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AN INNOVATIVE AND NON-INVASIVE TECHNOLOGY FOR PEF FOOD PROCESSING

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Abstract

The use of pulsed electric fields (PEFs) is a mature technology used in the industrial processing of food, for example, fruit juice. It is however restricted to liquid (pumpable) food and involves metal electrodes in direct contact with the foodstuff – i.e. it is at present an inherently ‘invasive’ technology.

Recently, Loughborough University has undertaken an experimental programme aimed at demonstrating a new and ‘non-invasive’ technology that uses an antenna coupled to a fast high-voltage pulse generator to produce an intense pulsed electric field. The machine that has been built and undergone preliminary testing uses a Tesla-transformer-based pulse forming line generator coupled to a Valentine antenna to produce very intense electric fields in water.

The technology developed offers considerable scope for use with any type of food, including solid foods such as meat. Apart from the much greater volume available for processing, and other more or less obvious advantages, the new technique is also *highly energy efficient* as, unlike the existing invasive approach, it does not drive a current *through* the food being processed.

The paper presents the experimental equipment and explains the type of sensors that need to be developed for measurement of the electric field produced. Some of the major implications the technique may offer for the future of PEF food processing are introduced.

I. INTRODUCTION

The first results for PEF research applied to food processing appeared in the late 1960s [1] and more recently use of the technique for liquid sterilization has widely investigated.. Noteworthy results have been reported by Old Dominion University, Washington State University and Ohio State University in the USA, Kumamoto University in Japan, the Technical University, Berlin in Germany, Technical University of Delft in the

Netherlands and the Efremov Institute in Russia. In the UK important results were obtained by pulsed power groups at Strathclyde University and more recently at Loughborough University, when results providing a first step towards clarifying the mechanism for the lethality of ns-duration electric field pulses on prokaryotes were reported [2].

Briefly, the action of a PEF on a biological cell can be explained by considering its effect on membranes, the outer or plasma membrane and the inner membranes separating subcellular structures such as the nucleus. These membranes isolate regions of different materials, whilst at the same time facilitating the flow of selected ions and molecules between the regions [3]. The membranes are good electrical insulators, and the application of a strong electric field for a time comparable with their characteristic RC time (about 1 μ s for the outer membrane) results in a charge redistribution and the build up of a transmembrane voltage. Once this reaches a threshold of approximately 1 V, the membrane permeability increases and cell death may result, by a phenomenon termed irreversible electroporation.

Most recently, it has been demonstrated that by applying much faster pulses (tens of ns down to 10 ns), with field strengths up to 100 kV/cm, the intracellular membranes of the nucleus or the mitochondria can also be affected. Very fast and strong pulses can trigger apoptosis (programmed cell death), a key phenomenon already being exploited for medical purposes such as cancer treatment. To date however, neither the established outer membrane electroporation induced by μ s pulses nor the intracellular interactions triggered by ns pulses are satisfactorily understood [3]. Nevertheless, this has not prevented the development of PEF technology for the bacterial decontamination of industrial liquid food [4].

In commercially available systems for PEF processing, production of the required voltage pulses uses either conventional Blumlein generators or generators similar to those found in radar power sources [5], both with a high pulse rate. The liquid is passed through a number of treatment chambers or cells, in each of which it is exposed

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to a number of pulses. ***In all cases***, even when generators from radar systems are used, ***there is a pair of electrodes*** in each cell between which the electric field is applied and which are ***in direct contact*** with the liquid. This technology is therefore termed ***invasive, and it can be used only with liquid (or pumpable) food!***

To the best of the authors' knowledge, Diversified Technologies in the USA is the only present manufacturer of industrial scale PEF machines [5] and at least one company in the USA (Genesis, [6]) uses the technique in the processing of a range of fruit juices with an extended shelf life of up to four weeks. A significant feature of their advertising is that, due to the relatively low temperature attained, the flavor of the product is much better than that of those produced by conventional pasteurization.

II. THE NOVEL NON-INVASIVE METHOD COMPARED TO CONVENTIONAL INVASIVE TECHNOLOGY

The novel non-invasive method proposed here is very simply a technique in which the PEF is generated with the aid of an antenna powered by a fast high-voltage generator. What type of antenna, and consequently which frequencies are best for this application, are both subject for future research.

In what follows, the most important issues regarding industrial PEF systems applied invasively to liquid (pumpable) food are outlined and the differences from and possible advantages over the proposed non-invasive PEF technology are highlighted.

i) To increase the overall effectiveness, i.e. to minimize the number of PEF shots required to lower sufficiently the number of living bacteria, the applied electric field must exceed a certain threshold level. The aim is for at least a 5-log reduction of most pathogens, as obtained with a conventional pasteurization process, after which the food must be kept refrigerated. There is a critical electric field strength below which bacteria are not killed. However, applying too strong a field is uneconomic and, although the optimum strength depends on many factors, almost all successful PEF machines use electric fields with μ s-time pulses and intensities between 30 kV/cm and 40 kV/cm.

