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Acoustic cavitation by means ultrasounds in the extra virgin olive oil extraction process

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Abstract

The virgin olive oil extraction process has changed very little over the past 20 years when the mechanical crushers, malaxers, horizontal and vertical centrifuges, took place in the olive mills. However, malaxation process remains the main critical step due to the discontinuity of this process. In previous activities, the same authors demonstrated how application of new emerging technologies could offer an interesting number of advantages to remove this bottleneck and, among the others, the ultrasound (US) technology is the most promising one, due to its mechanical and thermal effects due to the acoustic cavitation phenomenon. Acoustic cavitation, provided by means of low frequency high power ultrasounds, increases the quality, the work capacity and efficiency of the extraction plant, guaranteeing the sustainability. The paper shows how the authors have designed, realized and tested the first in the world continuous ultrasonic full-scale device for the extra virgin olive oil industry, with the aim to obtain the best product quality at the highest efficiency. Considering the heterogeneity of the olive paste, which is composed of different tissues, and considering the large number of parameters able to influence the process, a 3D multiphase CFD analysis was used as auxiliary tool in the design a so-called Sono-Heat-Exchanger (SHE). This innovative device, to be placed between the crusher and the decanter, is a combination of a heat-exchanger with plate-shape ultrasonic transducers. Finally, experimental results about yields and phenols contents demonstrated the relevance of this innovation.

Keywords: Virgin olive oil, cavitation; batch process versus continuous process; emerging technologies, ultrasound, heat exchanger.

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1. Introduction

Ultrasound (US) is a promising emerging technology that has already found application in the food industry [1–3] due to its significant effects on the processes, such as higher product yields, shorter processing times, reduced operating and maintenance costs, improved taste, texture, flavour and colour [4]. Recent findings reported in the literature have highlighted that US has promising application in the field of virgin olive oil industry as well, due to the mechanical and thermal effects useful to guarantee adequate oil yields, thus reducing the process time and improving the process efficiency [5–7]. The thermal effect occurs when kinetic energy of the ultrasound waves is converted into the thermal energy due to the turbulence increment in the matter [8,9]. The mechanical effect is due to the cavitation phenomena. In other words, when ultrasound is applied on a continuum fluid, it produces sinusoidal acoustic waves and tiny gas bubbles grow within the fluid when the local pressure falls below the vapour pressure of the liquid [10,11]. If the bubble growth reaches a critical size, it implodes causing the phenomenon of cavitation, the most important effect in high-power ultrasound. Generally speaking, the phenomenon of violent bubble implosions is characterized by extreme local conditions, such as high pressure differentials, shock waves and liquid jets [12], that promote the rupture of the solids that are in the liquid medium, thereby increasing both the total solid surface in contact with the liquid phase and the mass transfer [10,13–16]. In the case of the olive paste, cavitation, by means of ultrasounds, promotes the disruption of tissue structures, including membranes of elaioplasts (i.e., specialized leucoplasts protected by a cellular membrane, responsible for the storage of lipids) freeing the trapped oily phase [17,18] . Thus, the application of ultrasound-waves to olive paste can effectively enhances the release of soluble compounds from the plant tissue and improves mass transfer also in the olive tissues [19]. Moreover, ultrasound can increase the hydrophobic effect, improving the kinetic of the coalescence phenomena by enhancing the probability of particles collision leading to an increase of coalescence and oil recovery [18,20]. It has been also demonstrated that, at low frequencies (<30 kHz), ultrasound can split the emulsion into its component, aqueous and oily phases. [17].

Currently, the mechanical methods used to extract virgin oils from olives is generally made up of a mechanical crusher, a few malaxers and horizontal (decanter) and vertical-axis centrifugal separators. The mechanical crusher and the centrifugal separators operate continuously, while, the malaxer is a batch machine, which works between continuous devices. For this reason, the malaxation represents the bottleneck of the continuous extraction process [21]. Moreover, the malaxer is an inefficient heat-exchanger due to a not favourable ratio between its large volume and small surface [6].

Olive trees represent an economic and social resource in the Mediterranean area [22–25] since virgin olive oil (VOO) is the main component of the Mediterranean diet due to its excellent sensory and nutritional qualities [26]. Therefore, it is of interest to develop innovative and sustainable plant solutions able to increase both the yield and the quality of the VOO extraction process [21,27,28]. And the development of a fully continuous process presents some tangible, positive features that can help to achieve this aim [29]. As consequence, increasing research efforts have been put into the design of advanced machines able to transform the discontinuous malaxing step into a fully continuous phase [6,20,30]. For the abovementioned reasons, high power ultrasound for the treatment of olive paste represents a practical solution able to reduce the duration of malaxation and, at the same time, increase both the yield and the quality of the resulting VOO.

