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Air Bubble in Liquid Food under Pulsed Electric Field Pasteurization using Coaxial Chamber

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***Abstract*—Dielectric breakdown of air bubbles embedded in liquid food is a limiting factor in the pulsed electric field (PEF) pasteurization. Therefore, a proper chamber's geometry, air degasification, and estimation of electric field enhancements (due to gas bubbles) are powerful strategies to overcome this limitation. In this study, a coaxial treatment geometry loaded by an orange liquid sample encompassing a gas bubble demonstrated importance in the electric field distributions. The development of a gas bubble induces the non-uniform electric field near the bubble surface. A numerical analysis through COMSOL Multiphysics was done to observe the effects of a bubble diameter and the liquid's flow inside the coaxial chamber geometry. An air bubble with a comparable diameter has influenced more to the electric potential difference, and the position of the air bubble also affects the value of perturbation in the electric potential. This study supports the development of an electroporator for PEF pasteurization of liquid food.**

Keywords— pulsed electric fields, dielectric breakdown, air bubbles

I. INTRODUCTION

Pulsed Electric Field (PEF) is a non-thermal technology with extensive food applications. Repetitive electric pulses (8–40 kV.cm^{-1}) are used for inactivating microorganisms in liquid food pasteurization. PEF technology guarantees microbes' inactivate with no loss of tastes and nutrients than the conventional thermal process [1, 2]. However, the PEF treatment is limited to sample the food without any air bubbles. The existence of bubbles may significantly enhance the likelihood of breakdown and a technological bottleneck of PEF food pasteurization. Furthermore, electrical discharges hinder the product from obtaining the necessary treatment and cause the product to be damaged by the radicals produced in it [3]. Besides, a strong current generated with this arcing can severely damage the equipment and treated product during the breakdown.

The breakdown focuses on the theory of gas ionization. According to the theory, the incoming free-electron must have kinetic energy equal to or greater than the ionization energy of the colliding neutral atom [4]. As a result, the voltage (V) between two electrodes is enhanced at a given pressure (p) before the electric field (E) hits a critical point that enables the current to rise substantially. Thus, due to collisions between accelerated electrons and gas molecules, increasing charged particle density, and eventually, a breakdown, a transition to high conductivity discharge.

The bubbles behave like impurities in the sample food and have lesser breakdown strength (BS) than the sample food. The breakdown strength (BS) is the highest electric field strength resisted by an electric spark until it experiences an insulator-to-conductor' transformation. Gas's BS is much lower than liquid foods at atmospheric pressure, reducing gas's electrical strength in a liquid medium [5]. Pulsed discharges and breakdowns have been well studied in pure liquids. Pulse attributes, such as pulse-width, pulse shape, and frequency, along with the electrode's arrangement, have been accepted for essential vapour-gas bubble formation [6].

Conventional electrical discharges in water or solutions have been investigated with the unipolar (negative or positive) point-plane or rod-rod electromagnetic pulse with high energy per pulse low pulses repeating intensity [7]. It has a substantial mechanical impact, such as shock waves, that vary considerably from the state of PEF treatment. However, it distinguished significantly from the PEF treatment, and, thus, simple bubble initiating and development principles cannot apply to PEF treatment. The electrical discharge's key source within the PEF chamber is the vapour gas bubble caused by the electric field. The air in the sample meal is just a small portion of the bubble, and it has little effect on the size and form of the bubble [6]. However, there is limited research available on the production and growth of air bubbles during PEF treatment and electrical discharge.

This research aims to investigate the process of bubble formation in a PEF liquid food pasteurization. In this study, a model was developed to study the electrostatic properties using a two-dimensional coaxial chamber connected with 20kV and contained orange sample liquid. Finally, Paschen's curve was used to calculate the needed pressure to avoid arcing.

