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Research Article

Experimental analysis of heat transfer characteristics using ultrasonic acoustic waves

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ABSTRACT

In this experimental work, heat transfer intensification using ultrasonic waves was investigated. A heat source, consisting in a parallelepiped aluminum block in which two electrical heating cartridges of 160 W each were mounted to heat four liters of distilled water contained in a tank made of Plexiglas. To demonstrate the effectiveness of heat transfer enhancement with the use of ultrasounds, three different configurations were analyzed. In the first one, considered as a reference case, the heat transfer was studied without ultrasound field. In the second configuration, ultrasonic acoustic waves were generated using one transducer vibrating at a fixed frequency of 40 kHz with a total power of 60 W. In the last configuration, ultrasounds were generated with two similar transducers mounted on two opposite walls of the water tank while maintaining the same power and frequency. The effect of the distance separating the heat source to the transducers on the convective heat transfer coefficients and the average temperature of the water in the tank were analyzed in detail. The results revealed that the natural convection heat transfer in the water tank was intensified by means of low frequency acoustic waves. Indeed, it was shown, particularly, that more the distance between the transducer and the heater is low more the heat transfer improvement is better. The heat transfer enhancement factor was estimated to 2.5 on the surface facing the transducer while it was only about 1.2 on the opposite surface in C2 configuration. In C3 configuration, the heat transfer enhancement factor is nearly the same with, however, more homogenous water temperature. The acoustic cavitation and streaming were identified as the main phenomena leading to these results. This study successfully demonstrated the feasibility of heat transfer intensification using low frequency ultrasonic waves.

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INTRODUCTION

Nowadays, the intensification of heat transfer in thermal equipment such as heat exchangers is a major concern of both scientists and industrialists to improve efficiency and thus reduce energy consumption, atmospheric pollution, preserve fossil energy resources, and so on. This interest is motivated also by the several environmental

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issues raised by the use of fossils fuels. In addition, improving the energy efficiency of thermal installations has also been a continuous concern since the end of the 19th and the beginning of the 21st centuries. Thus, a growing interest has been devoted to this aspect, from the scientific and industrial communities. Two types of intensification techniques are usually used and known as the passive and active approaches. Passive techniques are those which do not require external energy supply, and without any moving parts. For instance, the use of extended surfaces, metallic foams and phase change materials belong to this method [1]. On the other hand, active techniques require external energy input and the use of moving devices such as fans and pumps to promote forced convection [2]. It is well known that a high mixing level of the different fluid layers can intensify the heat transfer. To obtain such effect, the use of vibrating devices, for instance, induces the propagation of mechanical waves in a fluid in which secondary flows are generated, and promoting thus the mixing level of the fluid. These vibrations can be obtained using ultrasounds which belong to acoustic waves. The frequency of ultrasounds is higher than the hearing limit of the human ear (~ 20 kHz). They are generated using the piezo-electric effect [3]. The ultrasounds have numerous industrial applications such as medical imaging, non-destructive control (welding and drilling pipes for instance), chemical synthesis, therapeutics, environmental protection, electrochemistry, food processing, binary fluids separation. They are generally classified into low and high frequency ultrasounds depending on the phenomena they induce. The frontier between low and high frequency ultrasound is not clearly demarcated and the generally recognized transition range is between 200 kHz and 1 MHz, as shown in Figure 1. A local decrease in a liquid pressure due to the propagation of an acoustic wave can lead to the formation of vapor–gas bubbles which then implose. This effect is called acoustic cavitation. Low frequency ultrasounds generate mostly cavitation micro-bubbles, which can intensify fluid mixing, mass transfer, break up agglomerates and prevent clogging by detaching particles deposited on heat exchangers surfaces [4]. Whereas, with high frequency ultrasound, the acoustic flow is predominant. Therefore, the use of ultrasonic waves as a technique of heat transfer enhancement, which is relatively recent, exploits these two effects. This section mainly reviews the literature related to ultrasounds, enhanced fluid heat transfer by ultrasonic cavitation. The first studies date back to the sixties, Bergeles and Newell [5] analyzed the impact of ultrasonic vibrations on forced convection heat transfer of water in an annular duct. They reported an increase in the heat transfer coefficient up to 40%. However, given the energy context of the time characterized by a low cost of energy, this route did not give rise to in depth research. Meanwhile, the large-scale use of fossil fuels has raised countless environmental issues such as pollution and global warming, which will eventually run out. Thus, several techniques for efficiency improving, which were previously considered unsuitable, have been revisited. Among them, one can cite the use of ultrasounds. Mannot et al. [6] investigated the effects of high frequency ultrasounds on the heat transfer rate in a reactor equipped with a cooling coil. They reported a systematic improvement of the heat transfer coefficient about 100%. Baffigi and Bartoli [7] studied the heat transfer characteristics due to ultrasonic agitation in a circular horizontal cylinder immersed in distilled water under subcooled boiling conditions. They showed an enhancement in heat transfer coefficient up to 57% at a subcooled temperature of 25°C. Bartoli et al. [8] performed an investigation on how natural convection between a circular cylinder heated and distilled water subjected to ultrasounds at 40 kHz/500 W is affected. A significant increase of the heat transfer coefficient was observed. Tajik et al. [9] studied the heat transfer between

