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Impact Of An External Static Electric Field During The Foaming Process: Equipment Design And First Results

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Abstract- This study focuses on a set-up, called ElectroFoamVision, designed to evaluate the stability of a foam, generated by gas phase incorporation into a liquid medium placed within a chamber, with a glass column that incorporates stainless steel flat parallel electrodes (30x200 mm, gap 5cm). Experiments were performed on Whey Protein Isolate (WPI) and Chickpea aqueous solutions. Experiments revealed a remarkable shift in the foam's stability according to the applied electric field. Under the influence of an external electric field during the foaming period, the liquid remains in the foam state for a longer period. This was attributed to a reduction in the size of gas bubbles escaping from the frit, thus diminishing surface tension. These results are promising for the conception of an innovative food foam equipment able to produce a high-quality foam.

Keywords- Foam, Bubbles, Stability, Electric field.

I. INTRODUCTION

Foams play a significant role in the food industry, revolutionizing the texture, appearance, functionality and sensory experience of various food products [1]. Food foams are intricate systems of gas bubbles dispersed in a liquid. Their stability, i.e. maintaining their structural integrity over time, remains a challenge for various applications. The primary hurdle arises from the natural tendency of foams to collapse, coalesce, or break, leading to a loss of their porous texture and functionality. By nature, foams are highly thermodynamically unstable systems and evolve irreversibly. An important mechanism is the drainage of liquid from the foam structure due to gravity [2]. This inevitable drainage takes place through the Plateau borders and by capillary action from the lamellae to the Plateau borders. Thus, over time, the foam dries out as the volume of liquid in the foam tends to decrease. Free drainage is the spontaneous evolution of the liquid fraction under the influence of gravity, starting from an initial state different from the equilibrium. Over time, the irreversible flow of liquid downward dries out the foam. The position of the interface between the foam and the drained liquid rises with time. In many applications, it is required to control the lifetime of a foam by limiting the drainage or triggering the collapse at a specific location or a given time. Applying an external electric field at the edge of the foam induces some liquid flows and, depending on the flow magnitude, it controls either gravity driven drainage, the foam stability, or the foam collapse at a specific location [3]. A work has been carried out to study electro-osmosis, a method to cancel and even reverse the drainage [3, 4]. The principle is as follows: due to ionic surfactants covering the liquid-gas interface, liquid is locally charged near this surface and can therefore be set in motion by an external electric field. By controlling the applied field and the resulting flow of liquid, the foam can be maintained in a superstable state and even rejuvenated in some way on demand.

This experimental study aims to unravel the dynamics of foam formation and stability under the influence of a static electric field. Our investigative tools include a new apparatus, called ElectroFoamVision, and advanced analysis algorithms, allowing real-time assessments of foam volume and behavior. Utilizing solutions of animal derived Whey Protein Isolate (WPI) and plant derived Chickpea protein (CKP), we explore the influence of electric fields during the foaming process.

II. METHODOLOGY

A. Experimental set-up

The ElectroFoamVision (Fig. 1 and 2) is purposefully developed to evaluate the attributes of foam, encompassing its generation and stability. This involves introducing gases such as Air, N₂, O₂, CO₂, etc... into the liquid medium to generate the foam. The experimental setup entails placing the liquid sample within a designated chamber. This chamber was augmented with a glass column that incorporates flat parallel electrodes, spaced 5 cm apart; this rectangular chamber with flat electrodes is a completely original setup compared to existing FoamScan systems. Using a high voltage source (Ottersweier, Germany), an electric field can be applied to the foam either during foaming or after foaming or eventually both, using the two parallel electrodes (30 x 200 mm / 1 mm thick / stainless steel). Foam is generated in the sample chamber through sparging, leading it to ascend into the glass column. Within this column, the evolving foam is continually monitored via a video camera. The visual data captured by the camera is subsequently extracted and processed on ImageJ (NIH), an open source Java-based image processing program. A specific algorithm for interface tracking was developed. This information serves as the basis for real-time

calculations and visual representations of the foam's volume.

