Ultrasound technology: effect of processing conditions and material on cavitation level

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Abstract**– *Ultrasound technology has been widely studied for its application in food area to improve different processes and properties of food. The most used form of application is by immersing the product in a medium placed directly or by using containers. During the ultrasound application, different conditions such as powers, media for the transmission of waves, container materials, or pressure levels have been applied. However, it has not yet been described how these conditions impact the level of acoustic cavitation. In this work, by using an ultrasound bath with 40 kHz and power levels (30% - 100%), the effect of the position of beakers, their type of material (plastic and glass), the type of medium (water and ethanol) and pressure (atmospheric and vacuum), in the acoustic cavitation level was studied. As results, the acoustic cavitation level increased as the power level increased. The position in the transducers allowed a higher level of acoustic cavitation, while the influence of the type of material in the acoustic cavitation depended on the power level. At 100% power, the acoustic cavitation decreased by more than 14% when using containers of glass, while, at 30% power level, cavitation highly increased compared to plastic containers. Regarding the medium type, at high power levels (>70%), the acoustic cavitation in water was greater than in ethanol. However, it remained similar at low power level (30%). Finally, when vacuum was used, cavitation decreased in both media, but the level of reduction was greater when the medium was water. In conclusion, the different processing conditions showed a significant impact on the level of acoustic cavitation. This must be considered when the ultrasound technology is applied since the observed effects in food will depend on this.***

Keywords—ultrasound, cavitation, food processing, ultrasonic bath

I. INTRODUCTION

Ultrasound technology is based on the propagation of mechanical acoustic waves throughout the materials at frequencies over 20 kHz. In food processing, the ultrasound can be applied as a pre-treatment in a liquid media (by using ultrasonic baths or ultrasonic probes) or simultaneously as in the case of drying process (by using contact or contactless transducer systems for airborne applications) [1-4]. This technology demonstrated capacity to accelerate the mass and heat transfer processes, such as extraction [5] drying [1, 6], hydration [7], microbial and enzymatic inactivation [8, 9], salting and desalting [10, 11], among others. The improvement of the mass transfer processes is related to the reduction of internal and external resistances. The internal resistance is reduced by the sponge effect and acoustic cavitation, which mechanisms cause structural changes improving the water and compounds mobility from inside the food matrix [12]. Regarding the external resistance reduction, it occurs due to the acoustic energy is dissipated on the system, pressure variations occur, microstirring on the solid-gas interface, and gradients in momentum promoting turbulence [1, 13]

The ultrasound baths are devises that were mostly used for cleaning purposes. However, over time its use in food has intensified [14]. The ultrasonic baths are available in different volume capacities and they present one or more acoustic transducer at the bottom of the tank. These transducers are the responsible for converting electric energy into acoustic energy. The ultrasonic wave is propagated from the bottom to the upper zone of the bath [15]. In fact, a liquid medium is required for propagation and the properties of the medium influence the distribution, dissipation, and effectiveness of the ultrasound on the material is processed.

In general, the most common way to apply ultrasound to improve mass transfer is by immersing the food in a liquid of interest or water, that is commonly used to transmit the acoustic waves. However, water can be replaced by other fluids such as osmotic solutions [16-18] or ethanol [19-21], which has been used combined with ultrasound to accelerate drying processes. On the other hand, recently the application of ultrasound has been explored under vacuum pressure conditions. The combined use of ultrasound and vacuum has been studied during osmotic dehydration of apple [22], garlic [23] and black jamun fruit [24]. Also as a pre-treatment for convective drying of melon [25] and okra [26], banana [27], chicken meat [28]. In these studies, it has been found that the combined use of ultrasound and vacuum improves the efficiency of the drying process and the properties of dehydrated products.

The observed effects because of ultrasound application depend on the intrinsic characteristics of the food (structure and composition) as well as the ultrasound characteristics and the processing conditions. Among them, the amplitude, power and temperature have been the most studied variables [29-31]. However, other little-explored processing conditions can promote or impair cavitation levels and therefore the effects of ultrasound, such as the material where the food is located, the type of medium used for the propagation of acoustic waves, and pressure conditions.

