Study of High Intensity Ultrasound Application in Solid-Liquid and Solid-Gas Systems. Influence on Mass Transport Kinetics and Product Structure

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Abstract

Nowadays, High Intensity Ultrasound (**US**) has gained a considerable interest in food technology due to its ability to induce mass transfer intensification. When travelling through a medium, US causes a series of effects that can affect both the external and internal resistance to mass transfer, but it can also influence the structure and the quality of the final product. In order to achieve a better understanding of the effects of US on both the mass transfer and the food quality, it is important to be aware of the interactions between ultrasonic energy and the food structure. Therefore, the main aim of this thesis was to evaluate the influence of US on mass transport and its interaction with the structure of treated materials for some relevant applications in solid-liquid and solid-gas systems.

Regarding the US application on solid-liquid systems, the study of meat brining and cod desalting has been addressed. In both of them, the main objective was to evaluate the influence of US application on moisture and NaCl transport kinetics as well as, how microstructure, and other physical properties, are affected by US. Moreover, in meat brining (5±1 ºC), the effect of NaCl concentration in the brine (50, 100, 150, 200, 240 and 280 kg NaCl/m^3) was evaluated. In this sense, the brine concentration affected the moisture transport direction. Thus, at brine concentrations lower than 200 kg NaCl/m^3, samples were hydrated and at higher concentrations, samples suffered dehydration. In the case of cod desalting (4±1 ºC), two acoustic powers were tested. Mass transport was analyzed by considering a separated diffusion of both moisture and NaCl. Microstructure was characterized by SEM, Cryo-SEM and Light

Microscopy, and among others physical parameters, sample hardness and swelling have been determined.

The diffusion models were accurate for describing moisture and NaCl transport kinetics in both brining and desalting processes, providing a similar trend between the calculated and experimental data. In all the cases studied, US application significantly ($p<0.05$) intensified mass transport, increasing both moisture and NaCl effective diffusivities and not affecting the mass transport direction. In cod desalting, it was also observed that the higher the applied ultrasonic power, the larger the enhancement of mass transport induced by US.

The NaCl gain during meat brining promoted changes in the meat texture thus, high NaCl contents led to harder samples. Then, the higher values of hardness of US treated samples, compared with the conventionally brined ones, could be linked to the higher NaCl content. Otherwise, the desalting process produced the swelling and the hardness reduction, which was more evident in US treated samples. The microstructural analysis showed that US brought about noticeable effects on the product structure. For example, a more homogeneous NaCl distribution was observed in the US brined meat and thicker cod fibers were observed in US desalted samples.

In solid-gas systems, the air-borne US application was addressed in both hot-air and low-temperature drying. First of all, the feasibility of US application in low-temperature drying of salted cod was addressed by quantifying its influence on the drying kinetics and in some physical properties of the final dried product. For that purpose, drying experiments at -10, 0, 10, 20 °C were carried out with salted cod slabs at constant air velocity (2±0.1 m/s) and relative humidity (9±4 %) with (20.5 kW/m^3) and without US application. The dried-salted cod rehydration capacity (4 °C) as well as microstructural, textural and color changes were determined. Diffusion and empirical models were used in order to quantify the influence of US application and the drying temperature on drying and rehydration kinetics, respectively.

At every temperature tested, US application sped up the drying rate, being drying time shortened by up to 50%. The diffusion model described adequately the drying kinetics with percentages of explained variance of up to 99%. The US application significantly ($p<0.05$) increased the effective moisture diffusivity up to 110%. Regarding the physical properties, US dried samples were softer and presented a higher rehydration capacity than those conventionally dried. This fact was linked to induced structural changes, such as the formation of large spaces between myofibrils and a more intense salt redistribution on the sample surface, such as the microstructural analysis highlighted. In addition, significant ($p<0.05$) color changes were brought about by US application.

In the air-borne US application on the hot-air drying, the response of different fruits and vegetables to the acoustic energy was addressed. For that purpose, experimental drying kinetics (40 ºC and 1 m/s) of eggplant, potato, cassava and apple were carried out by applying different ultrasonic powers (0, 6, 12, 19, 25 and 31 kW/m^3). US application shortened the drying times in every case, but the magnitude of the reduction ranged from 27% (cassava) to 68% (eggplant) depending on the product considered.

In order to study the influence of US in both internal and external resistance to mass transfer, diffusion models with differing degrees of complexity were used. For the experimental conditions tested, the external resistance was found significant. Thus, its inclusion in the diffusion model increased the explained variance from the 84%, the obtained value neglecting external resistance in the model, to above 98%. However, it was noticed an overestimated effective diffusivity when the shrinkage was significant, such as in the case of eggplant. Thereby, a more complex model, which considered both external resistance and shrinkage to be significant phenomena, was used to accurately describe the drying kinetics of eggplant (explained variances higher than 99% and mean relative errors of under 1.2%).

The ultrasonic power had a significant ($p<0.05$) influence on the kinetic parameters, thus significant ($p<0.05$) linear relationships were found between both the effective moisture diffusivity and the mass transfer coefficient with the ultrasonic power applied. Although, the magnitude of the improvement for the kinetic parameters was greatly product-dependent.

In order to contribute to the understanding of how the properties of the material being dried affect the effectiveness of air-borne ultrasonic application, the experimental results obtained in this work for eggplant, potato, cassava and apple were completed with others already published in previous works for carrot, orange and lemon peel. Drying kinetics were analyzed considering a pure diffusion model in which the effective diffusivity was considered as a global mass transport parameter. Moreover, in every product, structural, textural and acoustic properties were assessed. The **S**lope of the relationship between the effective **D**iffusivity and the **U**ltrasonic **P**ower (**SDUP**) was used as an index of the effectiveness of the ultrasonic application, thus the higher the slope, the more effective the US application. SDUP was well correlated ($r \geq 0.95$) with the porosity and the hardness of the samples. Then, the larger the porosity and the lower the hardness, the higher the SDUP figure. In addition, SDUP was greatly affected by the acoustic impedance of the material being dried. In such a way, the relationship between SDUP vs. impedance and SDUP vs. transmission coefficient of the acoustic energy in the interface showed a similar pattern. This fact illustrates that the ultrasonic application is at least partially controlled by how US is transmitted in the air/solid interface. On the one hand, products with softer and more open-porous structures showed a better transmission of the acoustic energy and were more prone to the mechanical effects produced by US. On the other hand, materials with a harder and more closed-compact structure were less affected by the acoustic energy due to the high impedance mismatch between the product and the air causing high energy losses on the interface.

Summarizing, common facts have been highlighted between the US applications in liquid-solid and solid-gas systems. First of all, the ability of US to intensify mass transport kinetics in both systems has been illustrated. Moreover, in both cases, the mechanical effects induced by US induced changes on the product structure, as well as on the physical properties of the treated product, which have to be considered aiming to better preserve quality traits. Moreover, in solid-gas systems, it was observed the influence of product structure in the effectiveness of US during drying. This fact was linked to the large impedance mismatch between the air and the product.