Simulation Study of Coaxial Treatment Chambers for PEF Pasteurization: A Critical Review

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Rai Naveed Arshad[1](✉), Zulkurnain Abdul-Malek[1], Ali M. Dastgheib[2]
[1]Universiti Teknologi Malaysia, Johor, Malaysia
[2]Islamic Azad University, Marvdasht Branch, Iran
rainaveed@yahoo.co.uk

Abstract—A pulsed electric field (PEF) produces pasteurized liquid foods with fresh and nutritional properties. The treatment chamber is a crucial part of the PEF processing system where a high voltage is applied, producing an electric field to treat the liquid foods. The proper construction of the treatment chamber regulates the distribution of the electrical field inside the treatment zone. Mixing of liquid inside the treatment zone is an effective tool to overcome this heterogeneous effect. The coaxial treatment chamber offers a heterogeneous electric field and temperature distribution inside the treatment zone. A helical insulator inside the coaxial treatment chamber provides a mixing effect. In this research, a numerical simulation was done to measure the electric field in different geometries of treatment chambers at different flow rates. The simulation aimed to optimize the new coaxial treatment chamber design. The modelling findings showed homogeneous electrical field strength in the helical treatment chamber. This study provides new insights for industrial-scale setup using multiple helical chambers in a continuous flow PEF treatment.

Keywords—pulsed electric field (PEF), non-thermal pasteurization, treatment chamber, coaxial electrodes

1 Introduction

Sustainable food supply is a primary concern for food industries, governments, and international agencies worldwide [1–3]. Food industries are under continuous pressure to develop processing technologies that simultaneously preserve the nutritional value of foods, improve the bio-accessibility of nutrients, environment friendly and meet consumers' demands of sensory attributes [3, 4]. Numerous research has shown that pulsed electric fields (PEF) processing can successfully disable microbes at low temperatures without affecting liquid food sensory and nutritional attributes [5–7]. PEF processing in food has numerous benefits over thermal processing, for example, low processing cost, less emission, short processing time and minimal effects on nutritional values [8–10]. A high voltage pulse supply provides an electric field to the liquid sample placed in the treatment chamber to conduct membrane electroporation [11]. The transmembrane potential is developed when the applied electric field exceeds a critical value for sufficient time, bringing about cell death [12, 13]. Therefore, electrical field intensity and treatment duration are the most critical factors affecting PEF microbial inactivation performance.

An adequately designed treatment chamber is essential to bring about a much powerful and uniform electric field to either kill or weaken the microorganisms in the juices [14–17]. An increased uniformity is achieved by altering the dimensions of the treatment chamber and its geometry [18]. Modification of the chamber's geometry may include either changing the insulator part or both of the electrodes.

Recently, many research papers have improved the co-linear PEF treatment chamber by examining the consequence of insulator and electrode shape on regulating the electric field and temperature [19–21]. On the other hand, very little attention has been given to the design of the coaxial treatment chamber. The coaxial chamber reduces or eliminates the peak value of the electric field in the treatment area. The electrodes have a large effective area, which results in a strong current flow and a low resistance in the treatment chamber due to the large effective area [22]. Furthermore, it is easy to construct a coaxial treatment chamber and provide well-defined electric field distribution. As a result, the outer electrode surface is enriched by the electrical field in the treatment area and decreased field intensity outside of the treatment area.

The flow rate is the interdependent parameter in the continuous PEF processing and plays an unavoidable role [18, 23]. Laminar flow is a reason for inhomogeneity in most co-linear and cylindrical treatment chambers because a turbulent flow is likely produced with a higher flow rate. A high-power, high-frequency power modulator must thus accommodate the laminar flow to provide the necessary energy per volume element. The Helical Chamber was also the motivation due to the flow geometry because the swirl of the helical treatment zone produces turbulent samples irrespective of its viscosity [24]. Furthermore, it provides an enhanced exposure time with a low rise in temperature. Thus, combining coaxial electrodes with a helical treatment zone can provide uniform electric fields to the entire sample without a dielectric breakdown.

This study simulates and compares the earlier designed coaxial treatment chambers' assembly and the new helical treatment chamber. Then, the uniformity of the electric field intensity was compared with its predecessors. This comparison showed that the helical treatment chamber provides uniform electric field distribution.