Therefore, the present work aims to clarify the influence of different processing conditions (power, pressure, immersion medium, material and position) on the level of acoustic cavitation. This would help future research to better use

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ultrasound technology for improving food processing. In addition, this would help to select the better material and medium to process food in laboratory and industrial scales.

II. MATERIAL AND METHODS

A. Ultrasound (US) equipment description

It was used an ultrasonic bath (ACP-120H, MRC, Israel) made of stainless steel, finished surface, 3 L capacity, with 40 kHz frequency, two transducers located to the right and left of ultrasonic bath and power control among 0% to 100% level. The power density at 100% was 32 ± 2 W/L which was measured by the calorimetric method [15] containing 1.5 L of distilled water

B. Effect of position and material

Firstly, a map of cavitation zones was obtained, which allowed to know the areas of high cavitation intensity based on aluminum foil erosion [32-34]. For this, aluminum foil was placed at the bottom of ultrasound bath covering all the area (Fig. 1). Then, 1.5 L of water was placed. The locations of high cavitation intensity (transducer position) were identified based on holes created in the aluminum foil after ultrasound application. The bigger the erosion is, the more powerful the cavitation is.

After identifying the location of the transducers, the ultrasonic bath was cleaned and 1.5 L of water at 25 °C was placed. Then, plastic (polyethylene) or glass beakers containing 150 mL of water were placed in two locations (as observed in Fig. 1): between ultrasound transducers (A) and over the ultrasound transducer (B). Acoustic cavitation was measured at two ultrasound power levels (100% and 70%) by introducing a cavitometer probe (CAV-METER-2, MRC, Israel) in each beaker. In addition, as a control, cavitation was measured directly in the water of the ultrasound bath.

C. Effect of pressure and immersion medium

The Fig.2 shows a schematic representation of the constructed system to evaluate the pressure and immersion medium effect. Two pressure conditions were evaluated during ultrasound processing: atmospheric pressure (101 kPa) and vacuum pressure (-75 kPa). In addition, two media (water and ethanol) through which the acoustic waves propagated were used. Each liquid (150 mL) was placed in a glass kitasato flask with a capacity of 500 mL. Then, the flask containing the liquid was connected to a vacuum pump and placed inside the ultrasound bath containing 1.5 L of water.

The above mentioned was evaluated at three ultrasound power levels (100%, 70% and 30%). In each condition, the acoustic cavitation was measured by immersing the cavitometer probe in the middle of the liquid inside the kitasato flask.

D. Statistical analysis

A descriptive statistical analysis of the effect of the power level, the type of material, the type of medium and the position on the acoustic cavitation level was performed. Excel 2016 software was used for data processing.

