A novel and non-invasive Pulsed Electric Field technique for industrial food processing

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Keywords: food processing, electric fields, pulsed power

Abstract

A novel and non-invasive pulsed electric field (PEF) technology for use in the food processing industry is under development at both Loughborough University (UK) and the University of Pau (France). The technology uses an antenna coupled to a high-voltage pulsed generator to produce short duration pulses of very intense electric field strength.

In the Loughborough scheme, a Tesla transformer charges an oil-filled pulse forming line to more than 500 kV, and electric fields are generated by a pulsed antenna with a rise time of 1 ns with a figure of merit of about 130 kV.

In the Pau scheme, a gas pressurised pulse forming unit, comprising a peaking stage and a crowbar switch, is incorporated into the last stage of a ten-stage Marx generator. When a Valentine travelling wave antenna is attached, the overall system is capable of generating electric fields with a rise time of 300 ps with a figure of merit of 450 kV.

During the common research programme, the combination of a Tesla transformer and an ultrafast Marx generator technology will bring complementary improvements in the design of intense pulsed electric field generators and allow measurements to be made over the wide radiated field frequency spectrum, essential for the present research.

The novel non-invasive PEF technology offers considerable promise and in principle opens the possibility to process for the first time solid foodstuff such as meat. A possible major potential application also exists in the wine industry, with the possibility of accelerated ageing after bottling.

The many aspects of commercial implications of the successful development of the novel technique will be highlighted.

An essential requirement arising in the common research programme is the measurement of intense fast transient electric fields. Field measurements are conventionally performed using D-dot probes and special purpose antennae, but since these methods are unsuitable for the present application both Loughborough and Pau are developing fast electro-optic sensors based on the Kerr effect for measurements in water and the Pockels' effect for measurements in air. These techniques offer several advantages over conventional sensors, such as high bandwidth, miniaturisation, non-invasion and complete immunity to electromagnetic perturbing influence from the high-voltage generators, which together make them extremely suitable for innovative electric field treatment applications. However, some precautions have to be implemented to ensure reliable measurements and the paper will present the major principles involved in the design of dedicated experimental arrangements.

Preliminary results will be presented and evaluated from the experimental research programmes underway at the two Universities.

1 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 of 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 prokariotes were reported [2].

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 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!***

2 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) Almost all successful PEF invasive machines use electric fields with µs-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 invasive systems presently in use are generating, large currents through the liquid, sometimes of about 500 A, between a pair of cell electrodes. *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) Inter-electrode current inherent in the invasive PEF technology generate unwanted side effects. *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. *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. *In the non-invasive technique this issue can be easily solved.*

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. 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. *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.*

3 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.

4 Preliminary work at Loughborough and Pau Universities

Loughborough

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 Fig. 1. It consists of a Tesla-charged 0.5 MV PFL, which can be discharged at a PRF of 200 Hz and with a rise time approaching 1 ns by a SF_6 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 [3] 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 a very few 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

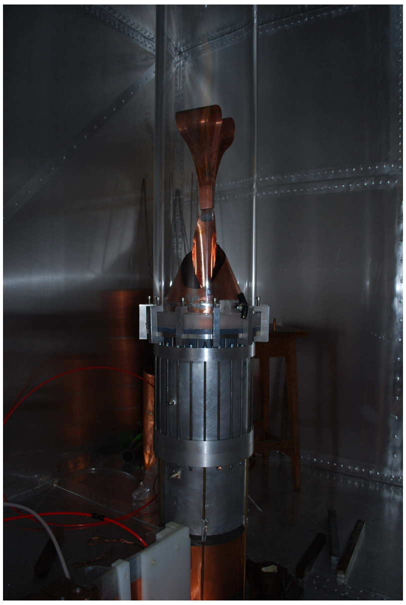


Figure 1 Non-invasive PEF system installed in Loughborough laboratory. Note the vertical plastic tube surrounding the antenna and filled with water

critical in quantitatively assessing the treatment efficiency in respect to microscopic bacteria.