2 Literature review

Maximum continuous treatment chambers have designed based on the static treatment chamber, or, additionally, many continuous flow treatment chambers have been replaced by comparable static chambers. Therefore, PEF treatments are enhanced when conducted in continuous treatment chambers through provided exceptional treatment homogeneity [25]. The main treatment chambers' designing objective is to attain a generally uniform electric field in the treatment area. However, a heterogeneous electrical field distribution produces a local improvement of the electric field due to the design of the electrodes [26].

A treatment chamber equipped at greater and consistent electrical field intensities, preventing dialectical malfunctions, is challenging to design treatment chambers. The chambers with parallel plate electrodes typically provide modest throughput but high-treatment uniformity. Collinear treatment chambers provide constant high-throughput operation; nevertheless, they often exhibit poor treatment uniformity. Changing the treatment chambers' design may include form modifications in the design of the insulator or electrode or insert an insulator or metal grid into the designs of the flow shapes [21].

Coaxial treatment chambers can be effectively produced for medium-size volumes and provide well-defined electric field distribution [27]. The formula to find the electric field inside coaxial electrodes is:

$$E = \frac{V}{r \ln\left(\frac{R_2}{R_1}\right)} \tag{1}$$

Where r is the radius of the electric field measurement, R_1 and R_2 are the respective radii of the interior and exterior surface of the electrode.

The temperature change during the PEF treatment ought to be checked and controlled to attain a non-thermal operation. Heat dispersion resulting from ohmic heating is responsible for the unavoidable difference in temperature between the input and exit temperatures (Alkhafaji and Farid, 2007). High voltage pulses created by capacitor discharge contain a limited measure of energy (Q_{pulse}) that achieves the treatment chamber, as characterized [28]:

$$Q_{pulse} = \left(\frac{R_{ch}}{R_T}\right)\frac{CV^2}{2} \tag{2}$$

Where 'C' represents the discharging capacitors' capacitance, 'V' represents the maximum voltage stored in the capacitor, 'R_{ch}' represents the treatment chambers' resistance, and 'R_T' represents the total electrical resistance of the system through which the capacitor is discharged. Repetitive use of high voltage pulses is characterized as energy is discharged into the treated item by heating the treated item (ΔT). Pasteurization of food using PEF influences the dielectric breakdown of the cell membrane rather than the dielectric breakdown of the liquid food [29].

Table 1. Coaxial treatment chamber developed for pasteurization

Dimensions	Study Type	Additional Feature	Observation	Reference
Volume was 8 cm^3, electrodes' gap 0.51 cm	Experimental	Cooling system with electrodes	Work in an electric field higher than 76 kV.cm^{-1} without dielectric breakdown.	[30]
	Simulation		The coaxial treatment chamber has a lower temperature than the collinear chamber. A larger treatment volume (larger gap) in the chamber model resulted in a higher temperature rise.	[31]
Gap 4.9 mm, length of treatment zone 5 cm	Experimental	Separate cooling system with electrodes	A considerable log reduction have found in these designs.	[32]
Volume 30 mL, gap 5 mm	Experimental			[33]
Gap 1 mm	Parallel connection three treatment zones		Increasing the number of treatment zones increase both loading impact and treatment time.	[34]
Volume 300 ml, dimension 15 x 25 x 10 cm	Experimental	NA	Enhanced the shelf life of the treated juice.	[35]
Volume 29 mL, gap 1.5 cm	Simulation	Multi-stage cascaded treatment chambers	Non-homogeneous velocity distribution.	[36]

Table 1 shows different coaxial continuous treatment chambers for PEF pasteurization. Maximum continuous treatment chambers were designed based on the ideas of the static chamber, or, more precisely, many continuous flow treatment chambers have been replaced by comparable static chambers. Therefore, PEF treatments are enhanced when conducted in coaxial treatment chambers as a result of the exceptional treatment homogeneity provided by continuous systems [25]. The primary objective in designing the treatment chamber is to attain a uniform electric field in the treatment area. However, due to the design of the electrodes, an uneven distribution of the electric field may arise, which may result in a growth in the electric field around the electrodes [26].

A cooling system is desirable to preserve the liquid at a moderate temperature inside the designed treatment. This cooling system served as the heat exchanger and located either inside the treatment chamber or between the electrodes since systems with several treatment chambers are often used [26].