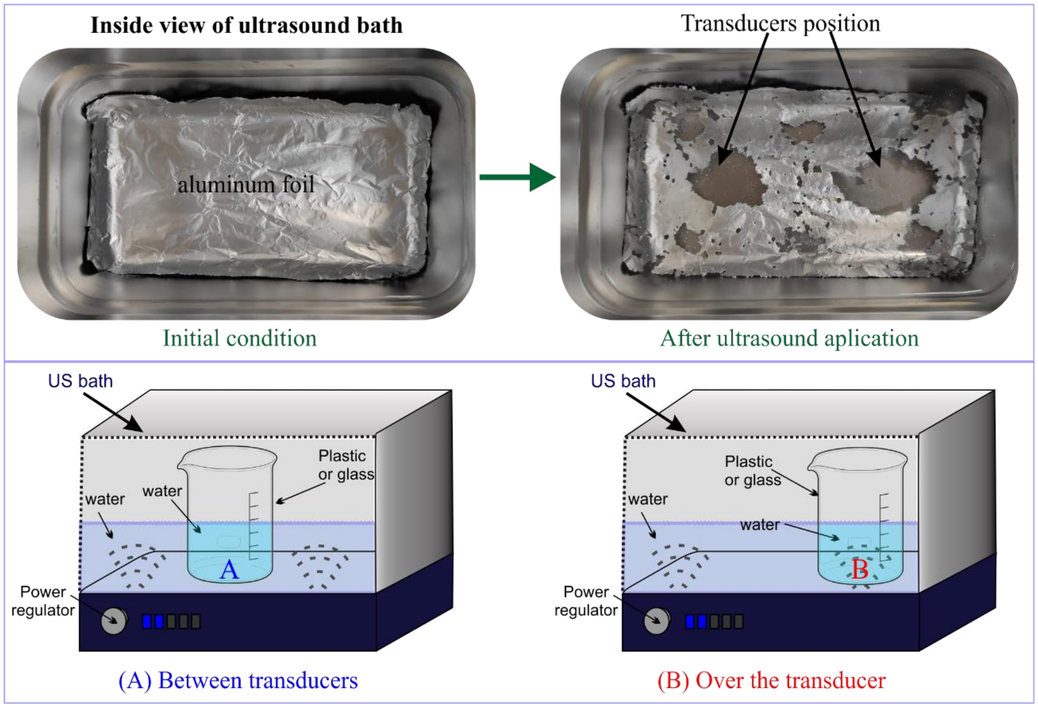

Fig. 1 Up: Location of the points with the highest acoustic energy (holes in the aluminum foil). Down: (A) position between transducers, (B) position over the right transducer.

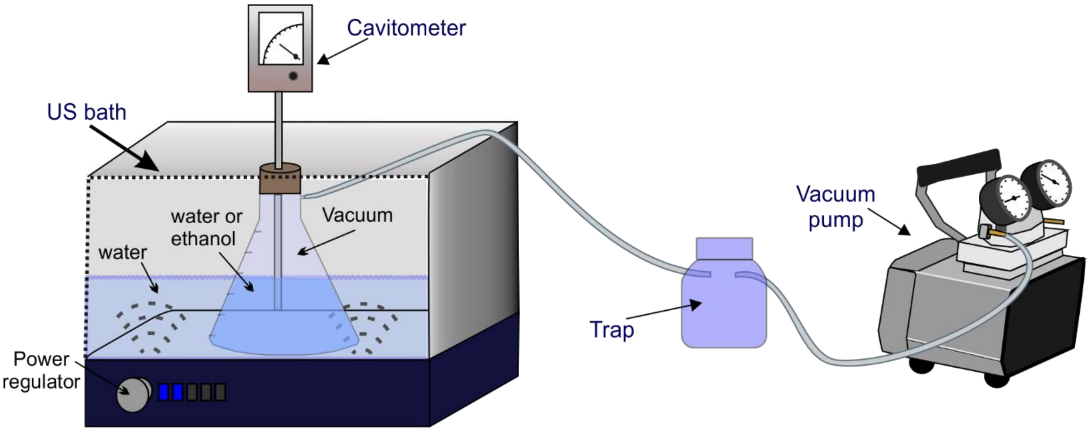

Fig. 2 Representation of the system used to evaluate the effect of pressure and immersion media on cavitation level.

III. Results and Discussion

A. Effect of position and material in acoustic cavitation

Figure 3 shows that in all cases, the higher the level of ultrasound power is, the greater the acoustic cavitation is. This makes sense since more acoustic energy is being supplied to the system. On the other hand, by analyzing the position in which the cavitation analysis was carried out, it is shown that when the beakers are placed between the transducers (Fig. 3 A), the cavitation level is less than when the beaker is placed over the transducer (Fig. 3 B). In this case, at 100% of power level, the cavitation level was above 100% for all conditions. In fact, in position B (over transducers), the acoustic energy is generated in the transducer, and the waves must pass through the bottom of the ultrasound bath and the wall of the beaker. On the contrary, in the position A (between transducers), the waves also must travel through the water of the ultrasound bath and only a part of them could reach the beakers. Therefore, the energy dissipation was lower in (B) than in (A) position resulting in higher cavitation. For this reason, Vinatoru [35] recommends positioning the beaker above one the transducers to ensure a constant acoustic field entering into the beaker.

According to Gallego-Juárez, et al. [36], Ozuna, et al. [37], Mulet, et al. [38] the effectiveness of energy transfer between two media mainly depends on the acoustic impedances. The more similar the properties (density and speed of sound propagation in the material) between the materials, the better the impedance match between the materials is. Therefore, better penetration of the acoustic energy. At 100% power level, there was greater vibration at the bottom of the bath, which does not favor the contact with glass beakers (in A position) creating a thin layer of water between them. It probably generated higher acoustic impedance decreasing the cavitation level. At 30% power level, the cavitation measured directly in water was lower than the registered using the glass beaker in both positions (A and B). At this power level, the vibration of the system is minimal, promoting the contact of the glass beaker with the bottom of the ultrasound bath. This could benefit the impedance matching between the glass and the bath bottom (stainless steel), therefore, improving the transmission of acoustic energy. Contrary to this, when any recipient is used, acoustic energy dissipates through all the contained water in the ultrasound bath resulting in more heat energy and less cavitation detected.