Due to the much shorter pulses that can be produced by a reasonably sized antenna and taking into account that faster pulses require more intense fields it is anticipated that it will be necessary to generate inside the food sample electric fields having peak values of at least 200 kV/cm and because each pulse duration can only be a

few tens of ns (or even less), a very high repetition rate will be required.

ii) All PEF systems presently in use are invasive, with large currents, sometimes of about 500 A, being passed between a pair of cell electrodes. All authors agree that the current passing through the liquid being treated does not play a significant role and it is only the applied electric field that is apparently important. Very few results are however published and at present there is no absolute proof of this claim. The current certainly deposits Joule energy, thereby causing the local temperature of the liquid to rise substantially, and in some cases cooling is required to avoid the liquid reaching pasteurization temperatures. On the other hand, the temperature of the liquid is very important, with higher temperatures increasing the effectiveness of the treatment because the effect of temperature on the structural fatigue of the cell membrane is to make it more susceptible to electrical breakdown. This synergy is therefore used in practice, with the liquid usually being preheated to around 40°C *prior* to being processed. For preservation of the flavor the final temperature should be less than 70°C and if it exceeds 80°C some flavor is certainly lost.

As no current (apart from a very small displacement current) is passed through either liquid and solid samples during non-invasive PEF treatment, no temperature rise is expected, even following a very large number of pulses. This implies a very important reduction in the energy consumption, making the non-invasive method apparently extremely energy effective.

iii) It is important to note that the inter-electrode current inherent in the invasive PEF technology may also generate unwanted side effects. For example hydrolysis may introduce metal particles from the electrodes into the liquid food or produce toxic chemicals such as hydrogen peroxide (which ironically actually helps in killing micro-organisms!). For obvious reasons, only minimal comments on these effects appear in the literature produced by either equipment manufacturers or food producers.

When using a non-invasive technology, none of these problems arise!

iv) The distance between a pair of electrodes in a cell should be as short as possible to minimize the applied voltage and therefore the energy consumption. However, this presents an obstacle for any 'chunks' present in the liquid. A number of important issues also relate directly to the cell and its electrodes, such as the need for regular cleaning due to formation of surface deposits, replacement because of corrosion every 100 hours or so and, most importantly, accidental electrical breakdown.

When using a non-invasive technology, any difficulties related to the electrodes are eliminated, for the obvious reason that no part of the equipment is necessarily in contact with the food being processed. The limitation, when using an antenna to generate the electric field in air, is its skin penetration depth, which at 100 MHz in the worst case of brine is 2.7 cm, and is normally about 5 cm for meat and tomato juice and about 10 cm for orange and apple juice. More importantly, the method promises, at least in principle, that a much more generous volume can be processed and certainly is not limited to liquid food. The latter may turn out to be actually the most important advantage of the non-invasive method!

v) The shape of the applied electric pulse is important. Square wave pulses, as produced by a pulse forming line, are energetically more efficient than those with an exponential decay obtained by discharging a capacitor (or a Marx generator) into a resistive load (the liquid). The rise time of each electric pulse is apparently unimportant. However, the electric pulse should (for obvious efficiency related reasons) achieve the threshold value as quickly as possible and a fast rise time is therefore advisable. Bi-polarity of the applied electric pulse is probably less important and work at Strathclyde University [7] showed that bi-polar pulses give a very slight increase in efficiency over mono-polar pulses, and only under certain conditions. This result is not however trivial, as any alternating electro-mechanical stress imposed on a membrane will, at least in principle, induce an enhanced structural fatigue.

In the non-invasive technique this problem can be easily overcome.

vi) The conductivity of the liquid passing through the treatment cells effectively changes the load impedance and therefore constitutes a potential source of great danger to any pulse power generator used for invasive treatment. To avoid this usually requires permanent monitoring of the liquid conductivity which, for example in the case of orange juice, can vary by 100% due to changes in the raw material.

With the non-invasive PEF technology the sample conductivity will certainly have a much reduced effect on the generator.

vii) According to the available literature there is an orientation effect, and to produce a given level of decontamination in a rod-shaped bacteria by a field applied radially will require pulses having a five fold increase in the intensity of a field applied axially. Some level of fluid turbulence is therefore generated in industrial systems, to ensure that the bacteria are attacked at various angles as they pass through the treatment cells

where the only direction of the applied electric field is along the two electrodes.