3 Materials and methods

Two concentric cylindrical electrodes formed the coaxial treatment chamber. The internal (high voltage) electrode of a diameter 4.5 cm made of hollow Stainless Steel was linked to a power supply. The external (grounded) electrode was made of Aluminium foil and was connected to the ground. A treatment zone between the internal and the external electrodes was permitted the foods to flow (Figure 1). The treatment zone was made by a Pyrex glass tube with an inward diameter of 8 mm and 1 mm thickness arranged in a helical shape. The 8 mm inner diameter of the treatment zone allowed the fruit juice to flow easily. Hence, the distance between the two electrodes was 1 cm. Figure 1 illustrates the designed helical treatment zone with its cross-sectional view.

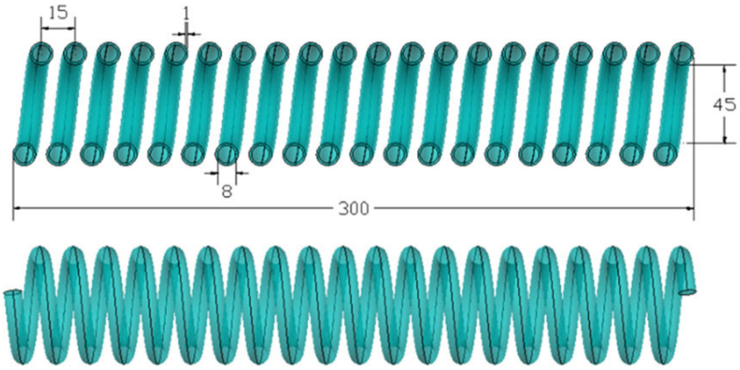

Fig. 1. Helical treatment zone (all dimensions are in mm)

If we put E = 30 kV/cm, r = 5 cm, Ro = 5.5 cm and Ri = 4.5 cm in equation 1 so we can calculate the maximum required voltage for given electric field i.e. 30 kV.

The finite element technique (FEM) with COMSOL Multiphysics was utilized to compute the electric field in the coaxial treatment chambers. The physics of this module was governed by the conservation of charge, Coulomb's Law, and classical electrostatics. The Electrostatics module enables the application of electric potentials, charges, and grounds to various geometrical. Materials were selected from the libraries of the COMSOL following the data gathered from the literature. The automated mesh was generated for the individual model of the treatment chamber. The most important part has ensured that the minimum element size is lower than the mesh diameter in the models. The "fine" mesh is tiny enough to provide satisfactory results, and the "Normal" mesh was selected. The computation was performed on a computer equipped with a 64-bit operating system, a four-core CPU running at 3.40 GHz, and 8 GB of RAM. It took no more than 8 minutes during the actual calculation. Electric fields and electric potential were graphed and analyzed using the tools provided in this module.

Based on charge conservation, the electrostatic governing equation may be written as

$$\nabla \cdot (\sigma(T) \cdot \nabla \cdot V - J^{e}) = 0$$

Where $\sigma(T)$ indicates the electrical current conductivity, V denotes the electric potential, J denotes the current density of the electric current and ∇ is the vector differential operator.

The following equation defined the electric potential 'V' under static conditions,

$$E = -\nabla V$$

Where E is the electric field.

The electric potential ‘V’ indicates the potential at the inner electrode, and the outer electrode has zero potential (grounded). The inlet, outlet, and insulator were all configured to be electrically insulated.

$$\mathbf{n} \cdot J = 0$$

Where n is the normal direction to the boundary.

4 Results and discussion

In coaxial treatment chambers, liquid food is regularly delivered into a treatment zone between an optimal configuration of two coaxial electrodes. Qin, et al. [37] modified the electrodes due to advancements in the electric field and technological innovation and designed the final electrode arrangement in the treatment region (Figure 2). An insulating substance (Plexiglas) was used in the shaded area to control the liquid flow path.