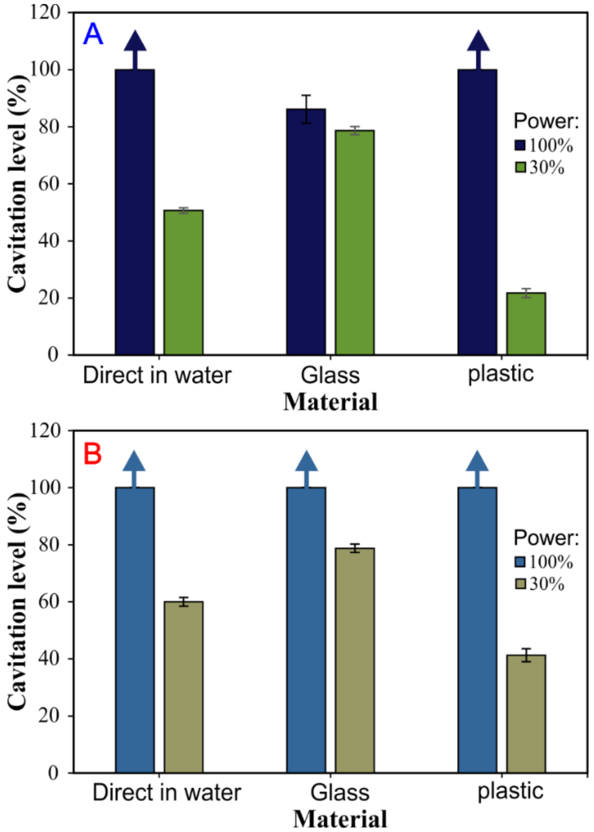

Fig.3 Acoustic cavitation level measured directly in the water of the ultrasonic bath, inside glass and plastic beakers containing water located between the transducers (A) and above the transducer (B), at 100% and 30% power level. The upward arrows indicate a level of cavitation above the level detected by the cavitometer used. That is, it exceeds 100%.

Furthermore, at 30% power, in the plastic beaker, the cavitation measured was higher in the B position, but was less than the cavitation recorded in the glass beaker in both positions, it could be explained by the mismatch between the acoustic impedances of bath bottom (stainless steel) -plastic. On the contrary, the effect observed in plastic is different at high power levels (100%) since, at this power level, the cavitation registered in both positions has been higher than that registered in the glass beaker. Therefore, at 100% power level, probably the acoustic impedances among stainless steel-water-plastic coincide to a greater extent than the impedances among stainless steel-water-glass, being greater transmitted energy when plastic is used at a high power level.

In conclusion, it is recommended to place the samples on the transducers in glass containers. If the position is between the transducers, it is recommended to use plastic containers in high ultrasound power, while glass containers if the power is low.

B. Effect of pressure and immersion medium in acoustic cavitation

Fig. 4 shows, as in the case of Fig. 3, that as the power level is reduced (from 100% to 30%), the cavitation level also decreases for all experiments. For example, comparing power level of 100%, when 30% power was used, cavitation was reduced by 46% when ethanol was used (US+OH) and 78% when water and vacuum were used (US+W+V). Therefore, this level of cavitation reduction varies with the type of medium used and the pressure.

Comparing the type of medium used, the level of cavitation when using water (US+W) is higher than when using ethanol (US+OH), especially at powers of 100% and 70% while it remains similar at a power level of 30%. According to Verhaagen and Fernández Rivas [33] the dynamics of cavitation (bubble coalescence, clustering and fragmentation) depend on the physicochemical aspects of the used medium. Therefore, the observed differences between water and ethanol acoustic cavitation (Fig. 4) could be explained by their different properties. Ethanol compared to water presents higher vapor pressure, lower surface tension and density and slightly higher viscosity. For example, it was observed that cavitation bubbles coalesced instantly in water but in the presence of surface-active solutes (such as n-propanol) the coalescence was hindered and low-density bubble cluster is formed [39]. In addition, the different media used result in different lectures of real power density delivered to samples. It was determined, under the same conditions, that the volumetric power was higher when ethanol medium was used, compared to water [19]. The volumetric power was determined by the calorimetric method [15], i.e. measuring the temperature increase with ultrasound application in the first seconds. As is observed, it seems to make no sense that with ethanol the cavitation level is lower, but the volumetric power is higher, this is probably due to the specific heat of ethanol, which is lower than that of water, so it needs less energy to increase their temperature.