Kerr-effect experiments, with the aim of developing a reliable tool for measuring accurately the pulsed electric field in the close vicinity of a metallic structure also started recently. As ***the literature provides very contradictory values of the Kerr constant for water***, a preliminary electro-optic arrangement based on a water cell is necessary to determined it, under the characteristic pulsed conditions of the future PEF experiments. The two electrodes of the water cell have a Bruce-type geometry with a flat region of diameter D, and are mounted parallel to each other, the distance d between them being controlled very accurately. Voltage pulses are generated using a TG -70 generator, a trigger generator produced by L3-Sciences, USA, capable of producing voltages up to 140 kV. A typical voltage pulse V(t) generated across the water cell and its corresponding light signal I(t) modulated by Kerr-effect, are both presented in Fig. 2. The latter can also calculated from: $I(t) = I_{max}\sin^2\left[\pi LB(V(t)/d)^2 + \alpha\right]$ where I_{max} is the maximum light intensity, $L = D + \pi/d$ and α is the angle between the polarisers. The preliminary conclusion is that at the present level of precision, ***the Kerr constant of water is most likely*** $B_1 = 4.082\cdot10^{-14}$ ***m/V²*** ***at*** $\lambda_1 = 630$ ***nm***. This value has been calculated before the start of the experiments from $B_2 = 4.4\cdot10^{-14}$ m/V^2 at $\lambda_2 = 589$ nm [4], using Havelock law together with the water refractive index dispersion. More precise experiments are however required for an increased confidence.

Pau

Pau's powerful 'all electric' system (Fig. 3) is constituted from a DC/DC 60 kV autonomous power supply, a subnanosecond Marx generator, generating a few hundreds kV output voltage and incorporating its own pulse forming

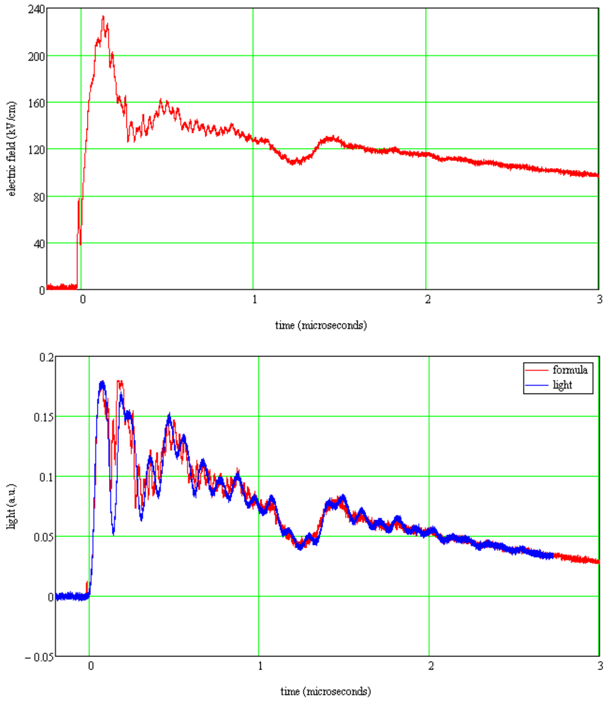


Figure 2 Kerr-effect experiment
(upper) pulsed electric field obtained as V(t)/d
(lower) experimental light signal compared with I(t)

device, and a travelling wave high gain antenna improved to withstand very high amplitude pulses in a large frequency band. According to the design specifications, the system generates radiation in the bandwidth ranging from 300 MHz to 2.5 GHz [5].

As a validation example, using air-SF_6 mixture, voltage pulses with an amplitude of 250 kV and having a rise time of 300 ps were measured at the output of the generator. Due to a highly-efficient original UWB antenna design (Fig. 3), it was proved in practice that the radiating system can withstand voltage pulses in excess of 250 kV without introducing significant pulse distortions. Consequently, the peak-to-peak figure-of-merit value of the radiated field measured in air has been measured to be close to 450 kV.

For PEF treatment, a first option is to have the food immersed in water. To investigate this alternative, the electric field generated in a water sample positioned in the high-field region at the end of the antenna water (i.e., 30 cm after the strips end, see Fig. 4), was modelled using the time-domain electromagnetic software CST Microwave Studio.