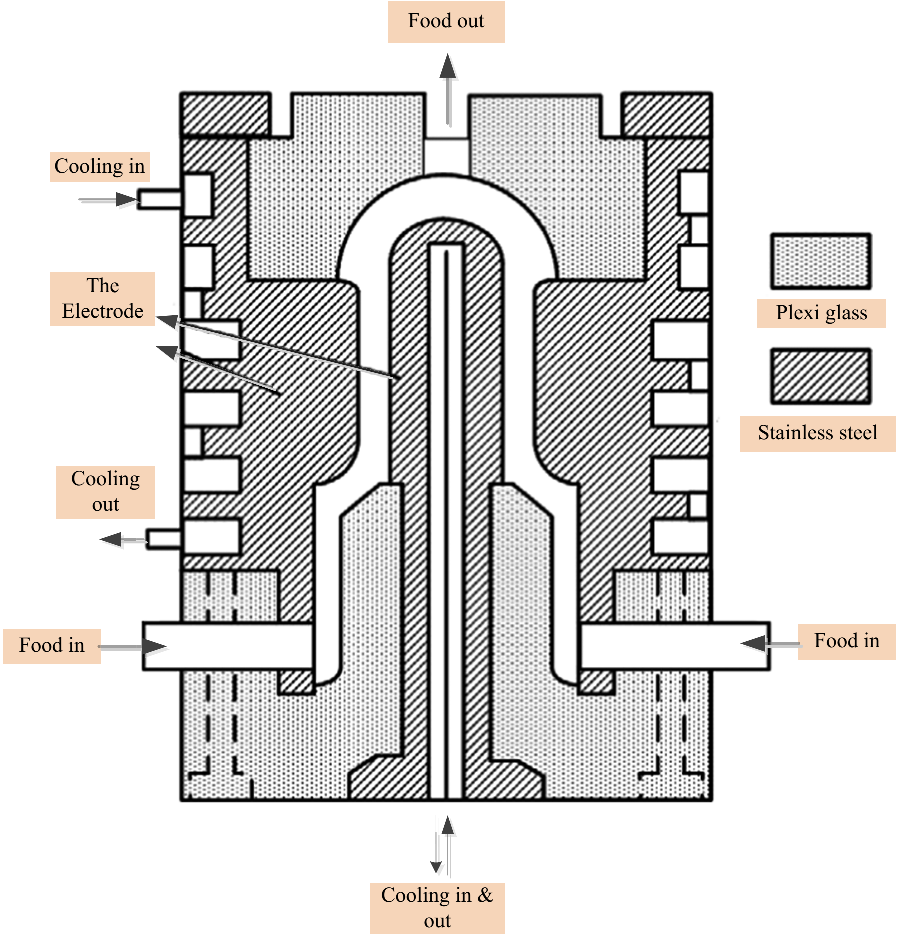

Fig. 2. 2D-sketch of coaxial treatment chamber designed by Qin, et al. [37]

Figure 3 demonstrates the 2D electric field distribution in the treatment chamber designed by Qin, et al. [37]. The following figure illustrates the non-uniform portions in the present treatment chamber owing to some design edges.

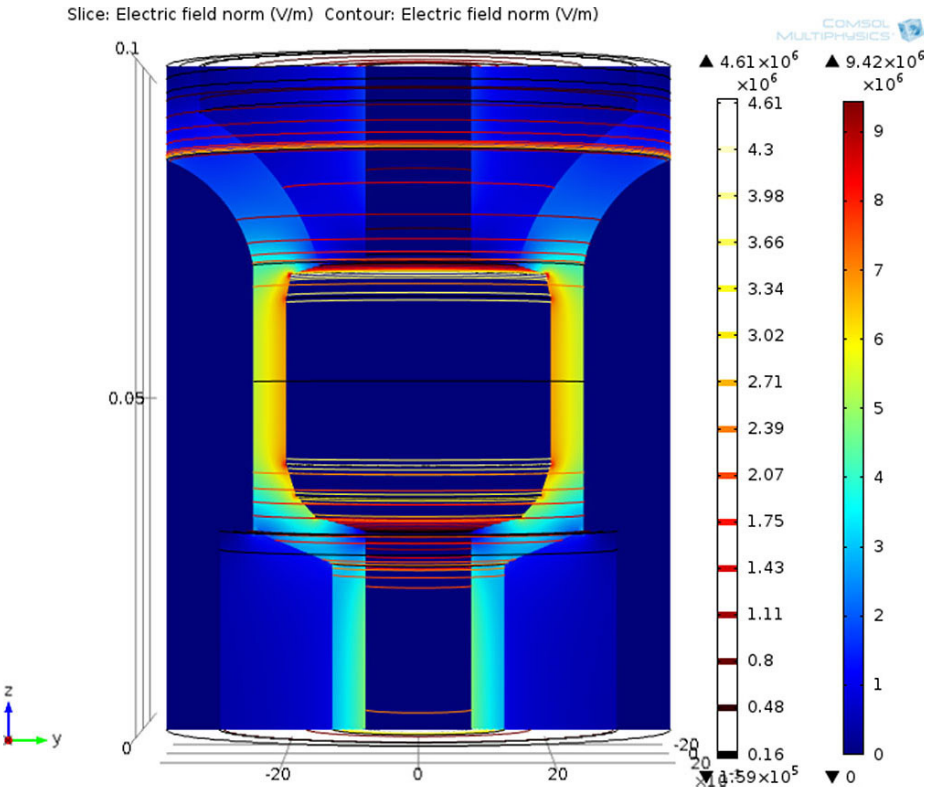

Fig. 3. 2D electric field strength of coaxial treatment chamber designed by Qin, et al. [37]