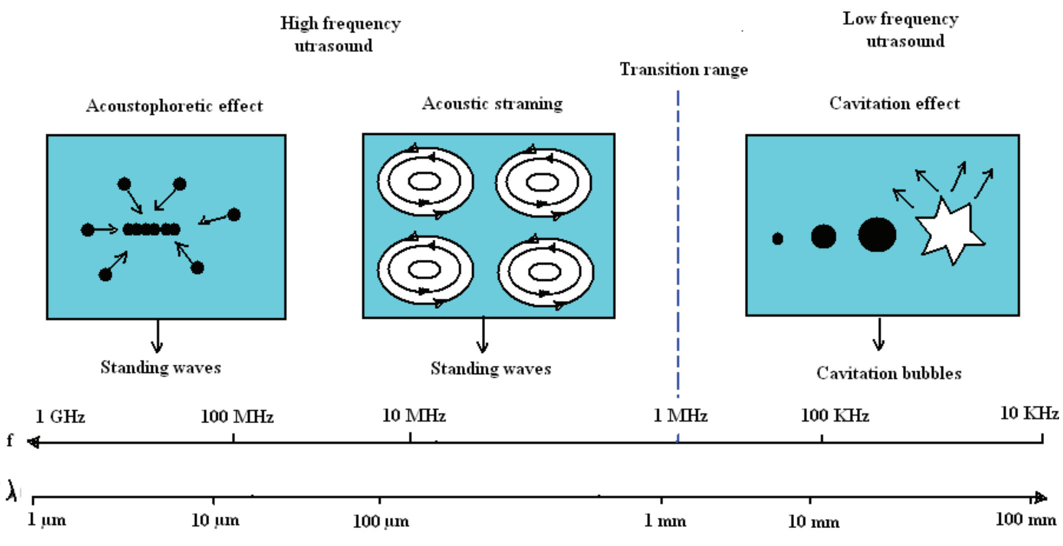


Figure 1. The different phenomena associated with high and low frequency ultrasound.

a heat source and water. Their results showed an improvement in heat transfer up to 390% with an 18 kHz ultrasonic vibrations source. The influence of ultrasonic vibration at 25 kHz on forced convection heat transfer was studied by Kiani et al. [10]. They pointed out a heat transfer enhancement up to 119% between a copper sphere immersed in a mixture of ethylene glycol and water (1:1) cooled between 0°C and 20°C.