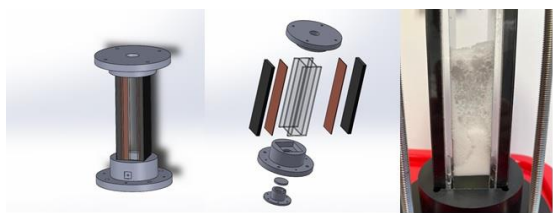


Fig. 1. Sketch of ElectroFoamVision, focus on the column

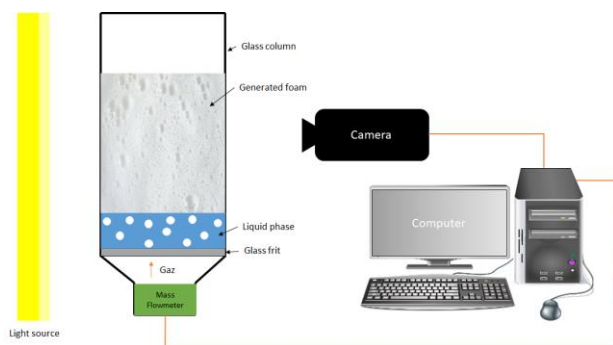


Fig. 2. Sketch of the experimental set-up (High voltage source not represented).

By systematically capturing and analysing the foam's development and behavior, ElectroFoamVision allows for a comprehensive understanding of its properties. This apparatus facilitates insights into foam generation mechanisms, its ability to retain structural integrity, and its real-time volumetric changes. The integration of video imaging technology enhances the precision and detail of data collection, enabling more accurate characterization of foam behavior.

B. Experimental procedures

The foam-type food matrices can be assimilated to liquid protein solutions in which a gas injection is performed. Experiments were performed on two foam models from Whey Protein Isolate (WPI) and Chickpea (CKP) solutions.

WPI is a protein of animal origin, an isolate's short chain proteins that are extracted from Whey Protein Concentrate, derived from milk. We prepared solutions containing 3% WPI. The total mass of WPI was incorporated in 4 times, staggered at 15min intervals, under moderate agitation (3-blade propeller, speed 100 rpm), at room temperature (20°C), to guarantee the complete dissolution of the powder.

Considering a clean label approach, a protein of plant origin was considered for the second model solution, namely an aqueous chickpea protein solution (CKP). Aquafaba has shown good food functional properties, as this plant-based liquid has the ability to function as both a foaming agent and an emulsifier under conditions of pH and NaCl concentrations that happen to be those readily encountered in food products. As a vegetable alternative

to egg white or WPI, CKP aquafaba seems to be an interesting candidate for foamed products. Therefore, we decided to use a chickpea aquafaba-based solution. The aquafaba from 10 cans was collected by sieving. It was then centrifuged to ensure homogeneity of the mixture. A sample of this aquafaba was taken for determination of the protein content by the Dumas method (protein content of 3% +/- 0.2%).

50 mL solution of the model system is meticulously prepared. This solution is then introduced into the ElectroFoamVision with great care, utilizing a syringe and tubing to avoid foaming. Once the solution is in place, the next steps involve preparing for image acquisition. The experiment begins by switching on the light source and inserting a millimeter paper between the glass column and the camera. A photo is taken, which serves as a reference for metric calibration during image analysis. Each measurement was conducted with five repetitions. The gas injection rate is set to 10 mL/s, and the desired voltage value is adjusted on the high-voltage generator. When these settings are in place, the gas injection and high-voltage generator are initiated simultaneously. This marks the beginning of the foaming phase, which lasts 120 seconds. Once the 120-seconds foaming phase is completed, the gas injection is stopped, as is the high-voltage generator.

C. Foam stability

To analyze the evolution of the foam stability, image acquisition is then automatically initiated, capturing one image per second (Fig. 3); the liquid phase at the bottom is clearer than the foam. This stage captures the destabilization phase of the foam during 15 minutes.

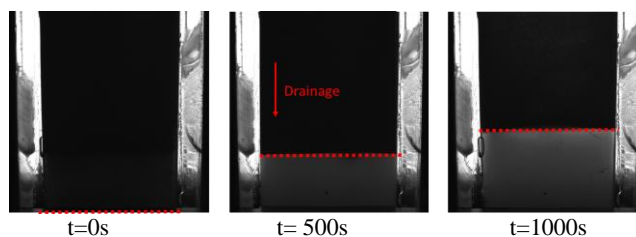


Fig. 3. Images captured during the drainage of a foam generated with the chickpea model solution. The red dotted line indicates the position of the foam/liquid interface.