II. LITERATURE REVIEW

In PEF pasteurization, the sample food's conductivity affects equal resistance and dissipated energy to the treatment chamber, significantly impacting the liquid heating and bubble formation. Heating the sample food under the pulsed electrical field stimulates dissolved air production [8, 9]. The creation of air bubbles in the liquid food is the primary source of partial discharge and electrical breakdown inside the treatment chambers. However, one of the most direct factors influencing electrical discharge is solution temperature in the treatment chamber [10].

The amount, size, and shape of bubbles are essential for electrical discharges to occur. In PEF, the formation and development of bubbles result from the complex effects of electrostriction tension and Joule heating. Electrostatic tension mainly influences the bubbles in the early stage and the convergence phase of the bubbles. In contrast, Joule heating usually leads to the growth of the bubble region [11]. Higher electric field strength, more extended pulse widths, and a greater frequency improve pasteurization and enhance liquid heating [11]. In consequence, bubbles grow and converge faster and shorten average discharge time. The electric field is maximal at the electrode's sharp edge [10]; therefore, the most likely region in the liquid form a bubble.

The minimum (critical) electrical field strength is needed to form a large, critical bubble. The vapour bubble does not form if the field intensity is less than the critical value of 'Ec.' The bubble forms at the end of the electrode as soon as the field's magnitude equal to or higher than the critical value [6]. However, when the field magnitude is higher than the critical value, the homogeneous field does not exist in the liquid. Reference [12] has given the expression of this critical field, Ec in the strongly non-uniform electric field; this is

$$E_c = 0.67/\left(1 - 1/\varepsilon_2\right)^{0.5}\ (\mathrm{kV.cm^{-1}}) \qquad (1)$$

ε_2 is the permittivity of the liquid,

The radius of the bubbles more than a particular critical value leads to a dielectric breakdown of the bubble's vapour [7]. Therefore, the critical radius evaluation of the bubble and the essential dimension of the external field capable of triggering the creation of this bubble can help to decide if this sample liquid can be treated under these process parameters. Reference [13] addresses the dynamics of the behaviour of the bubbles. Equipotential lines are concentrated in the bubble's cavity, distorting the electrical field inside the gap and producing higher voltage potentials as the gap width becomes shorter and/or the bubble becomes larger [6]. An unexpected electrical variation ultimately leads to one of two choices: (1) the sample is undertreated and treatment efficiency is decreased if the breakdown is ignored or (2) immediate breakdown and resulting arcing happens. The arcing may cause the fluid feed to thicken and/or evaporate and solid deposits from the electrode's surface.

The electric field's complex effects, including electrostriction tension and Joule heating, play a role in developing and developing bubbles in PEF. Electrostriction tension mainly influences the number of bubbles in the early stage and the process of bubble convergence, while Joule heating primarily contributes to the growth of the bubble area. Hence, a stronger electric field, a wider pulse width, and a faster repetition rate increase the impact of electrostriction tension and make liquid heating easier [13]. Consequently, bubbles grow and converge more quickly, and the average discharge time is reduced, as predicted by prediction formulae.

III. RESEARCH METHODOLOGY

The present study is based on the following criteria:

- A fixed spherical shape air-bubble has studied.
- There are no variations in the liquid temperature.
- Other important aspects such as cavity alignment, dielectric thickness, electrode edge shape, and the existence of floating electrodes or other objects that interfere with the surrounding field were not taken into consideration in this work.

Fig. 1 shows the asymmetric geometry of the coaxial treatment chamber with a food sample and an air bubble. The impacts of gap lengths of 1 cm and bubble sizes (0.1, 1, 3, and 5 mm) in the treatment zone were examined using steady-state modelling based on the assumptions mentioned above. An air bubble was inserted at the intersection of the vertical and horizontal distances between the chamber gaps. A bubble was also simulated around the treatment chamber's inner electrode and outside electrode. Two different liquid flow rates (10 and 100 $\mathrm{mm.sec^{-1}}$) were used to determine the influence of bubble width and location on the voltage potential and electric field.