Rahimi et al. [11] studied the use of ultrasound waves at a high frequency of 1.7 MHz to enhance the heat transfer rate in natural convection. They put emphasis on the effect of the transducers position. They observed that with a single transducer installed in front of the heat source, the heat transfer enhancement ratio increases significantly compared with the case of transducers located at the tank bottom. Following the same idea, Tam et al. [12] investigated the influence of the position of ultrasonic heads on the heat transfer inside a horizontal mini- tube. Their results showed a substantial heat transfer enhancement in the laminar regime. The use of acoustic vibrations in different heat exchangers configurations have been studied by several authors. Gondrexon et al. [13] treated the heat transfer intensification in a plate heat exchanger which was subjected to ultrasonic waves of 24 kHz and 120 W. They found that the overall heat transfer coefficient can be increased up to 1.2 times of its original value without ultrasound. Azimy et al. [14] investigated the effect of ultrasonic waves on heat transfer and nanofluid stability in a heat exchanger. They obtained a heat transfer enhancement when increasing nanofluids concentration. Legay et al. [15] reported experimental results showing an improvement in heat transfer enhancement by a factor of 1.2 to 2.3 for a double-tube heat exchanger subjected to 35 kHz ultrasounds. Mahmood et al. [16] designed miniaturized traveling wave thermoacoustic refrigerator driven by an ordinary loudspeaker. They obtained a maximum cooling power of 65W and coefficient of performance (COP) of 2.65. Yao et al. [17] investigated experimentally the potential use of ultrasounic waves of 21 kHz for heat transfer enhancement in water-water shell and tube heat exchangers. Their results indicated that the heat transfer enhancement was influenced by the fluid temperature, the fluid velocity and the power level of the ultrasounds (40 W, 60 W and 100 W). Shen et al. [18] found that in the natural convection, ultrasonic waves can enhance convective heat transfer in water-Al_2O_3 nanofluids, but this heat transfer efficiency decreases with increased heat flux. Azimy et al. [19] investigated the effects of ultrasonic waves on the heat transfer coefficient inside a heat exchanger. Their results showed that the effectiveness of ultrasonic waves on heat transfer decreases by increasing the flow rate. Li et al. [20] studied the influence of ultrasound vibrations on sub-cooled boiling on horizontal copper tubes with different surface characteristics. They showed that the obtained heat transfer enhancement at 21 kHz was higher than that of 45 kHz. Helsroni et al. [21] investigated the heat transfer enhancement from wires in sub-cooled pool boiling assisted by ultrasonic waves of 40 kHz. The experiments were carried out using wires of 0.05, 0.09, and 0.2 mm diameters immersed in a water bath. Their results indicated a decrease of the wall temperature about 10-15°C to 30-35°C depending on the wires size. Franco et al. [22] analyzed the physical mechanisms altering the heat transfer coefficient by convection in a heat exchanger subjected to ultrasonic vibrations. Sauret et al. [21] confirmed experimentally that a heat transfer enhancement is more intense in laminar than in turbulent flow in the presence of 2 MHz ultrasound. Poncet et al. [24] studied experimentally the heat transfer enhancement in forced convection by using dual low-high frequency ultrasound. A local heat transfer enhancement factor up to 366% was obtained. In summary of the above, there is a lack of researches on how the position and distance separating the ultrasonic transducers and the heat sources affects the heat transfer enhancement in natural convection. In the present work, ultrasonic waves with a low frequency of 40 kHz were used to explore such effect. A variable positions heat source was immersed in a tank filled with water. The ultrasonic waves were generated using transducers placed on the lateral walls of the tank in front of the heat source in two configurations. The effect of the distance separating the transducers from the heat source on the convective heat transfer.

EXPERIMENTAL METHODS

Expermental Setup

Figure 2 shows the experimental set-up and the different parts that make it. This device was designed and built at the laboratory of Polyphasic Transport and Porous media of the USTHB in Algeria as well as the test section shown schematically in Figure 3. The experiments were conducted on a transparent acrylic plexiglas rectangular parallelepiped tank of n200x150x200 mm filled with 4 liters of distilled water. Two electric 48 VDC cartridge heaters with a power of 160 W each were mounted in a heat source made of aluminum and immersed into the water as illustrated in Figure 4. The ultrasound generation system includes an ultrasound generator (40 kHz, 100 W) and piezoceramic ultrasound transducers PZT (titanate zirconate de plomb). To protect the transducers against high electric power, we have reduced the power delivered to the transducers to 60 W. The two piezoelectric transducers were attached to the tank in front of the main faces of the heat source with an acrylic structural adhesive and connected to the ultrasonic generator. A translation device outfits the tank; it keeps the heat source in a fixed vertical position and allows its precise movement with respect to the ultrasonic transducers as shown in Figure 4a. shows. To measure and follow the evolution of the water temperature overtime, four K type thermocouples (T5 to T8) with 0.5 mm diameter and an accuracy of 0.5°C were used and placed close to the tank walls (Figure 4b).The thermocouples were connected to a

