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Fast flow-through non-thermal pasteurization using constant radiofrequency electric fields

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ABSTRACT

Pulsed electric field technologies have captured the attention of researchers on food pasteurization because of their non-thermal inactivation mechanism, which results in fresh-like products. Nevertheless, high voltage pulsing required by these technologies implies complex and costly generators. Here, as an alternative, it is proposed a method, partially inherited from research on cell electroporation for gene transfection, in which the liquid to be treated flows at high speed through a miniature chamber where the electric field is permanently applied. In particular, it is proposed that the constantly applied electric field consists of an AC signal (>100 kHz) so that electrochemical by-products are minimized. The method, while being compatible with batch processing, will allow use of lower voltages and will avoid the pulsation requirement. The proposal is accompanied by a numerical study and an in vitro study which demonstrate its feasibility.

Industrial relevance: This paper describes an electroporation based method for non-thermal pasteurization of liquids that, in comparison to existing pulsed electric field technologies, does not require high voltage pulsed generators. The method consists in circulating the liquid at high speed through a miniature chamber where an AC electric field of moderate magnitude is permanently applied. By combining several miniature chambers in parallel and in series batch processing will be possible. Here it is analyzed and demonstrated the performance of a single miniature chamber.

1. Introduction

Mainly due to their simplicity, thermal methods are the basis of most pasteurization technologies intended for food preservation. High temperatures, however, not only inactivate harmful microorganisms but also damage constituents of the medium under treatment, which may result in detrimental effects on nutrients, color, flavor and texture (Alwazeer, Delbeau, Divies, & Cachon, 2003; Lee & Coates, 2003; Polydera, Galanou, Stoforos, & Taoukis, 2004).

In the last decades, pulsed electric field (PEF) technologies have captured the attention of researchers on food pasteurization (Raso & Heinz, 2006). This is in part a consequence of the growing demand for fresh-like foods; unlike thermal methods, PEF technologies do not cause a major impact on the organoleptic properties of treated foods as their cell killing mechanism is specifically targeted at cell membranes (Cserhalmi, Sass-Kiss, Tóth-Markus, & Lechner, 2006; Elez-Martínez, Soliva-Fortuny, & Martín-Belloso, 2006; Espachs-Barroso, Barbosa-Cánovas, & Martín-Belloso, 2003). Moreover, as an additional advantage, PEF technologies have the potential to minimize energy consumption in comparison with other pasteurization and extraction methods (Zhang, Barbosa-Cánovas, & Swanson, 1995). Nowadays, in the context of renewable resources, this last aspect is particularly relevant for efficient oil extraction from microalgae for biofuel production (Sheng, Vannela, & Rittmann, 2011; Zbinden et al., 2013).

Nevertheless, it must be mentioned that, prior to current resurgence of interest in PEF technologies, there were a number of attempts to adopt PEF methods in the food industry at medium and large scale without much success (Allen & Soike, 1966; Beattie & Lewis, 1925). Failure to industrially adopt PEF processing was mostly attributed to the high cost of electrical pulse generators and, to a lesser extent, to their maintenance costs due to electrode erosion and, in fact, both aspects are still not satisfactorily resolved by current PEF technologies (Jeyamkondan, Jayas, & Holley, 1999; Toepfl, 2011).

Cell killing action in PEF technologies is based on the phenomenon known as irreversible electroporation (Palgan et al., 2012), which is very briefly described in the next paragraph.

When a cell is exposed to an external electric field, charge is accumulated on the cell membrane resulting in an artificial increase of the transmembrane potential (TMP). If such TMP increase is large enough, and sustained for long enough, cell membrane permeability to ions and macromolecules will increase very significantly. The increase in permeability is, presumably, related to the formation of nano-scale defects or pores in the cell membrane; from which the term electro-"poration" stems. If the induced permeabilization is moderate, cell membranes will reseal and the cell will be fully viable minutes after field delivery. On the other hand, if the permeabilization is made