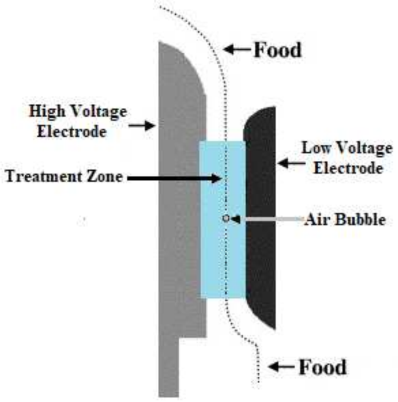

Fig. 1. Two-dimensional view of a coaxial chamber with liquid food and air-bubble

The finite element approach was used in two-dimensional simulations based on real-world chamber geometry, sample food, and electric parameters for each element in the simulated chamber. COMSOL 5.5 software has been used to model the electrostatic behaviour of a coaxial treatment chamber with and without air bubbles entrapped in a sample liquid. For each domain of the model, Table I lists the material and electrical attributes that were employed in this modelling.

TABLE I. MATERIALS AND PROPERTIES OF THE USED DOMAINS

Domains	Typical characteristics		
	Relative permittivity	***Conductivity (S/m)***	***Dimension***
High Voltage Electrode (Stainless steel)	-	$1.1\mathrm{x}10^6$	d_i = 2cm l = 3cm
Low Voltage Electrode (Stainless steel)	-	$1.1\mathrm{x}10^6$	d_o = 3cm l = 3cm
Bubble Air	1	0.343	0.1 mm, 1 mm, 3 mm, 5 mm
Dielectric medial Dielectric	30	0.6	10 mm/sec, 100 mm/sec

