also opens feasibility of other investigations such as précised studies with real characteristics of different components of the cell, different characteristics, and contexts.

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