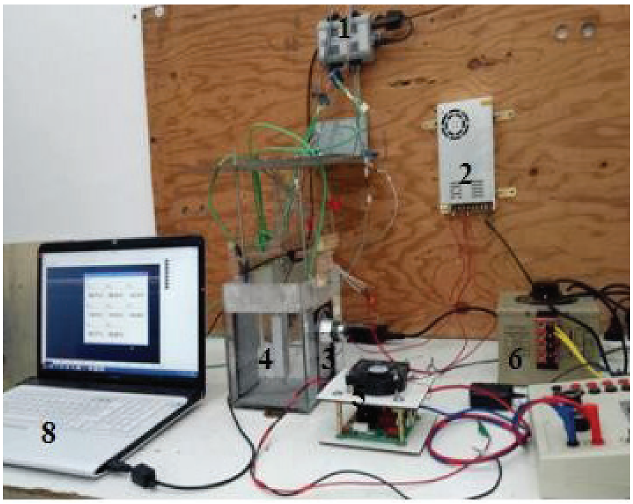


Figure 2. Picture of the experimental set-up. 1- Data acquisition, 2- DC power supply, 3- 40 KHz piezoelectric transducers, 4- Water tank, 5- Ultrasonic geneator, 6- Voltage variator, 7- Wattmeter, 8- PC.

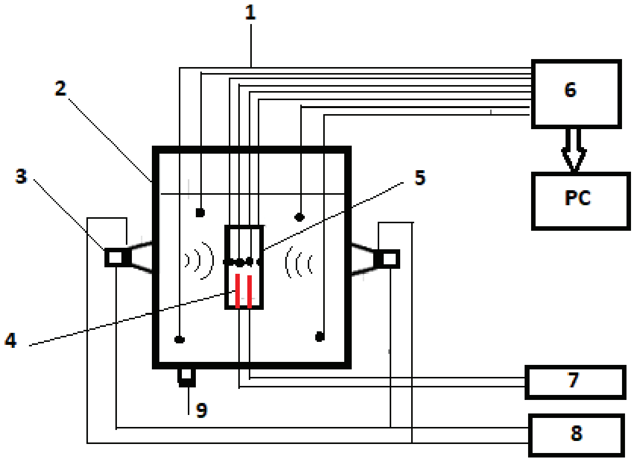
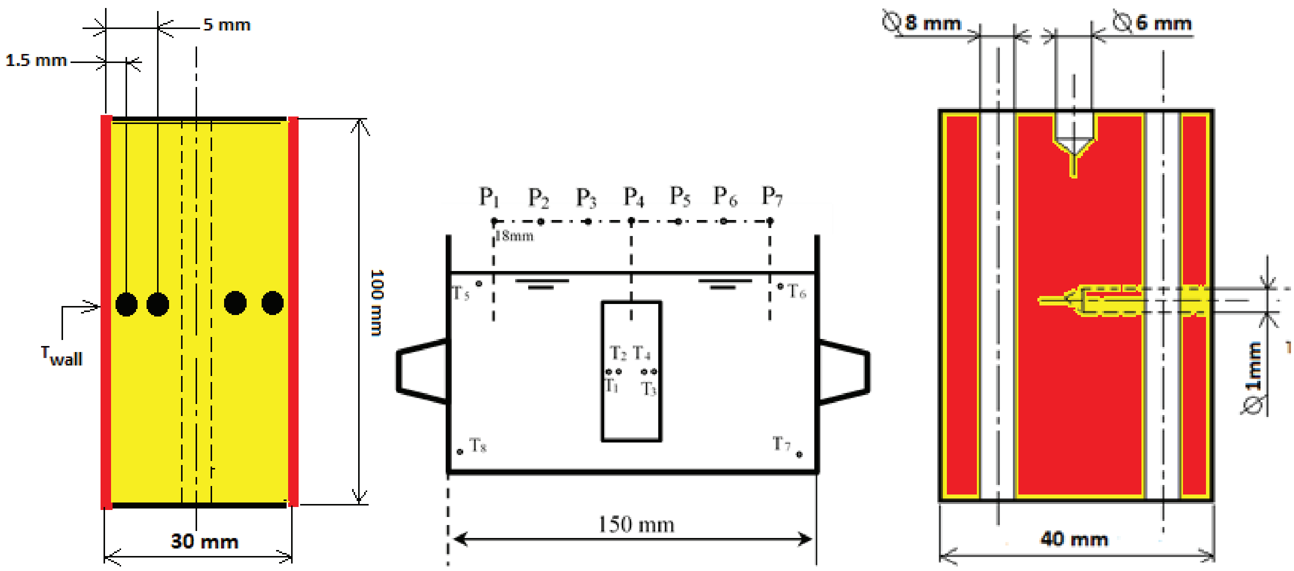


Figure 3. Schematic of the experimental device. 1- Thermocouples, 2- Tank, 3- Piezoelectric transducers, 4- Cartridge, 5- Heat source, 6- Data acquisition system, 7- DC power supply, 8- Ultrasonic generator, 9- Drainage valve.



