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Full Length Article

A comparative study on the performance of three treatment chamber designs for radio frequency electric field processing

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ABSTRACT

The performance of three different chamber designs: co-linear, Steinmetz and parallel-plate, for radio frequency electric field (RFEF) processing of liquid foods was evaluated and compared. The study was conducted via a computational model that predicted the electric field, flow, and temperature distribution in those three chambers. The parallel-plate, in spite of having the highest electric field peaks, exhibited not only the most uniform electric field distribution inside the treatment zone but also the most homogeneously distributed velocity profile along with the lowest temperature increase and energy consumption. The model was validated by comparing the predicted and experimentally measured outlet temperatures. Experiments of *E. coli* inactivation were performed in all three chambers at a volumetrically averaged electric field strength of 13.2 kV cm^{-1}, a treatment time of 500 μs and outlet temperatures in the range of 20–50 °C showing equal inactivation given the uncertainties of microbial population quantification methodology.

1. Introduction

RFEF is a non-thermal food processing technology that uses radio frequency fields to inactivate microorganisms in liquid foods at sub-pasteurization temperatures (Geveke and Brunkhorst, 2004). This technology, which is similar to Pulsed Electric Fields (PEF), applies high intensity electric fields in a frequency range from 15 to 70 kHz, via an active and a ground electrode to foods flowing through a well-insulated treatment chamber. If the electric field strength is above a certain threshold, microbial inactivation occurs due to electroporation (Coster and Zimmermann, 1975), which is the formation of pores on the membrane of microorganisms, inducing leakage of intracellular liquids, subsequently leading to cellular death (Sale and Hamilton, 1967). The efficacy of PEF is sometimes questioned due to unwanted electrochemical reactions at electrode–solution interface (Chafai et al., 2015; Morren et al., 2003) causing concerns related to food safety (Evrendilek et al., 2004), degradation of food quality (Sun et al., 2011), and shortening of the electrode lifetime (Gad et al., 2014; Roodenburg et al., 2005a; Roodenburg et al., 2005b). In spite of similarities in mechanism of inactivation, PEF requires high capital investment (Jeyamkondan et al., 1999; Trujillo and Geveke, 2014) while RFEF uses low-cost equipment to generate electric fields.

Treatment chambers are integral components of both RFEF and PEF processes. Ideally, they should be designed to ensure a homogenous distribution of lethal agents, such as, electric field strength, temperature and treatment time to achieve a uniform treatment. However, in reality, most designs exhibit heterogeneous distributions leading to the formation of hot spots inside the treatment zone. Those hot spots are localized portions of fluid where the electric field and temperature are highly elevated increasing the risk of dielectric breakdown of the chamber, food contamination, electrode erosion, over-processing and destruction of heat liable nutrients (Fiala et al., 2001).

Continuous flow chambers are classified in terms of the direction of the electric field relative to the direction of flow. A co-linear design produces electric fields parallel to the direction of flow and has been frequently used in RFEF studies on a variety of microorganisms, such as, *Lactobacillus plantarum* (Geveke et al., 2009), and *Escherichia coli* (Geveke and Brunkhorst, 2004; Geveke and Brunkhorst, 2008; Geveke et al., 2007), for liquid foods, such as, apple cider (Geveke and Brunkhorst, 2008; Geveke et al., 2009), orange juice (Geveke et al., 2007), and apple juice (Geveke and Brunkhorst, 2004). A parallel-plate design generates electric fields perpendicular to the direction of flow. This design has been used for inactivation of *E. coli* in water (Uemura and Isobe, 2002), and *Bacillus subtilis* in orange juice (Uemura and Isobe, 2003). A novel

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Steinmetz design was proposed in our previous work for the inactivation of *E. coli* in saline water (Masood et al., 2017). The treatment zone of the chamber was defined as the intersection volume of two perpendicular cylinders of equal radius. The electrodes are fitted through one of the cylinders, while the liquid is allowed to flow through the second cylinder. The edges of the electrodes were filleted to avert the formation of high electric fields which could occur at sharp corners. The chamber was designed with the help of computational modelling by filleting the edges in a way that the electric field distribution in the treatment zone is relatively homogeneously distributed in comparison with other conventional designs. Another form of Steinmetz design, but with rounded electrodes, was employed for treatment of *Saccharomyces cerevisiae* in water (Geveke and Brunkhorst, 2003). A co-axial design, where the direction of the electric field points radially while the flow moves axially, was not considered in this study because electrodes with large surface areas push excessive currents, which is undesirable for RFEF processing. This is because larger areas reduce the chamber resistance increasing the current at a constant voltage drop between the electrodes.