The protruding surface of the outer electrode increased the electric field intensity inside the treatment zone while reducing it outside the treatment zone. Electrical potentials were not dispersed evenly across the treatment region. Additionally, the coaxial treatment chamber may operate 70 kV.cm^{-1} electric fields without dielectric breakdown. The electrode surfaces were intended to limit improvement in the field to ensure that the electric field and electrical breakdown were not increased due to regional requirements.

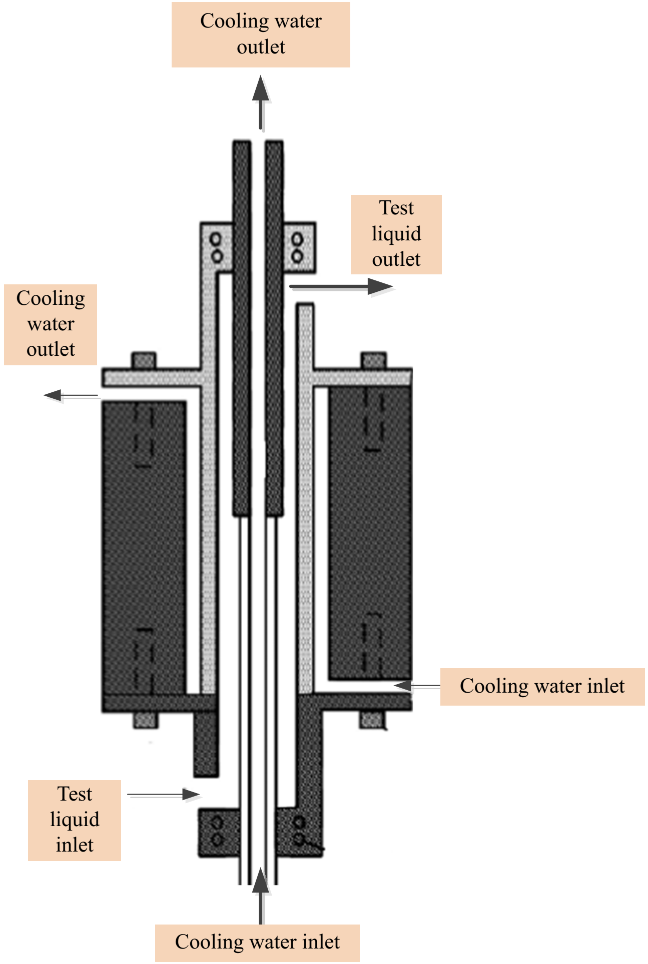

Fig. 4. Coaxial chamber designed by [38]

Pizzichemi and Occhialinia [38] developed a coaxial PEF sterilization chamber with a movable internal electrode to treat fluid products (Figure 4). The movable electrode enables the PEF processing to work with different values of resistivity. The dimensions of 5 mm for the internal electrode external radius and 4.9 mm for the electrodes' gap were optimized. Stainless steel for electrodes and PVC for dielectrics were the materials utilized. A suitable cooling system was designed to seal the treatment zone and controlling the temperature inside the chamber.