D. Foam quality

The quality of the food foam can be determined using two parameters: the "expansion" and "half-life." Expansion is defined as the ratio between the final volume of the food foam and the original volume of the food product. To calculate the expansion of foams generated under the influence of an electric field, some adjustments were made to the experimental procedure. The initial volume of the model solution introduced into the ElectroFoamVision remained unchanged. The foaming process with the electric field lasted for 120 s. At the end

of this foaming period, the foam height was carefully recorded.

Half-life is defined as the time during which the food foam loses half of its volume. To calculate the half-life of the foam, the same initial volume of the model solution was introduced into the column. The foaming process with the electric field was initiated and continued until the foam reached a physical limit marked on the column, which corresponded to 200 mL of foam. At this point, the high voltage was promptly disconnected. The half-life measurement was then conducted, observing the time it took for the foam to collapse and recede to another physical limit marked on the column, corresponding to half of its original volume.

The ElectroFoamVision experiment presents its own challenges due to complex 3D optical effects that can interfere with accurate measurements. Determination of bubble size and distribution is inherently not possible in the set-up.

III. RESULTS

A. Foam stability

Fig. 4 illustrates the evolution of the average volume of the liquid phase within the column over time. This data is presented for various applied voltages.

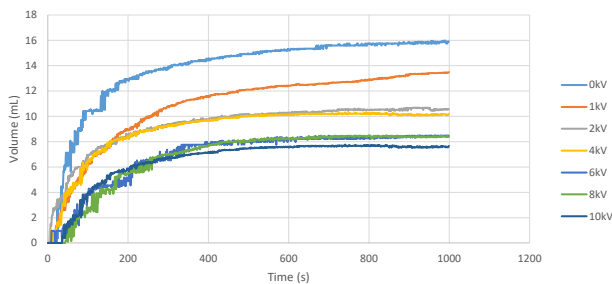


Fig. 4. Liquid phase volume as a function of time, according to the applied voltage during foaming - WPI solution.

Our observations reveal distinctive trends in foam stability concerning the influence of the applied voltage. Without any applied voltage during the foaming, the volume of the liquid increases up to 16 mL after 1000 s of drainage. When applying 1 kV (corresponding to a mean electric field strength of 20 kV/m), the drainage kinetic is reduced with a final volume of 13.5 mL after 1000 s. As the voltage is increased, we notice a shift in the foam's stability, which manifests as changes in the volume of the liquid phase. A clear pattern emerges: as the electric field strength increases, the volume of the drained liquid phase significantly decreases. This observation signifies that, under the influence of an electric field during the foaming period, the liquid remains in the foam state for a more extended period, ultimately resulting in enhanced foam stability. For instance, when applying a voltage of 10 kV (mean electric field of 200 kV/m), we recorded a substantial two-fold reduction in the volume of the liquid phase at the column's base. This effect of decreased recoverable liquid phase (indicating a foam stabilization)

is more pronounced at lower voltage electric fields. However, it becomes less prominent as higher voltage levels are applied, with minimal deviation between the results obtained at 6 kV and 10 kV, for example.

Experiments performed on the chickpea solution led remarkably to similar trends. Fig. 5 represents the final volume of liquid after 1000 s. of drainage for both solutions. As we increase the applied voltage, we consistently observe a noteworthy reduction in the volume of the liquid phase. This commonality strongly reinforces the earlier conclusions regarding the electric field's role in foam stabilization.

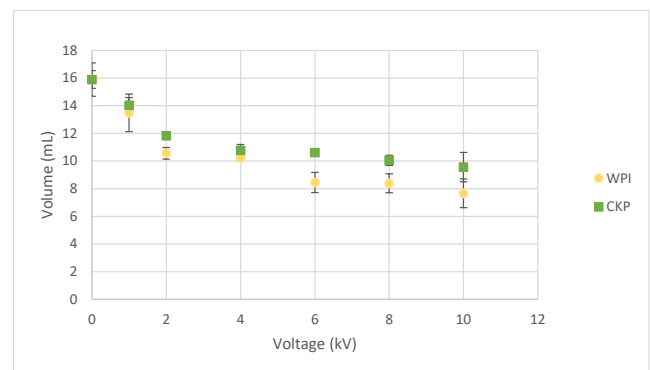


Fig. 5. Liquid phase volume in the ElectroFoamVision at the end of the drainage for WPI and chickpea solutions.