Following this intuition, innovative and continuous ultrasonic devices for the extra virgin olive oil industry have been developed. For instance, Pieralisi [31] proposed to accelerate the oil extraction process applying ultrasound directly in contact with the olive paste with the synergetic effect of a heater-conveyor; Masotti et al. [32] patented an ultrasound device useful to improve the quantity of polyphenols the turbidity stability of the EVOOs. Other research activities, such as the works made by Amirante et al. [8], Veneziani et al. [33], and Balzano et al. [34], concerned the effects of heat-exchange, in order to exploit the multiple combinations between different sonication power intensities and temperatures.

Clodoveo et al. [12], in 2013, tested at pilot scale the ultrasound treatment both on olive fruits submerged in a water bath (before crushing) and on olive paste before the malaxation (immediately after crushing). The ultrasound technology allowed a reduction in the duration of malaxing phase improving oil yields and its minor compounds content. Between 2015 and 2016, confirmed the results obtained by Clodoveo et al. [12], as also reported in [17]. They observed that the ultrasound treatment caused an improvement of the oil yield of about 1% and the oil extractability equal to approximately 5.7%. Furthermore, a slightly heating of olive paste can be obtained by high-power ultrasound and it can be considered an alternative at the traditional warming system based on the conductive and convective systems occurring in the malaxers. Evaluations regarding the effect of ultrasound on oil quality parameters, nutritional and sensory characteristics has shown no changes in the fatty acid composition and volatile compounds of the VOO occurred, while tocopherols, chlorophylls, and carotenoids enhanced [5,12].

A real-scale plant was realized and tested in Italy by Amirante and Clodoveo et al. [6]. In such a plant, a so-called "sono-exchanger" was placed immediately after the crusher. The sono-exchanger was made of two straight pipes connected by an elbow. Ultrasonic rod-style transducers were plugged into the straight pipes through the bend. Encouraging results were obtained: no alteration in the EVOO quality parameters and significantly higher contents of tocopherols, carotenoids, and phenolics were observed after the ultrasound treatment. However, it is still possible to improve the engineering design of the "sono-exchanger" and this paper represents a continuation and extension of Amirante and Clodoveo et al. work [6].

In the present paper, an innovative device able to simultaneously dispense the ultrasonic treatment and the thermal conditioning (either heating or cooling) to the olive paste is described. It is named Sono-Heat-Exchanger (SHE) and it is a combination of a heat-exchanger and plate-shape ultrasonic transducers. 3D multiphase CFD simulations were employed in the design the SHE cross section to obtain the best performances. The experimental measurement of the olive oil yield allowed to monitor the mechanical effects of cavitation. The improvement in the EVOO quality was evaluated by comparing the polyphenol content, with and without performing the ultrasound treatment.

2. Materials and methods

A new industrial processing plant set-up

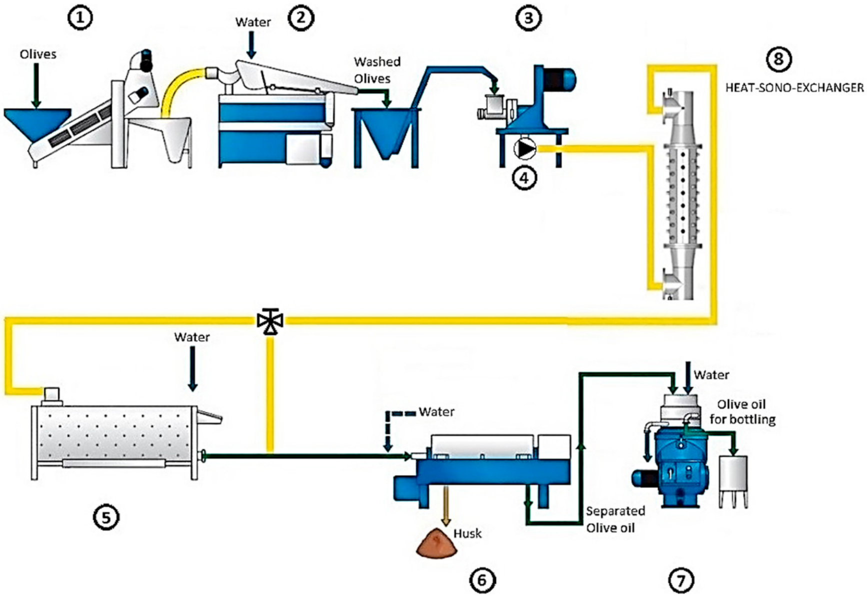
In this section, the proposed evolution of a typical set-up for a virgin olive oil extraction plant is described. The new configuration is compared not only with the "classical" one, but also with the modified-version presented in a previous work [6]. The aim of the work consists in demonstrating that the newest set-up represents a further step forward in the effectiveness in dispensing the ultrasound effects.