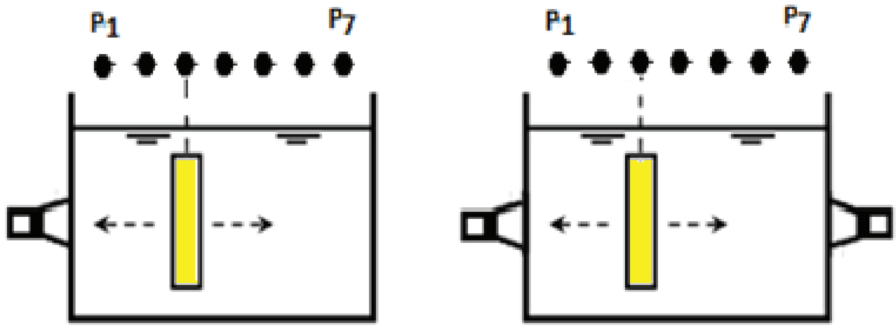
a) b) c)

Figure 4. a) Positions of the heat sink in the tank, **b)** Layout of the four K thermocouples on the heat source, **c)** Layout of the heater cartridges on the heat source.

data acquisition module OMEGA. In addition, to record the heat source temperatures, four more type K thermocouples (T1 to T4) were inserted in 1mm diameter holes with a depth of 20mm as shown in Figure 4c. The holes were coated with a thermal silicone grease to minimize the difference between the measured and the actual temperatures. The temperatures were recorded every 10 s using the aforementioned data logger. To analyze the impact of the ultrasonic field, three configurations were tested as Figure 5. A voltage variator connected to a wattmeter supplies the ultrasonic generator with a variable voltage to prevent damages the transducers.

Studied Configurations

In order to analyse how the presence of ultrasound sources impacts the convective heat transfer while putting an emphasis on the effect of the distance separating the heat source and the piezoelectric transducers, the following three configurations shown in Figure 5 were studied :



C1 **C2** **C3**

Figure 5. Configurations investigated in this study. a- Configuration 1 (C1), b- Configuration 2 (C2), c- Configuration 3 (C3).

Experimental Procedure

According to Baffigi and Bartolli's [7], it is impossible to obtain repeatable results in a non-degassed liquid. Therefore, before starting ultrasound-assisted experiments, the distilled water has been preheated for up to 1 hour to remove all dissolved gases in order to ensure that bubbles generated in the experiment were only caused by ultrasonic cavitation. Temperature measurements acquisition in the test section takes place in two phases. After thermal stabilization for a given position of the heat source, a first temperature measurement phase is carried out without ultrasound (configuration C1). The arithmetic average is then calculated for each of the measured temperatures in order to obtain the average heat transfer coefficient and then the Nusselt number in silent regime. After switching on the ultrasound (configuration C2, C3), a new period of thermal stabilization of the system is necessary, after which the procedure of configuration C1 is repeated in order to obtain heat transfer coefficient in acoustic mode.

Uncertainty Analysis

The uncertainty analysis, following Moffat [21], was performed to reveal the measurement and calculation errors. Table 1 summarizes the uncertainty sources and errors for the measured and calculated parameters. As shown in the Table 1, the error of heat transfer coefficient and heat transfer efficiency is less than 5%. The data show that the error of the experimental results is within a reasonable range and can ensure the accuracy and reliability of the experimental result.