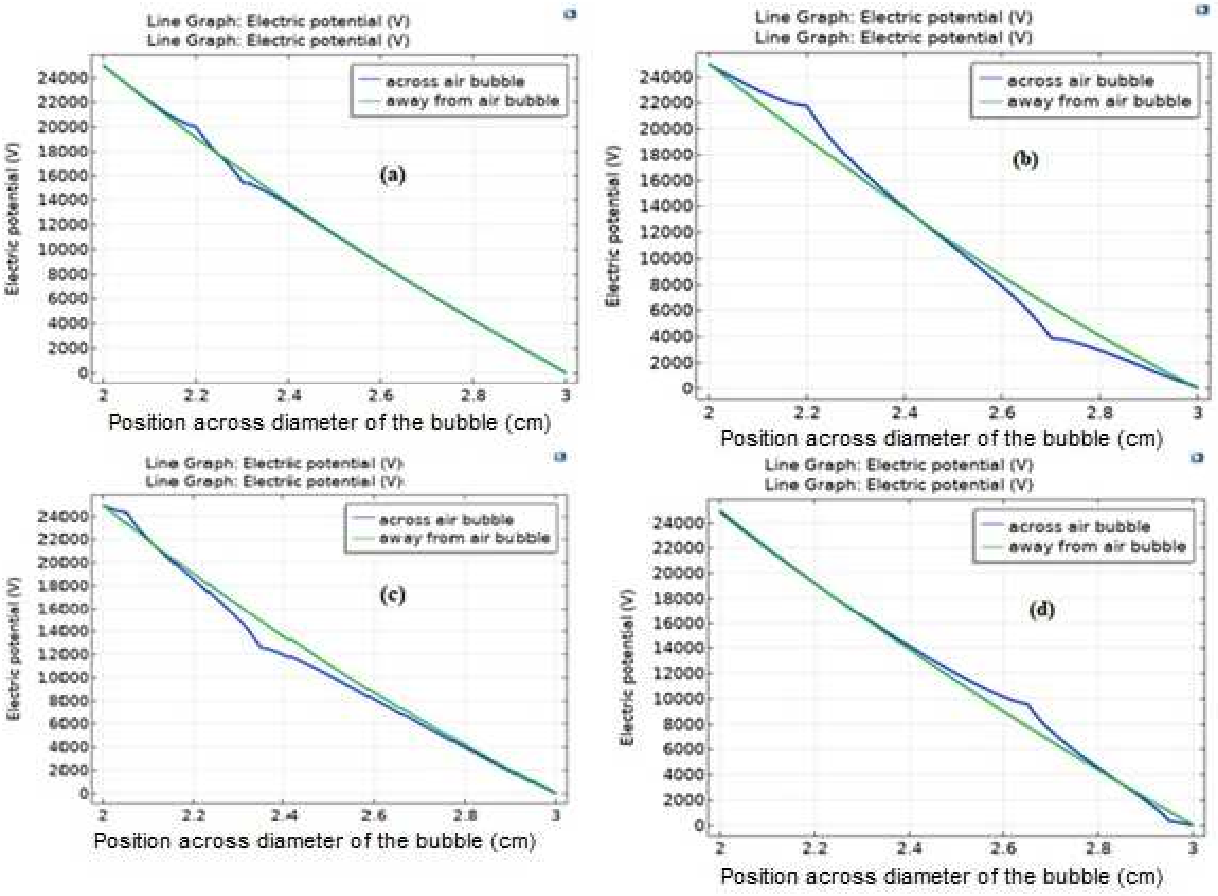

Fig. 2. Static line graph of electric potential with and without the presence of bubble with different bubble diameter and position inside the treatment zone; (a) bubble diameter = 1 mm located near to the high voltage electrode, (b) bubble diameter = 5 mm located in the middle of the treatment zone, (c) bubble diameter = 3 mm located near to the high voltage electrode, (d) bubble diameter = 3 mm located near to the ground electrode

IV. RESULTS AND DISCUSSION

Simulated electrical field profiles in the dielectric field, without air bubbles, were closely aligned with the theoretical calculations. As predicted, the electric field was approximately uniform but not constant in a coaxial configuration. As the inner electrode was connected to the positive terminal of the high voltage pulse generator at 20 kV, there is a gradient and decrement in the electrical field as it reaches the grounded electrode, i.e., the plots in figure 2 negative slopes.

The simulated results also showed that a bubble with a diameter of 0.1 mm did not disturb the electric potential and the electric field profiles with any flow rate. However, the size of the air bubble has a substantial impact on the line graphs beyond 0.1 mm, as seen in Figure 2. Since air has a lower permittivity than the dielectric medium, there is a concentration of potential inside the gas bubbles, as predicted. Therefore, with larger bubbles in a small treatment zone, the voltage loss across one single bubble diameter is more significant.

Surprisingly, the electric field distribution was more uniform with an air bubble with a 5 mm dia. Since the bubble's position was fixed in this study, it acted as a barrier in the liquid flow and disturbed the laminar flow in the treatment zone. Hence, the greater size of the bubble is a blessing in disgrace as it acted as a static mixer inside the treatment zone to overcome the laminar flow of the liquid. Practically, this trapped bubble can move out of the treatment zone with a higher flow rate. The current study observed that liquid flow has no significant effect on voltage perturbation. However, higher flow is recommended to overcome the trapped air bubble. Similarly, a 3 mm bubble at the high voltage electrode has a more significant effect than a bubble of the same size further away (Fig 2 c-d). These modelling predictions are congruent with several experimental findings that have significantly decreased treatment variability due to the air bubbles trapped inside the medium.

Table II shows the localized voltages (V_{lb} and V_{rb}) and the voltage potential (Vb) for each of the Pbd values based on bubble diameters at atmospheric pressure and the crucial P_{dc} value. The P_{bd} values are the points on the Paschen's curve where the Vb values for each of the bubbles meet. Curve.

The difference between the voltage at the left side of the bubble's diameter (V_{lb}) and the voltage at the right side of the bubble's diameter (V_{rb}) was used to calculate the potential produced (ΔV_b) inside the gas bubble. The highest potential (ΔV_b) across the bubbles was evaluated, mainly when the bubble was located near the surface of the electrodes. Hence, the maximum possibility of arcing is also near the electrode surface. Table II shows that around 1 atm pressurization is required with all diameters of the bubble. Also, increasing the hydrostatic pressure reduces the maximum radius by determining the pressure far away from the bubble [14]. This finding was consistent with an earlier study.