In a typical so called "continuous" process, the harvested olives are moved to the extraction plant and then the olives are dropped into a hopper and laid down onto a conveyor belt that carries them to the washing machines. A vibrating screen (1) – Figure 1(a) – remove leaves and other debris to protect the extraction plant and avoid the off-flavours deriving from the presence of foreign bodies. After that, the olives are also washed (2) to remove soil or other residues. After the pre-process stage is finished, another conveyor belt carries the olives to the next phase. Crushing (3) is the first phase of the extraction process. The aim of the crushing phase is the size reduction of olive fruit tissues and the breakdown of vegetal cells in order to facilitate the release of the oil by means of a strong mechanical action which also produces heat due to the energy dissipation. The olive paste obtained is moved to the following stage by means of a piping and an upstream mono pump (4). Malaxer (5) represent the subsequent step and it consists of a usual cylindrical tank equipped with a shaft with rotating arms and stainless steel blades. The walls of the malaxer are hollow allowing warm water to flow through these jackets to heat the olive oil paste. During the malaxation phase the olive paste is continuously agitated at a controlled temperature to help the small droplets of the oil formed during the milling to merge into large drops (coalescence phenomena), allowing an easier separation through centrifugal systems. Once the malaxing process has been completed, the paste is removed from the bottom of the tank by another pump which feeds the paste into a horizontal centrifuge (6) to perform the separation of oily phase from the solid and liquid phases of the olive paste. Water can be (or not) added to dilute the incoming paste according to the Stokes law to divide extracted oil from vegetation water and solids (olive pomace). Finally, a vertical centrifuge (7) allows clarifying the extracted oily phase by adding lukewarm tap water. In this way, the equipment separates the residual water and the solid impurities in order to obtain clear oil.

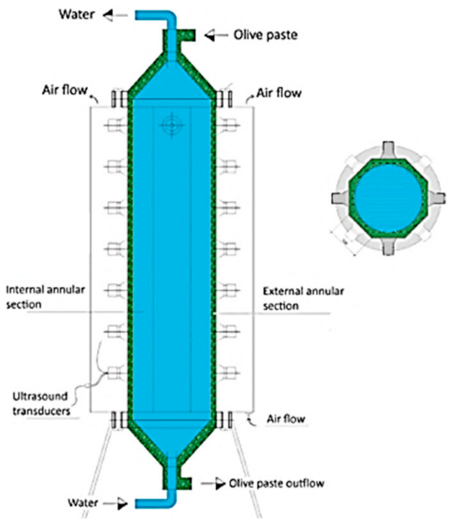
A first modification of original the original plant was provided in a previous work [6] and it consisted in the addition of a "sono-exchanger" and a "heat-exchanger" separately downstream of the crusher and upstream of the malaxer. The sono-exchanger was made up of two straight pipes connected by an elbow. Ultrasonic rod-style transducers were plugged into the straight pipes through a bend. The ultrasonic probes inside the pipe determined the cavitation phenomenon within the olive paste along with a vibrational energy transferred to the olive paste.

The schematic and the full-scale experimental set-up proposed in this work is shown in the same Figure 1(b) and (c). The tube-shaped "sono-exchanger" and the heat-exchanger have been replaced by an innovative device coupling the effects of a heat-exchanger and plate-shape ultrasonic transducers. The SHE was placed between the crusher and the decanter. Such a solution represents a more effective way in dispensing the ultrasound effects in comparison to the previous configurations. The present device ensures a more continuous and a better adhesion between the paste and the transducers (improving a weakness related to the previous configuration), avoiding air bubbles formation or flux separation phenomena, which worsen the ultrasound transmission. Moreover, it encases the ultrasound and the heat exchange processes and it can be scaled, according to the plant size, in a more flexible way due to its modular structure. Therefore, it represents a significant further step towards the transformation of the malaxing step from a batch operation into an actual continuous process and improves the working capacity of the industrial plants.