A comparative study of the performance of different chamber designs has neither been conducted thoroughly for RFEF nor PEF. Co-linear chambers are normally preferred for continuous processing because of a longer separation of the electrodes, reducing the likelihood of arcing. However, longer separations of the electrodes increase heat losses due to Joule heating. A persisting problem with co-linear chamber studies (which applies to RFEF as well as PEF) is that the electric field strength is conventionally estimated as the peak voltage between electrodes divided by the length of the treatment zone. This method overestimates the actual electric field strength inside the treatment zone at short electrode gaps, or underestimates if the electrodes are separated with longer distances to avoid arcing as done by (Geveke and Brunkhorst, 2004). This error in estimation has been reported by Buckow et al. (2012) and Lindgren et al. (2002) to be around 20% of the conventionally calculated electric field. The parallel plate design has been generally disregarded for continuous processing as it is more prone to arcing. It is known that co-linear chambers can withstand higher peak voltage drops between the electrodes without experiencing arcing compared to the parallel plate. However, parallel plate chambers can achieve the same electric field strength as a co-linear chamber at lower peak voltages if a correct estimation of electric field on co-linear chambers is performed. The Steinmetz design, in spite of offering a more homogenously distributed electric field by diminishing high peaks of the electric field, forms flow recirculation-stagnation regions where hot spots are formed due to longer local residence times. Therefore, this work aims to evaluate and compare the performance of co-linear, Steinmetz, and parallel-plate treatment chambers. These chambers were modelled and analysed using COMSOL Multiphysics® by coupling the electric field, fluid flow and heat transfer phenomena in a three-dimensional geometrical configuration. A comparison of electro-, hydro-, and thermo-dynamic profiles of these three chamber designs can reveal their strengths and shortcomings.

Computational modelling allows characterisation of the RFEF treatment chambers in terms of process variables distribution, showing their level of treatment uniformity. Modelling is preferred because it is intricate to experimentally identify regions of electrical field enhancement, flow stagnation, and over-heating due to the confined space of treatment zone. Computational modelling has been used to characterise PEF systems (Buckow et al., 2010; Buckow et al., 2011; Krauss et al., 2011; Knoerzer et al., 2012), however, elaborate computational investigations for RFEF treatment chambers have never been conducted.

The numerical model was validated by comparing the experimentally measured and computationally predicted outlet temperatures from the three chambers that were constructed and operated at conditions that, according to the model, ensure the same electric field, outlet temperature and treatment time. Inactivation studies of *E. coli* in saline water were performed in all chambers to test the hypothesis that the same inactivation should be achieved in all three designs if the electric field, outlet temperature and treatment time are equivalent. This experimental approach allowed direct comparison of the performance of the three designs.

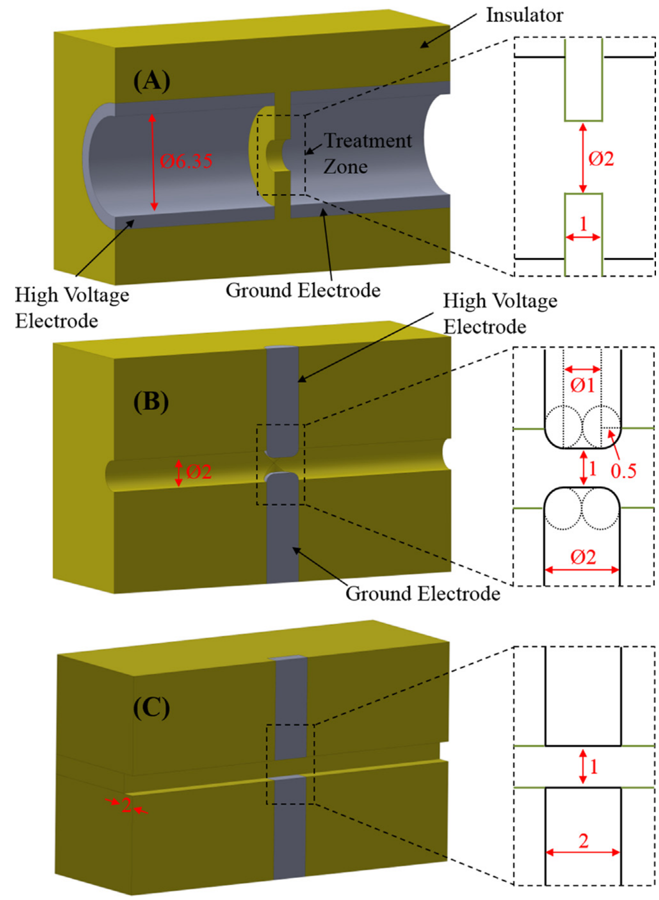

Fig. 1. Isometric views of treatment chambers sectioned through a longitudinal plane passing through the middle of the treatment zone. Liquid flows from left to right. Treatment chamber designs are: (A) Co-linear; (B) Steinmetz and (C) Parallel-plate. Dimensions are displayed in mm.

2. Mathematical model

2.1. Geometrical configuration

Three different geometrical configurations of treatment chambers, i.e. co-linear, Steinmetz, and parallel-plate were built in COMSOL Multiphysics®. The dimensions of these chambers are detailed in Fig. 1. The same chambers were fabricated for experimental studies (see Section 3.1 for construction details). The treatment zone is defined in Section 4.1 as the volume in close vicinity of the electrodes in where electric field strength is higher than the rest of the chamber. Both the geometry of the treatment zone and the shape of the electrodes are known to significantly impact the distribution of both electric field strength and temperature (Knoerzer et al., 2012).