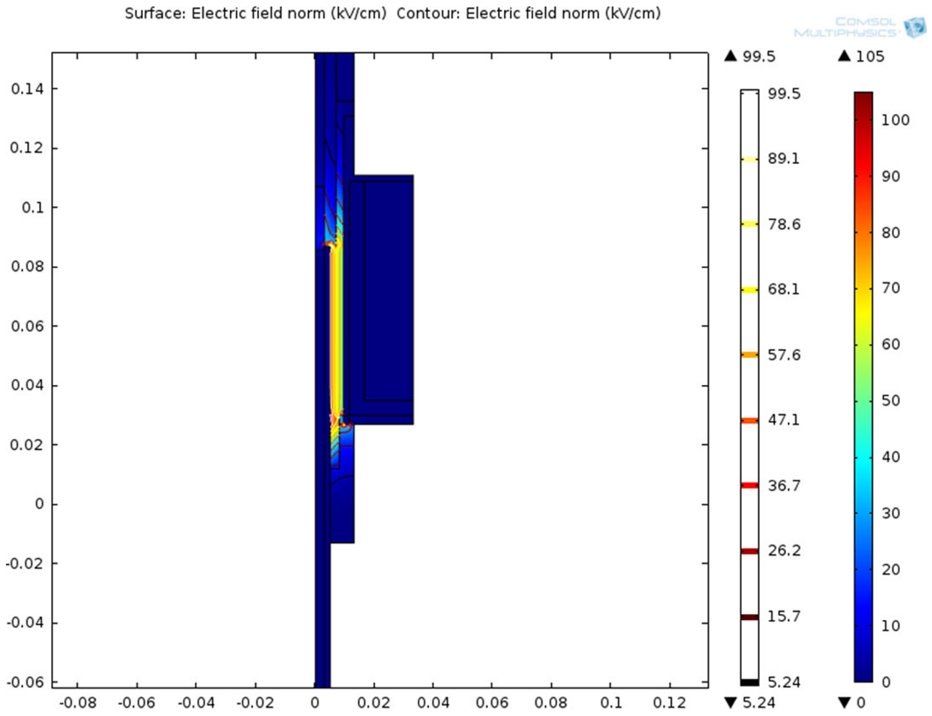

Fig. 5. Electric field norm in the PEF coaxial chamber developed by [38]

Figure 5 shows the electric field distribution for the coaxial electrode developed by [38] at an operational voltage of 30 kV and 50 Hz. Regardless of the electrode shape, the electric field strength was the maximum near the inner electrode. The electric field strength is higher near the corners and sharp edges. The electric field distribution is higher near the high voltage electrode and decreases towards the ground electrode, the coaxial treatment chamber's characteristic.

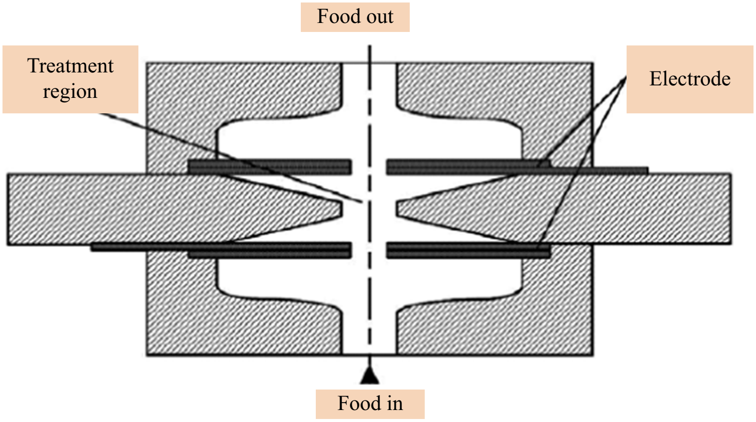

Fig. 6. A continuous treatment chamber designed by [39]

[39] attempted to avoid the stationary zone problem associated with prior designs (Figure 6). This design focused on a limited area of the electric field. It included a sterilizing chamber with two stainless steel mesh electrodes and an insulator element that formed an aperture separating the electrodes. The voltage across the orifice is about equal to the PEF provided (Figure 7). The liquid sample was introduced via the apertures of the two mesh electrodes and the orifice between them, which contained the concentrated electric field lines. The chamber's treatment capacity was 0.06 cm^3. The chamber's intended flow rate and residence duration in the treatment zone were 2.5 cm^3/s and 0.026 s, respectively. The stationary zone (microorganisms' habitat zone) and the liquid food that may overheat have been reduced in the present design.