The SHE, employing the plate shape transducers, is composed of a couple of annular sections, as shown in Figure 1(b). The olive paste flows into the external annular section, while water flows through the internal annular section to control temperature inside the olive paste. Outside the external annular flow section, a transducer for each side of an octagonal surface is placed to provide ultrasounds. The energy per kilogram of olive paste is due to the power of each transducer and the flowrate flowing inside the SHE. The choice of this couple of parameters should be performed keeping in mind that the best results can be achieved by means of 15−18 kJ/kg at 30 kHz [12,27].



(a)



(b)

(c)

Figure 1 (a) - VOO modified scheme proposed in the present work: reception (1); washing (2); crushing (3); mono pump (4); malaxing (5); separation (6); clarification (7); SHE (8). (b) Schematic representation of the SHE system. (c) - Full scale experimental plant in “Tre Colonne” farm, harvest season 2016/2017.

Engineering design and fluid dynamic analysis of the SHE

Preliminary experimental tests are usually expensive and time-consuming. For this reason, a 3D computational fluid dynamics (CFD) analysis was performed to gain insight into the flow inside the SHE. The problem of determining the pressure losses is important in order to achieve the indications needed to predict the cavitation phenomenon and to design the device and the pumping systems in a full-scale plant, thus avoiding expensive experimental tests.

The finite-volume method was used to discretize and solve the flow by employing the commercial software Ansys Fluent 17,1. The flow was modelled as laminar, due to the high viscosity of the olive paste, which remains laminar even at larger flow rates [35]. The olive oil paste was modelled as a non-Newtonian fluid, as wieldy discussed in a previous work [6] and it was defined as compressible-liquid following the Tait equation [36] and having a density of 1126 kg/m^3 at standard conditions (as proposed in [6]), a bulk modulus of 1.6e+09 and a density exponent equal to 11. For the transient simulations, in order to simulate the unsteady cavitating flow, the Schnerr model was adopted [37] and, specifically, a bubble number density equal to 1e+09 and a vapour pressure of 3540 Pa were set, according with the water value at the working temperature. The oscillating frequency of the transducers was set to 23 kHz and a time step equal to a tenth of a single oscillation cycle time was adopted. A whole structured dynamic grid was used to mesh a quarter of the geometry, in order to reduce the overall computational time, as shown in Figure 2. A grid convergence analysis was carried out in stationary conditions to reduce the total amount of CPU time, while maintaining a high solution accuracy. The best compromise achieved in in the mesh generation process is showed in Figure 2(b) and it was composed of about one million of elements.

The specific energy generated by the ultrasound transducers was set equal to the optimal value obtained from a preliminary analysis carried out in static conditions on small specimens [6,12,17]. From this consideration and for a total installed power of 5.5 kW, it was possible to estimate that 1500 kg/h represents the optimal mass flow rate. The outlet pressure was set equal to 2 bar, according to the pressure drop need to push the olive paste into the malaxer of the experimental plant. This pressure condition has been experimentally verified during the experimental test.

Considering that the climate conditions in which the oil extraction process is carried out can significantly vary due to the specific geographical location as well as due to more general climatic changes. Therefore, it is necessary to thermally control the olive paste in the range of 23–27°C, not merely for heating, but most of all to determine a cooling treatment. With the present device, it is possible to thermally control the olive paste, for either a heating or cooling treatment. A cold-water flow (4–5°C) can be provided into the inner annular section to decrease the olive paste temperature in the geographical areas characterized by a high ambient temperature. Conversely, a warm water flow (20–50°C) can be provided to warm up the olive paste in the geographical areas with low temperature during the harvesting season.

After having designed the SHE, a thorough experimental campaign was performed. In the following sections, the tests are described in detail, along with the quality indices that describe the performances of the proposed plant. The fruits were harvested by a trunk shaker machine and processed 6 h after the harvesting. The maturity index was determined according to the method proposed by the International Olive Council. Three aliquots of olive oil (500 ml), obtained from each experimental test, were acquired and stored in dark bottles at 15°C until analysis. The extraction yield (EY_{EVOO}) and the phenolic content were determined following the procedure described in details in the previous work [6]. Olive oil extraction experiments were performed in triplicate, and chemical analyses of the oil obtained were conducted in duplicate.