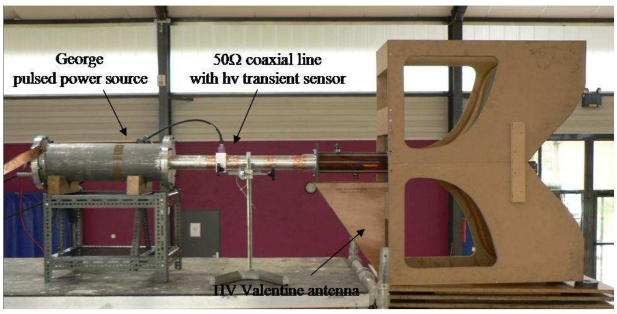
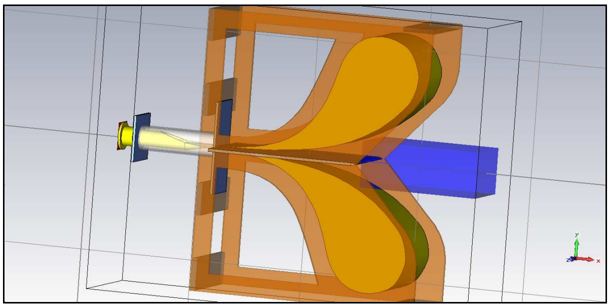
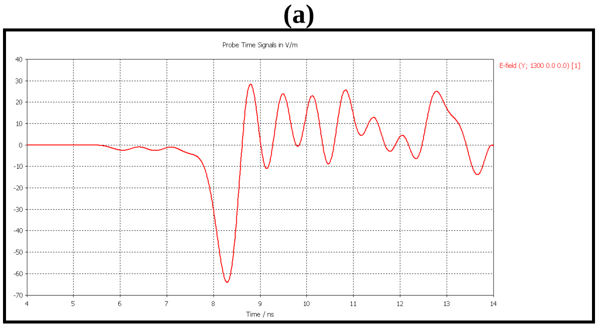


Figure 3 Repetitive high power UWB radiation source



(a)



(b)

Figure 4 Modeling the Valentine antenna with a water volume placed in the high field region
(a) schematic of the arrangement
(b) result from modeling

The first results, although interesting, are however not encouraging: for a typical 200 kV pulse generated by the Marx generator, the maximum electric field is only 4 kV/cm. The result is explained by the impedance mismatch of the antenna when water is used as dielectric medium at the output.

The study proved that the source, although capable of generating very strong axial electric fields in air (as it was designed for) is however not suitable for working in a water environment and therefore further options need to be explored. In a second option, matching lenses are positioned between the water sample and the air environment, to significantly improve the maximum radiated electric field value in the sample. This technique is not straightforward however and may not be the ideal arrangement. As a third option, work will start soon on the design of a novel antenna, capable of producing strong electric fields while submerged in water.

Work is also ongoing at Pau for the development of an electro-optic arrangement for the precise monitoring of very intense and fast rising electric field transients generated in water. Preliminary considerations, based on a literature survey, have concluded that the best way forward is through the use of either Pockels or Kerr effect, depending on the dielectric. Preliminary tests are under way at present with the aim of determining the Kerr constant for water using both 630 nm and 1550 nm wavelength laser sources. The electric part of the required electro-optic arrangement is presented in Fig. 5 and it consists of an energetic Marx generator named Leonardo [6] (right hand side in Fig. 5) which delivers a 3 ns rise-time high voltage pulse into water vessel (left hand side in Fig. 5). The optical part, presented in Fig. 6, is currently developed separately. In particular, the 1550 nm configuration should in principle allow obtaining 7 GHz bandwidth signals, leading to highly accurate transient electro-optic measurements.

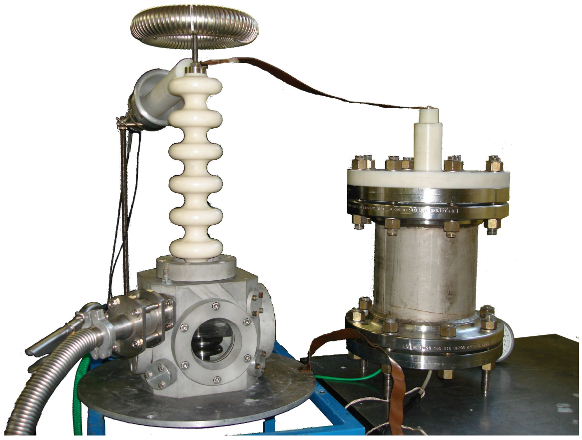


Figure 5 The electric part of the Pau electro-optic arrangement for the study of Kerr effect in water

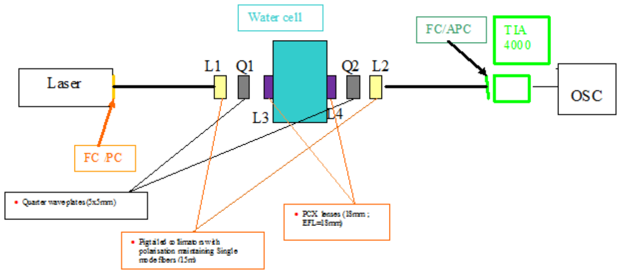


Figure 6 Schematic of the optical part of the Pau electro-optic arrangement for the study of Kerr effect in water

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