RESULTS AND DISCUSSION

Convective Heat Transfer Coefficients

The efficiency of the use of ultrasonic vibrations as a mean of heat transfer improvement was shown through the heat transfer coefficient and temperature behavior. The local heat transfer coefficients h1 and h2 were determined

Table 1. Uncertainty sources and error analysis

Sources	Uncertainty
Measured parameters	
Water temperature	30°C ±0.5 °C
Heat source surface temperature Distance	50°C ±0.5 °C
Distance	1.5 mm ± 0.1 mm
Thermal conductivity of the heat source	217 W/m.K ± 5 W/m.K
Calculated parameters	
Water bulk temperature	± 0.2 %
Distance	± 0.06 %
Thermal conductivity of the heat source	± 0.01 %
Temperature difference between (Tw –Tbulk)	± 0.2%
Temperature difference between (T2– T1)	± 0.2%
Heat transfer coefficient, h1	± 0.29 %

for each experiment based on the one-dimension Fourier law as follows [2]:

$$h_1 = \frac{\lambda(T_2 - T_1)}{e_{T_2-T_1}(T_{w1} - T_{bulk})} \quad (1)$$

$$h_2 = \frac{\lambda(T_3 - T_4)}{e_{T_3-T_4}(T_{w2} - T_{bulk})} \quad (2)$$

The average heat transfer coefficient was evaluated for each performed experiment following the procedure below:

$$\mathrm{h_{avg}} = \frac{1}{\Delta t}\int_0^t \mathrm{h_x dt} \quad (3)$$

With :

$$T_{w1} = T_1 + \frac{e_{T_1-T_{w1}}}{e_{T_2-T_1}}(T_1 - T_2) \quad (4)$$

$$T_{w2} = T_4 + \frac{e_{T_4-T_{w2}}}{e_{T_3-T_4}}(T_4 - T_3) \quad (5)$$

$$T_{bulk} = \frac{(T_5 - T_8)V_1 + (T_6 + T_7)V_2}{V_1 + V_2} \quad (6)$$

In the above equations, $e_{T_i-T_j}$ refers to the distance separating the thermocouples i and j. A heat transfer enhancement effectiveness factor (HTEF) of the use of ultrasonic waves was then defined as follows [21]:

$$HTEF = \frac{h_{avgUS}}{h_{avgWUS}} \quad (7)$$

Estimation of The Transmitted Ultrasonic Power [6]

Prior any experimentation with ultrasounds, it was necessary to evaluate the heat power amount transmitted by the ultrasounds to the water. To do so, the heat source was turned off while the ultrasonic transducers were activated. Then, the following energy balance was establish as in Eq.(8):

$$P_{ust} = T_{env} + P_w + P_s = P_{env} + \rho V C_l \frac{\Delta T_f}{t} + mC_s \frac{\Delta T_s}{t} \quad (8)$$

P_{ust} is the amount of the acoustic energy converted into heat and transmitted to the water. Figure 6 shows the variation of the water and solid temperatures versus time with two transducers in operation without heating, the heat source was being placed in the middle of the tank (position P_4). The energy rate absorbed by the heat source P_s under the effect of ultrasonic vibrations was negligible, as indicated in Table 2. Thus, we considered that the ultrasonic power is entirely transmitted to the water. The energy rate transferred to the environment was also neglected. Knowing P_{usr} the power delivered by the ultrasonic generator, the efficiency of the ultrasound transmission ratio ($P_{ust/}P_{usr}$) was then estimated to 86%.

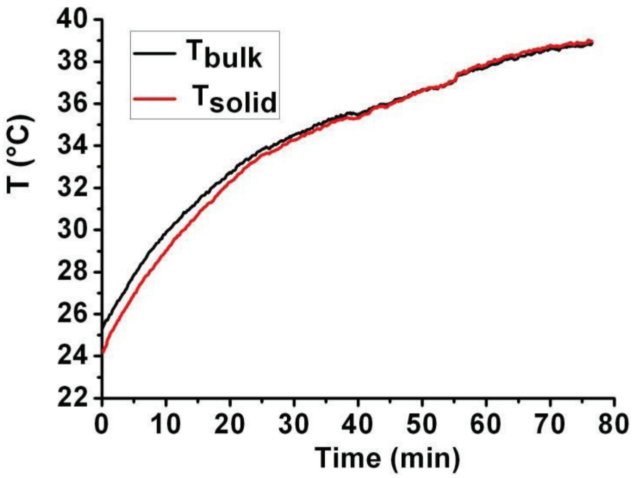


Figure 6. Evolution of water and solid temperatures versus time with two transducers in operation without heating.