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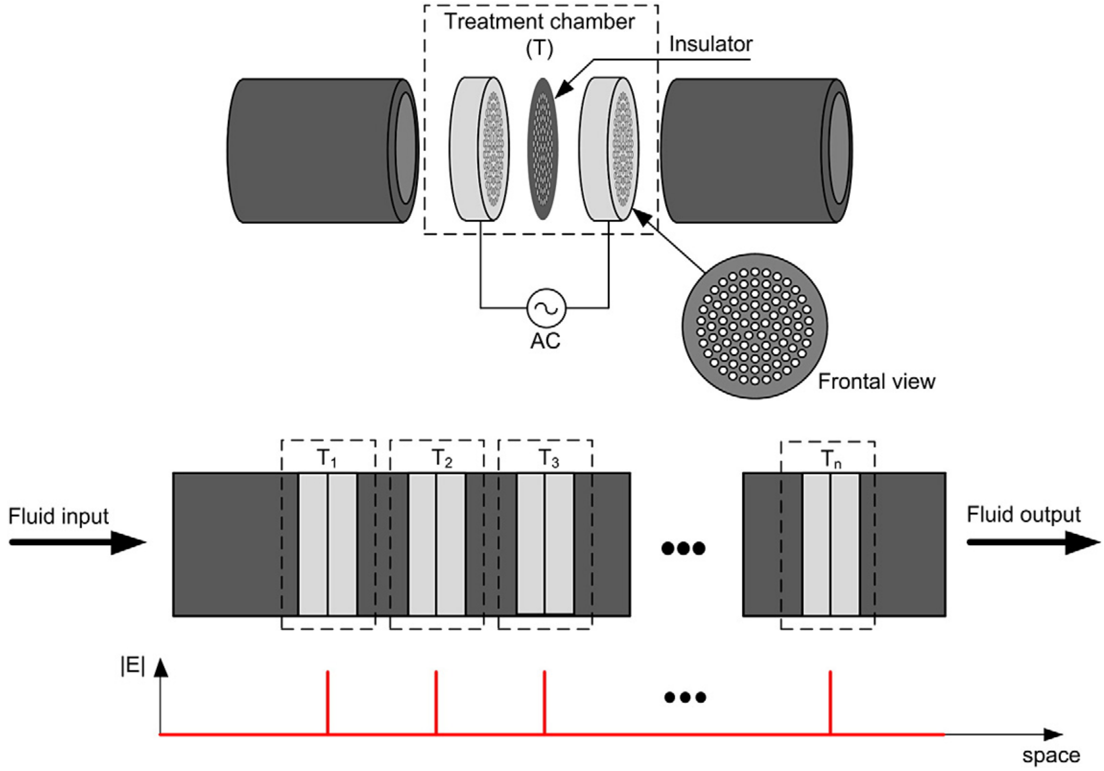

Fig. 1. Realizable implementation of the fast flow through electroporation concept for pasteurization. Top: parts of a single stage treatment chamber. Bottom: Concatenation of treatment stages and representation of electric field magnitude at each section along fluid path.

excessive by delivering very high or prolonged fields, cells will end up dying. The former output is known as reversible electroporation and the later as irreversible electroporation. Both, reversible and irreversible electroporation modalities have important applications in biotechnology and medicine. For instance, reversible electroporation is now a routine technique in microbiology laboratories for *in vitro* gene transfection (Neumann, Sowers, & Jordan, 1989). In addition, during the last fifteen years, reversible electroporation has been applied experimentally and clinically to living tissues for *in vivo* gene therapy (electrogenetherapy) and for enhancing the penetration of anti-cancer drugs into undesirable cells (electrochemotherapy) (Marty et al., 2006). More recently, irreversible electroporation has been proposed and demonstrated as a minimally invasive tissue ablation method (Rubinsky, 2007). Typically, electric fields are not applied as a long single pulse but as a series of brief pulses (from fractions of microsecond to a few milliseconds) as this strategy has been shown to be far more effective in terms of permeabilization for the same field magnitude (Miller, Leor, & Rubinsky, 2005). Moreover, brief pulses of moderate field magnitude also offer a key advantage: Joule heating – always present when electric field pulses are applied – is minimized.

In current PEF technologies, the liquid to be treated is forced to flow at moderate speed through a relatively long chamber containing electrodes between which high voltage pulses, or bursts, are applied so that the required high electric fields for electroporation are produced. Typically, the delivered high voltage signals consist of either monopolar square pulses or bipolar square pulses. Bipolar pulses are more difficult to generate but minimize electrochemical reactions at the electrodes, which have detrimental effects on both the electrodes and the liquids. Within the chamber, each portion of liquid has to be subjected to a number of short pulses, or bursts, in order to achieve effective inactivation of microorganisms. This limits the speed at which fluids can flow through the chamber and, more importantly, it imposes severe constraints on the voltage generator. Among those constraints, the most demanding feature is short pulsation. To generate high voltage pulses of short duration ($<1\ \mu s$) is technically feasible but it comes at an economic cost; particularly because it requires sophisticated high voltage and high-current switches. Spark gap switches – which show maintenance issues – were predominant in the past and now are being replaced by solid state switches (e.g. IGBTs), which are progressively achieving the required features in terms of speed and power. Costs associated with the generator would be greatly reduced if instead of requiring pulsated voltages it was possible to employ a constant high-frequency AC voltage. The generator in this case would be similar to those employed in RF heating in food processing (Zhao, Flugstad, Kolbe, Park, & Wells, 2000).

As mentioned, electroporation is not only employed for food processing but also for biomedical applications. In particular, electroporation is

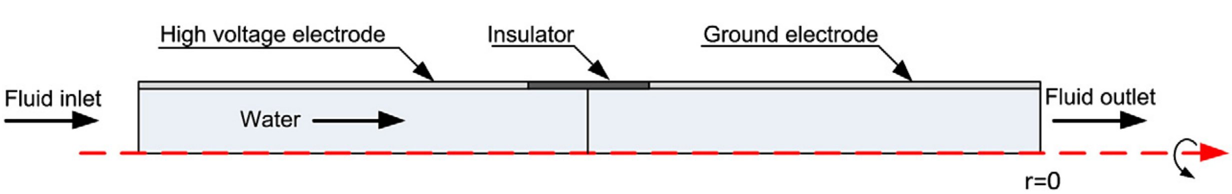

Fig. 2. Main parts of the model employed to numerically simulate a single conduit.