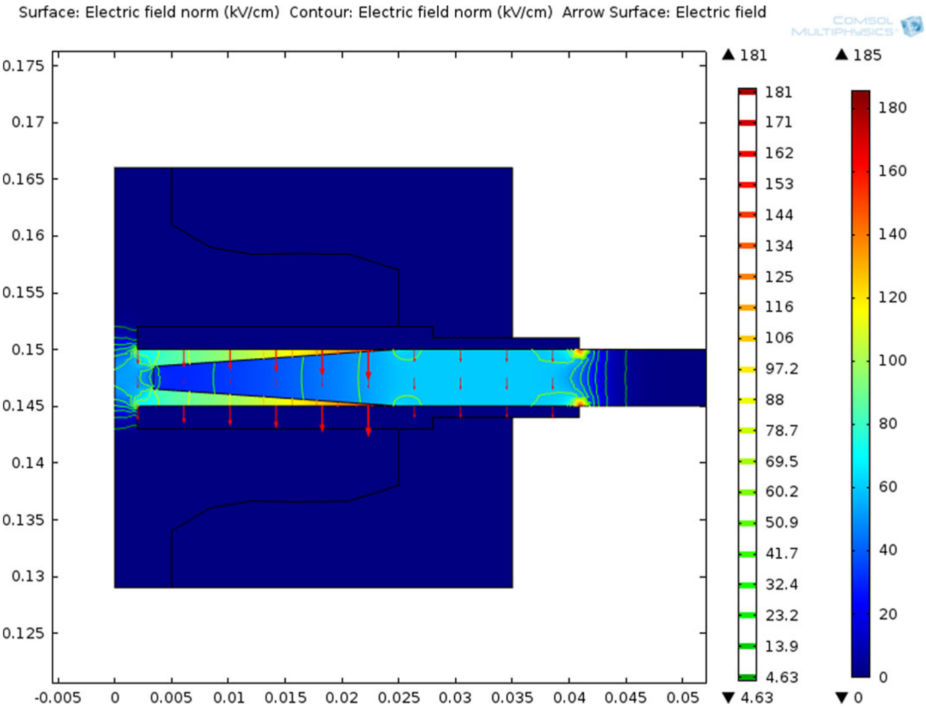

Fig. 7. Symmetrical view of electric field distribution inside a treatment chamber designed by [39]

As shown in the accompanying image, the electrode design and arrangement produce an electrical field that is not uniform and results in an undefined treatment zone. The electric field strength was greater than that of the treatment area at the electrode's and chamber body's edges. As previously stated, stagnant zones contribute to undesirable overheating at sterilization chamber corners, resulting in sparks.

The helix chamber layout significantly impacts the procedure's efficacy by affecting treatment homogeneity, peak electrical field quality, and item throughput. However, present PEF creative work mostly focuses on refining treatment chamber designs rather than developing more effective methods for applying high-voltage pulses to food systems [40, 41].

The plot of the helix treatment chamber with all characteristics is shown in Figure 8. The diameter of the glass tube is 5 mm. The cylinder electrode by 4mm diameter at the centre of the helix and the pulse voltage applied, and the aluminium ground electrode located around the helix glass. The aims to design the treatment chamber with more treatment uniformity and reduce the electrical breakdown. The treatment time is calculated by dividing the volume by the flow rate. Because of this, by increasing the length of the treatment chamber, the volume is increased, the PEF treatment time will also increment, which results in an increased Log reduction [42]. As indicated, a substantially uniform electric field must be provided throughout the liquid foodstuff treatment zone.

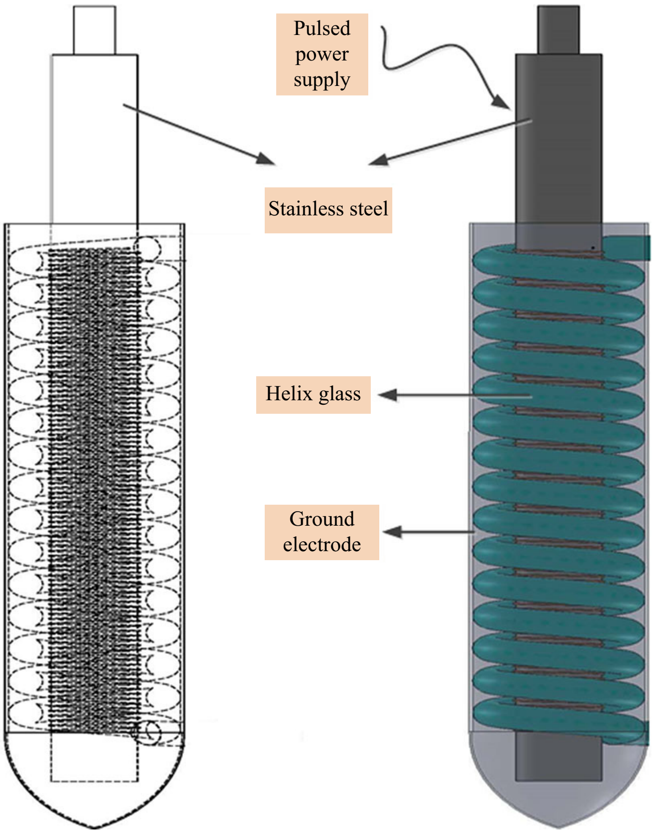

Fig. 8. 2D model of a helix treatment chamber

The 2D helix treatment chamber model shown in Figure 8 was created using the COMSOL programme. The electric field intensity is consistent throughout the treatment chamber, and the pulsed electric field influences the fruit juice sample current in the helix treatment chamber [43]. A homogeneous electric field is created within the treatment chamber by the equal spacing of the field shapers and the linear change in voltage. The field is consistent throughout the therapy chamber. The constant electric field maintains the quality of the fruit juice samples. The dialectical breakdown does not occur in the helix treatment chamber.