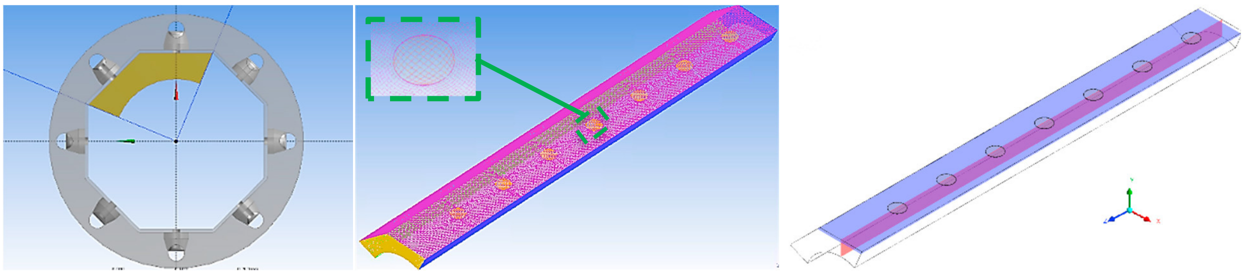

(a) (b) (c)

Figure 2 Modelled domain of the SHE (a). Computational mesh (b). Section planes used to plot the evolution of some variables of interest (c).

3. Results

Fluid dynamic analysis

The first crucial aspect for the SHE development is represented by the analysis of the pressure drop along the device. By analysing the stationary results, it was possible to determine the overall pressure drop along the SHE due to frictions. Namely, a pressure drop of 0.1159 bar, between the inlet and the outlet sections, was obtained from the steady-state numerical simulations. In addition, it was found that the pressure was highly uniform below the transducers surface and this allows an efficient energy exchange.

Whilst the vapour formation is localized in a tiny region below the transducer plate Figure 3, the propagation of intense pressure waves produces more global effects, as it is possible to infer from Figure 4. During the compression stroke, a drastic pressure increase is locally recorded. However, such a pressure wave quickly propagates through the domain in a spherical shape. Only when it reaches the opposite wall, is attenuated due to the high viscosity of the considered fluid.

Therefore, such a behaviour influences the olive oil past motion through the SHE and, therefore, it cannot be neglected during the design process. The transducer surface, vibrating at high frequency, imposes a very high speed to the fluid region that is in contact with it. The fluid near the transducer is forced to move radially, interfering with the regular axial flow. This aspect is showed in Figure 5, in which the streamlines (coloured by the velocity magnitude) are depicted. The propagating spherical waves act like a wall for the flowing fluid. Whilst, it is true that this stirring effect can be considered positive in terms of olive oil extraction process, it might result in adverse effects if the height of the SHE cross-section is not adequately designed. In other words, a thin section is desirable in order to maximize the ultrasonic effects, but can generate condition in which the flow might be completely locked by the propagation of pressure waves within the fluid region or, at least, it is forced to turn around the spherical obstacle in order to avoid it. Therefore, the chosen height of the SHE cross-section represents a compromise between the two conflicting effects. Furthermore, the proposed staggered disposition of the transducers between two adjacent sides of the machine aims in reducing the interference effects between transducers and, at the same time, produces a beneficial stirring effect due to the above-mentioned reasons. For sake of brevity, the optimization process employed in the SHE design will be presented in a future work, since it requires adequate space and attention in order to be treated.

Effect on virgin olive oil quality and extraction yield

The experimental tests of the harvest season 2016/2017, performed in the "Tre Colonne" farm in Giovinazzo (in southern Italy), allowed to compare the olive oil quality and extraction yield between the traditional and the ultrasonic treatment. By comparing the EVOOs samples extracted by means the traditional and the innovative system, an average increase of about 12% of the polyphenol content (Figure 6(a)) and around 5% (Figure 6(b)) of the oil extractability. To the authors knowledge, there are no other industrial solutions, in the EVO sector, that are able to produce a simultaneous increase in the oil yield and polyphenol content.