Experimental Results

Temperature of the heat source surface

The variation over time of the wall temperature of the heat source and measured with the thermocouple T1 for C2 and C3 configurations is portrayed in Figure 7. The heat source being located at position P1 as shown in Figure 4. When, the temperature T1, reaches 60°C, the ultrasound generator is turned on (C2 case) and ultrasonic waves are

Table 2. Amount of the energy dissipated into heat inside the water tank

Distilled water			**Aluminum Block**					
$V\,(l)$	$C_l\,(J/kgK)$	$P_w\,(W)$	$m\,(kg)$	$C_s\,(J/kgK)$	P_s (W)	P_{ust} (W)	P_{usr} (W)	P_{ust}/P_{usr}
4	4185	49.842	0.324	897	0.929	51.7	60	86

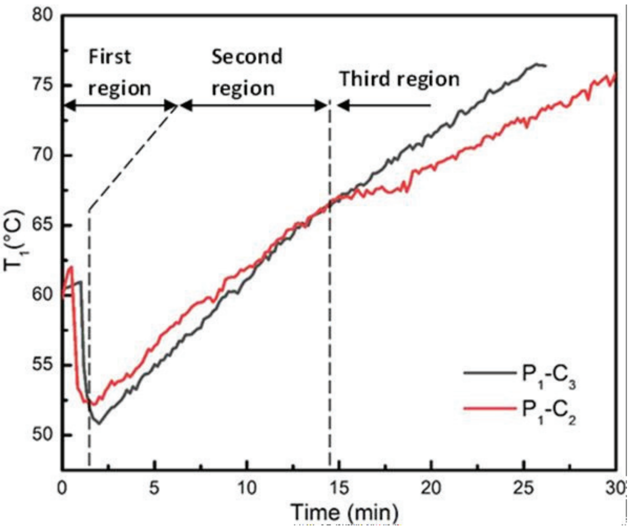


Figure 7. Evolution of the temperature T1 versus time for C2 and C3 configurations.

generated into water. A temperature decrease about 10°C is noticed after just 2 min. This first observation reveals an intensification of the heat transfer at the heat source surface due to the 40 kHz/60 W ultrasounds. Then, the temperature increases again because of the continuous heating of water. Due to the inherent noises in the voltage signal from the thermocouple, the signal was filtered using a low-pass filter and sampled at 20 Hz using a data acquisition board. For the C3 case, with the ultrasound power being shared on the two transducers, a similar trend is observed. Moreover, the two curves present the same value at approximately at t=1 and 14 min delineating thus three distinct regions. This behavior is the result of the competition between the ultrasound waves and the thermal heating block supplied by the resistors. In the first region, the two configurations show a fast drop in their temperature with nearly the same rate. However, this takes place slightly earlier for C2 case. Indeed, as the temperature was measured on the face in front of the transducer, it receives more acoustic energy which results