TABLE II. REQUIRED PRESSURE TO OVERCOME DIFFERENT BUBBLE SIZES INSIDE THE TREATMENT ZONE

Bubble diameter (mm)	**Bubble position**	**Flow rate (mm/sec)**	**V_{lb} (kV)**	**V_{rb} (kV)**	**ΔV_b (kV)**	**P_{bd} (atm-mm)**	**P_{bd} (mm)**	**Pmin= Pdc/ Pbd (atm)**
0.1	Centre of the treatment zone	10	No variation of the potential have observed					NA
		100						
1	Centre of the treatment zone	10	20.0	15.5	4.5	1.10	1	1.10
		100	20.0	15.5	4.5	1.10	1	1.10
5	Centre of the treatment zone	10	22.0	4.0	18.0	5.30	5	1.06
		100	22.0	3.8	18.2	5.30	5	1.06
3	Near HV Electrode	10	24.2	12.2	10.0	3.11	3	1.04
		100	24.2	12.2	10.0	3.11	3	1.04
	Near ground Electrode	10	10	1	9	2.9	3	0.97
		100	10	1	9	2.9	3	0.97

V_{lb}: Voltage at the left side of the bubble-diameter; V_{rb}: Voltage at the right side of the bubble-diameter; ΔV_b: Potential between two ends of the bubble diameter; P_{dc}: critical value from Paschen's curve against ΔV_b; **P_{bd}:** bubble diameter at standard atmospheric conditions; P_{min}: Minimum pressures required to reduce the probability of breakdown.

The voltage difference between the left side of the bubble (V_{lb}) and the right side of the bubble (V_{rb}) was used to calculate the potential produced (ΔV_b) inside the gas bubble. The highest potential (ΔV_b) across the bubbles was found near the surface of the electrodes. Hence, the maximum possibility of arcing is also near the electrode surface. Table II shows that around 1 atm pressurization is required with all diameters of the bubble. Also, increasing the hydrostatic pressure reduces the maximum radius by determining the pressure far away from the bubble [14]. This finding was consistent with an earlier study.

The electric field inside the bubbles can also be determined by the applied average electric field and the gas-liquid ratio. The bubble area ratio was used to determine the degree of gas-liquid mixing. Increases in the bubble area for a given electric field increase the distortion of the electric field, increasing the likelihood of discharges. Therefore, the average discharge bubble should be determined in terms of applied electric field and treatment chamber area to forecast the occurrence of an electric discharge. The impact of the air bubbles minimizes by shortening the pulse width or by simple pressurization and/or degasification. There would be no time for the ionization process to take place in smaller pulse width. Similarly, an increase in liquid flow leads to a decrease in the diameter of the bubble. The vertical positioning of the treatment chambers can also be used to eliminate the air bubbles; once the liquid is pumping in an upward direction against gravity.

V. CONCLUSION

Most of the gas bubbles emerge from water vaporization induced by local water heating under the PEF. The size of the bubble increases with the increase in the applied electrical field. One of the most direct factors influencing electrical discharge is solution temperature in the treatment chamber. As the starting temperature rises, the electrical field strength needed for the electrical discharge falls. Therefore, temperature curve fluctuations may be a good predictor of whether a bubble is starting to form. The amount of air dissolved in the samples is so slight that it hardly increases the size of the bubble. However, it does impact the likelihood of bubble formation and the number of bubbles created and the electrical discharge inside the PEF treatment chamber. Bubble near the electrode surface is more dangerous than others. Liquid flow has not influenced the variation in the electric potential and the electric field distribution. The impact of these air bubbles minimizes by reducing the ohmic heating through shortening the pulse width and frequency or by simple pressurization and/or degasification.

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