Pressures between 0.02 to 0.08 MPa have been applied in combination with ultrasound [25, 40-42]. However, it has not been measured how pressure influences the level of cavitation. As observed in Fig. 4, compared to treatment in water without vacuum (US+W), the cavitation level decreases when using water and vacuum (US+W+V) especially at a power level of 30% where the cavitation was reduced by 64%. However, when ethanol is used, the effect of the application of vacuum (US+OH+V) in reducing cavitation is lower than in water medium, observing that the level of cavitation remains similar that when vacuum is not applied (US+OH), especially at powers of 100 and 70%. In addition, when using ethanol and vacuum (US+OH+V), cavitation at 30% power is higher than when using water and vacuum (US+W+V) at the same 30% power level. When vacuum is applied, it causes the pressure in the system to drop and to approximate the vapor pressure of the liquid, depending on the vacuum pressure level. Therefore, the impact of this change is more significant when water is used since it presents a vapor pressure lower than ethanol. This may explain the greater reduction in the level of cavitation when using a vacuum with water as the medium.

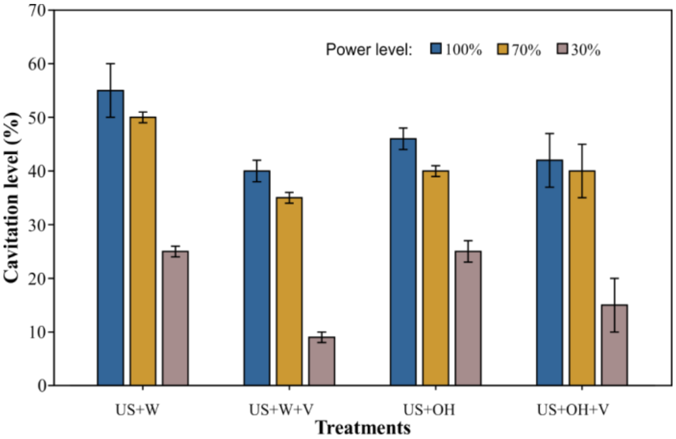

Fig. 4 Acoustic cavitation level of ultrasound application at 100%, 70% and 30% power level in water medium at atmospheric pressure (US+W), water medium at vacuum pressure (US+W+V), ethanol medium at atmospheric pressure (US+OH), and ethanol medium at vacuum pressure (US+OH+V).

In general, as stated by Huang, et al. [43] the effect of ultrasound decreases with the intensity increase of variables such as temperature, pressure, air velocity, among others. However, as demonstrated here, the level of acoustic cavitation reduction with vacuum application changes depending on the type of used medium.

Consequently, this work demonstrated that despite volumetric power, the material, position and medium should be considered and reported when ultrasound is used for a research. Therefore, this would allow us to discriminate which characteristic of ultrasound treatment affected the studied processes. In fact, future studies are always welcomed such as analyzing other media and other kind of ultrasonic systems and environmental conditions.

III. CONCLUSION

Using different power levels (30% - 100%), this study demonstrated the effect of the position (between the transducers and over the transducer), the type of material (plastic and glass), the type of medium (water and ethanol), pressure (atmospheric and vacuum), in the acoustic cavitation level. Among the main results, the position over the transducers allows a higher level of acoustic cavitation, while the influence of the type of material on the acoustic cavitation depends on the power level. At a high power level, the acoustic cavitation decreases when using containers of glass between transducers, while, at a low power level, cavitation increases compared to plastic containers. On the other hand, the acoustic cavitation recorded in water is greater than that recorded when the medium is ethanol. When vacuum is used in the system, cavitation decreases in both media (water and ethanol), however, when vacuum is used, the decrease in cavitation in an ethanolic medium is less drastic.

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