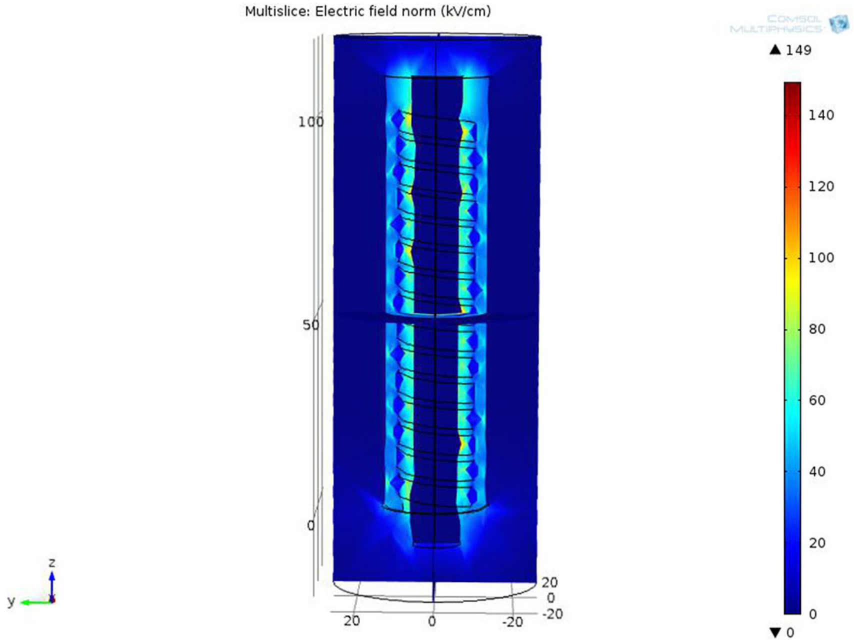

Fig. 9. Electric field distribution of the helix treatment chamber

Figure 9 illustrates the expected electric field distribution in the helical treatment zone. With this treatment chamber, the electric field is distributed upward from the central cylinder to the outer cylinder. The average electric field intensity varies somewhat across treatment zones. However, the turbulent flow of the liquid sample inside the helix ensures that the whole sample has an equal chance of being treated. As a result, compared to co-linear (or co-field) treatment chambers, this design provided an identical electric field intensity in the treatment zone. Furthermore, since the treatment time is calculated by dividing the volume by the flow rate, the volume increases as the length of the treatment chamber is extended.

5 Conclusions

The treatment chamber is a critical element of the processing system as it housed the foods exposed to a high-intensity pulsed pulsing electric field. The treatment chamber's distinctive design primarily regulates the dispersion of the electric field. The coaxial treatment chamber significantly lowers or eliminates the peak value of the electric field in the treatment region. The electrodes' wide effective area provides a high current flow and a low resistance in the treatment chamber. Additionally, it is simple to build a coaxial treatment chamber and give a well-defined electric field distribution. Within the treatment zone, the coaxial treatment chamber provides a heterogeneous electric field and temperature distribution. Liquid mixing inside the treatment zone is an efficient method of overcoming this heterogeneous impact. A mixing effect is provided by a helical insulator located within the coaxial treatment chamber. As a consequence, the electric field and temperature distributions become less heterogeneous. The modelling findings showed that the helical treatment chamber had a uniform electric field strength. This research adds to the body of knowledge about industrial-scale setups using numerous helical chambers in continuous flow PEF treatment.

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7 Authors

Rai Naveed Arshad, IVAT, School of Electrical, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia. E-mail: rainaveed@yahoo.co.uk

Zulkurnain Abdul-Malek, IVAT, School of Electrical, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia. E-mail: zulkurnain@utm.my

Ali M. Dastgheib, Islamic Azad University, Marvdasht Branch, Iran. E-mail: ali_m_dastgheib@yahoo.com

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