B. Foam quality

As a general rule, higher-quality food foam is achieved when the expansion is maximal and the half-life is longer [5]. To determine the optimal operating conditions, we generated a map of foam expansion as a function of half-life for applied voltage from 0 to 10 kV (Fig. 6). This analysis enabled us to swiftly identify the voltage setting that produced the best combination of expansion and half-life.

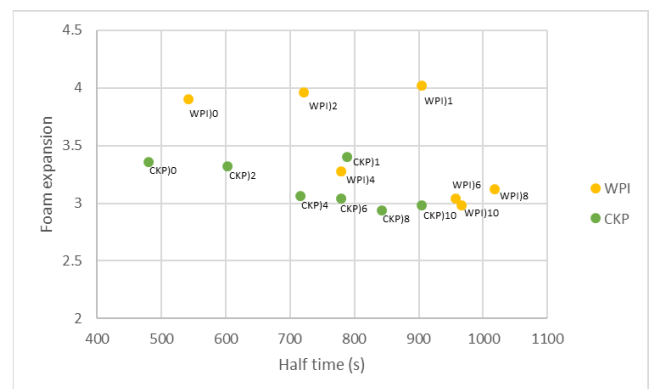


Fig. 6. Map of foam expansion as function of the half-life of the collapse (Numbers after bracket correspond to the applied voltage).

The foam expansion is stable for the moderate applied voltages up to 2 kV: it is close to 4 for WPI and 3.4 for CKP. For higher applied voltages, there is a significant reduction of the foam expansion for both foams. One significant factor is the increase in foam stability induced

by the high voltage. The electric field generated by the high voltage alters the properties of the gas bubbles within the foam, leading to enhanced stability and reduced coalescence between bubbles. As a result, the bubbles are less likely to merge and form larger bubbles, which ultimately limits the expansion of the foam.

Without applied voltage, the half-life is close to 500 s. for the WPI and CKP's foams. When foaming is performed under an electric field, the half-life of the foams increases up to 1000 s at the higher applied voltage. When the applied voltage is increased, there is a notable densification of the foam structure, leading to a reduced expansion and an extended half-life.

It can be considered that the optimal condition to obtain the maximal expansion of the foam with a long half-life is reached at a low voltage setting of 1 kV (20 kV/m) for both the WPI and chickpea solutions. Results indicated that at low voltage, foams exhibited remarkable expansion but had shorter half-lives, while at high voltage, expansion was reduced, but half-lives extended.

IV. DISCUSSION

Our observations revealed distinctive trends in foam stability according to the applied voltage. As the electric field increased, we noticed a remarkable shift in the foam's stability, which yielded changes in the volume of the drained liquid phase. This observation signifies that, under the influence of an external electric field during the foaming period, the liquid remains in the foam state longer. This was attributed to a reduction in the size of gas bubbles escaping from the frit, thus diminishing surface tension. These smaller and more uniform gas bubbles incorporated into the liquid phase exhibited heightened stability and limited the disproportionation effect of foam destabilization. Furthermore, the electric field may influence protein conformation and weak intermolecular interactions, further contributing to foam stabilization.

The densification of the foam structure can be attributed to several underlying factors. The intensified electric field induces stronger electrostatic interactions between the gas bubbles and the surrounding liquid phase, promoting closer packing and reduced bubble coalescence. As a result, the foam structure becomes more compact, leading to decreased expansion during the foaming process. Additionally, the electric field strength alters the interfacial properties of the foam, such as surface tension [6] and viscosity, which further contribute to foam densification. Moreover, the electric field may induce changes in the distribution and orientation of surfactant molecules at the gas-liquid interface, leading to enhanced foam stability and prolonged drainage time. Overall, the observed increase in foam density and extended half-life with higher electric field strength is attributed to the complex interplay between electrostatic forces, interfacial properties, and foam structure dynamics.

V. CONCLUSION

Experiments performed on the original set-up called ElectroFoamVision confirm that applying an electric field

during the foaming process lead to more stable foams. A low voltage is sufficient to decrease surface tension, which results in smaller and more numerous gas bubbles during the foaming process, thus enhancing the foam's quality. Moreover, the decreased surface tension contributes to foam stabilization, leading to a prolonged half-life. However, at high voltages, the effects on protein structure lead to a reduction in foaming properties. In conclusion, applying a low-level electrostatic field during foaming can potentially enhance both the foaming process and the stability of the resulting foam. These results are promising for the conception of innovative food foaming equipment able to produce a high-quality foam under an electric field while reducing the energy required to create the new interfaces.

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