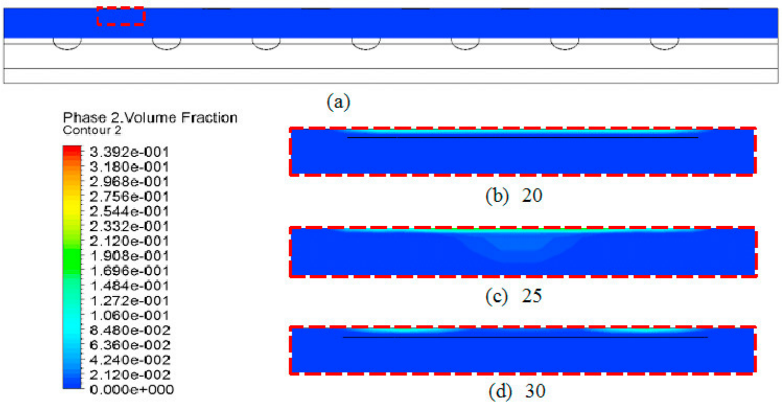


Figure 3 Time-evolution of the vapour volume fraction after 20 (a) and (b) 25 (c) and 30 (c) time steps. Sub-figures (b), (c) and (d) offer the values recorded around a plate-transducer. Each time step is one tenth of the transducer oscillating period, with the transducer surfaces starts moving down**.**

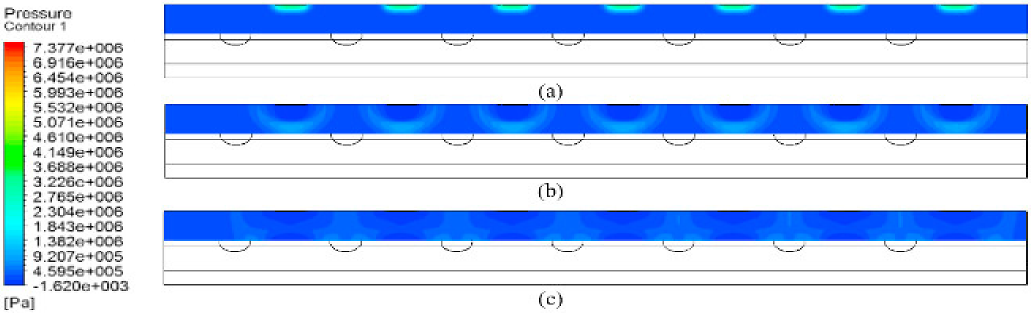


Figure 4 Time-evolution of the pressure after 5 (a) and (b) 15 (c) and 25 (c) time steps.