For non-invasive PEF, at least in principle, in the near field of some antenna such as a simple dipole or monopole this problem is solved inherently as equally powerful electric fields are produced in their immediate vicinity (i.e., in the near-field region), along both radial and axial directions!

viii) For each bacterium there are certain optimum conditions and most PEF machines cannot usually destroy viruses and spores!

The optimum conditions for antenna treatment will require a long research programme with an associated degree of risk.

III. UNIQUE POSSIBILITIES OFFERED BY THE PROPOSED NON-INVASIVE PEF METHOD

As proposed, the non-invasive PEF method offers various novel features, including an increased energy efficiency combined with the possibility (at least in theory) of a larger treatment volume and the possibility (again in principle) of processing solid foods such as pre-packed fresh meat, salads, etc.

If successfully proved in practice, application of the antenna-based method will allow food (both liquid and solid) in standard packs to be processed in a special room on, for example, a supermarket premises, thereby increasing the shelf life and reducing the (accepted) traditional losses. The reduction in wasted food would certainly provide a very significant economy.

Another very important application of the non-invasive PEF method could be to speed up the ageing process in bottled wine. The number of examples of possible applications is large such as in outer space exploration and the defense industry.

IV. GENERATION AND MEASUREMENT OF VERY INTENSE ELECTRIC FIELDS IN THE NEAR-FIELD REGION OF AN ANTENNA

An antenna can in principle generate extremely intense fields in the near-field region. Analytic calculations of the electric fields produced in this region are available for simple geometries such as a dipole, a monopole or a helical antenna. It is perhaps reasonable to

imagine that the electric fields are generated in water with the pre-packed food (containing mostly water) being immersed very close to the antenna structure. Otherwise, not taking into account possible losses by air breakdown, a relatively sophisticated lens to concentrate the energy in the target will be required in the case of the antenna generating electric fields in direct contact with the air.

In the future research programme, one of the most important issues will certainly be the design of an optimized impulse antenna configuration, most likely including metallic reflectors.

However, just to provide a feel for the numbers required, consider the simplest antenna in the form of an 'infinitesimally small' (i.e., $L \ll \lambda$) and 'very thin' (i.e., radius $\ll \lambda$) dipole of length $L=4$ cm, operating at a frequency of 100 MHz (wavelength $\lambda=3$ m) in water, for which the electric field E generated in the near-field region (i.e. $kr \ll 1$) at a distance r from its axis is [8]:

$$E(r) = \eta \frac{I}{2\pi kr^3} L, \text{ where } \eta=42 \Omega \text{ and } k = \frac{2\pi}{\lambda}. \text{ If a}$$

current $I=5$ kA is driven through the antenna the electric field produced at $r=3$ cm from its axis will be almost 240 kV/cm. How to generate the required current is outside the scope of the present speculative discussion.

In Figure 1 the results of a more detailed calculation are given for a monopole antenna in water driven by a 1 MV pulse rising in a few ns.

The accurate measurement of extremely intense pulsed electric fields near an antenna is not a simple task and requires dedicated instrumentation, which should not interfere in any way with the antenna. Our proposal is to develop ultrafast photonic sensors based either on the Kerr effect in water or the Pockels effect in a crystal. In the second case, a supplementary calibration is required. Work is underway on the design of these sensors.

V. FIRST PRELIMINARY TESTS AT LOUGHBOROUGH AND THE WAY AHEAD

Using a Tesla-driven generator technology, well proven at Loughborough, a very preliminary non-invasive PEF system for food processing was very recently assembled as shown in Figure 2. It consists of a Tesla-charged 0.5 MV PFL, discharged at a PRF of 200 Hz and with a rise time approaching 1 ns by a SF₆ filled spark-gap into a Valentine type antenna. A plastic tube allows the antenna to be operated in water. Apart from the antenna, the system was described elsewhere [9] and with the arrangement assembled quickly from existing parts, no attempt was made to match the antenna to the

generator output. Simple preliminary experiments with shrimps were very successful, indicating a high rate of mortality after application of just 2-3 electric field bursts.

A second round of experimentation, which will be prepared with the aid of Campden and Chorleywood Food Research Association (UK), will be critical in quantitatively assessing the treatment efficiency in respect to microscopic bacteria.

Because of the many unknown parameters, developing the non-invasive method to the level required for an industrial application is too difficult a task to be accomplished by Loughborough alone and collaboration is already established with the Laboratoire de Genie Electrique, Universite de Pau (France). Application for European funding for a research network dedicated to this subject is seen as a first priority.

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Figure 1 Electric field distribution around a monopole in water generated by a 1 MV impulse with a few ns rise time

Figure 2 Non-invasive system installed in laboratory
Note the vertical plastic tube surrounding the antenna and filled with water