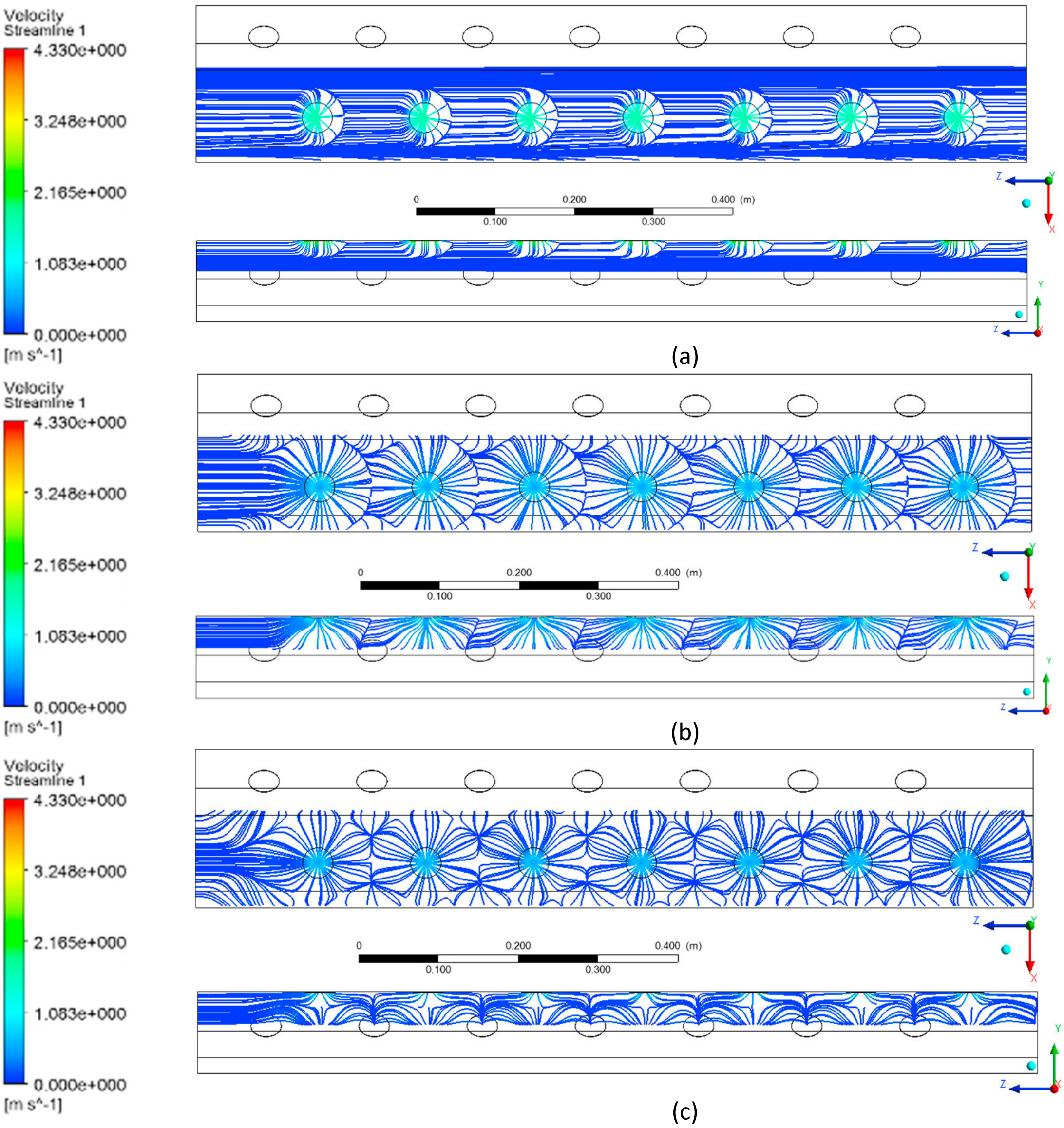


Figure 5 Time-evolution of the stream lines after 5 (a) and (b) 15 (c) and 25 (c) time steps. Stream-lines coloured by velocity magnitude.

(a) (b)

Figure 6 Comparison between the polyphenolic content and extraction yield for the traditional and ultrasonic treatment.

The significant increment of the polyphenols in the sonicated oils can be also attributed to the effect of ultrasound on polyphenoloxidase (PPO) activity. The EVOO quality is intimately affected by its content in phenolic compounds. PPO is responsible for oxidative losses of phenolics during olive paste malaxation. EVOO phenols play a key role in the shelf life of the product due to their activity delaying oxidation processes. They act as chain breakers by donating radical hydrogen to alkylperoxyl radicals, produced by lipid oxidation and contribute to the formation of stable derivatives [12]. Furthermore they have been included in a specific health claim for virgin olive oil by European Union [38].

4. Conclusions

The aim of the present paper was to design, realize and test a continuous ultrasonic full-scale device for the extra virgin olive oil industry, by means of which it was possible to simultaneously increase the work capacity, the extraction yield and the phenols content. The ultrasound technology is able to induce the rupture of cell walls thanks to the cavitation phenomenon, recovering the oil and minor compounds trapped in the uncrushed olive tissue.

A CFD analysis were used as auxiliary tool to design an innovative Sono-Heat-Exchanger (SHE), coupling a heat-exchanger with plate-shape ultrasonic transducers. The fluid dynamic analysis was performed by means of a commercial software package to predict the flow path around the ultrasound devices and to evaluate the flow parameters of the olive paste inside the SHE. The influence of each geometrical parameter was assessed to setup an optimal design of the SHE, and the results demonstrated that the pressure drops and velocity fields are suitable to ensure the best ultrasounds diffusion. Specifically, a pressure drop was obtained from the steady-state numerical simulations. Transient calculations highlighted that the vapour appeared in a region located extremely close to the transducer surface, but the propagation of the pressure waves affected the flow of the olive oil paste in a macroscopic way. Therefore, the cross section of the SHE was designed in order to achieve a reasonable balancing between the need of maximizing the ultrasound effect reducing the interference effects between transducers.

The experimental tests, performed on a real scale mill plant, demonstrated the simultaneous increase in the oil yields and the polyphenol content in the treated olive oil achievable by the designed machine and this demonstrated the goodness of the previous design phase.

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