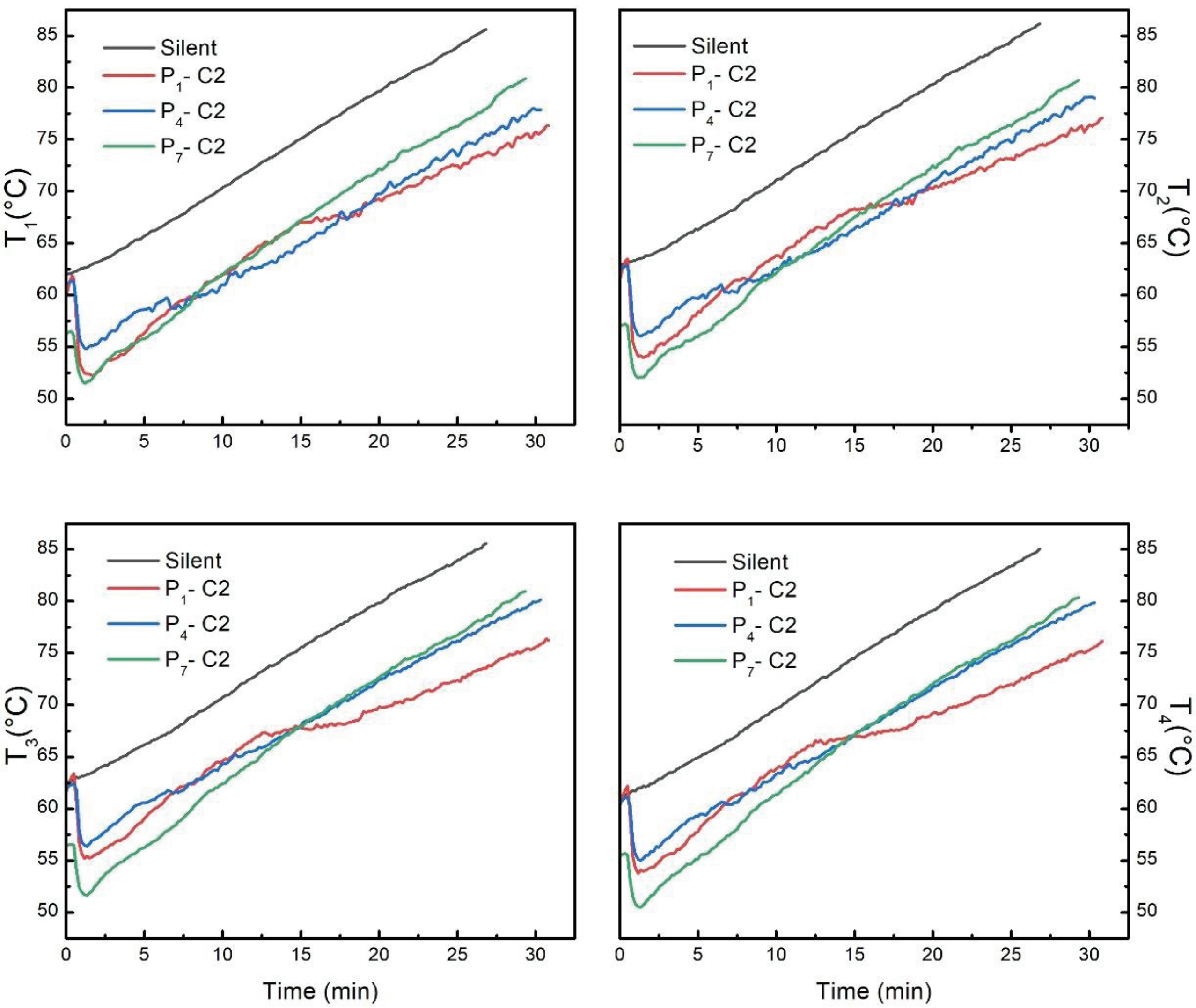


Figure 8. Evolution of the temperatures T1, T2, T3, and T4 versus time for the C2 configuration cas.

in higher fluid mixing than that of the C3 resulting in better heat transfer. However, the difference in temperature is low. Because with C3, the heated block dissipates more heat from the opposite face due to the second transducer which contributes to maintain T1 at nearly close values to those observed in C2. After approximately 2 min, the temperatures start increasing for the both configurations. As the water between the block and the source heats up it causes a decrease in the heat transfer with however lower values with the C3 configuration. This can be attributed to a higher heat dissipated through the opposite face of the block. Around 14 min, this trend is reversed again, and the temperature displayed by C2 is lower. The cooling effect due to the ultrasonic waves offsets the thermal heating, and a sort of the steady state sets in. The mechanism behind this heat transfer improving by ultrasound is mainly due to the acoustic cavitation (Figure 10).

Figure 8 displays the temperature evolution of the heat source for the C2 configuration while showing the impact of the distance between the heater and the transducer. In the silent mode, the temperature in the different location exhibits nearly a linear increase. Once the transducer is activated, an abrupt temperature decrease on the main face of the heat source is observed, revealing the strong impact of the ultrasounds on the heat transfer. The temperature drop (T1 and T2), over this period of time, diminishes as the distance separating the ultrasonic source and heated block increases. A similar trend is observed on the opposite face (T3 and T4) of the heater with less intensity. This is due to the attenuation of the ultrasonic waves. Few minutes later, the temperature begins increasing in all positions. Indeed, the ultrasonic cavitation intensifies (Figure 10) the flow mixing which increases the temperature of the water ,and consequently diminishes its heat absorption capacity. As stressed earlier, the ultrasonic field improves the convection while the continuous heating augments the water temperature, which gives rise to a complex behavior of the temperature when the position of the block varies. Thus,

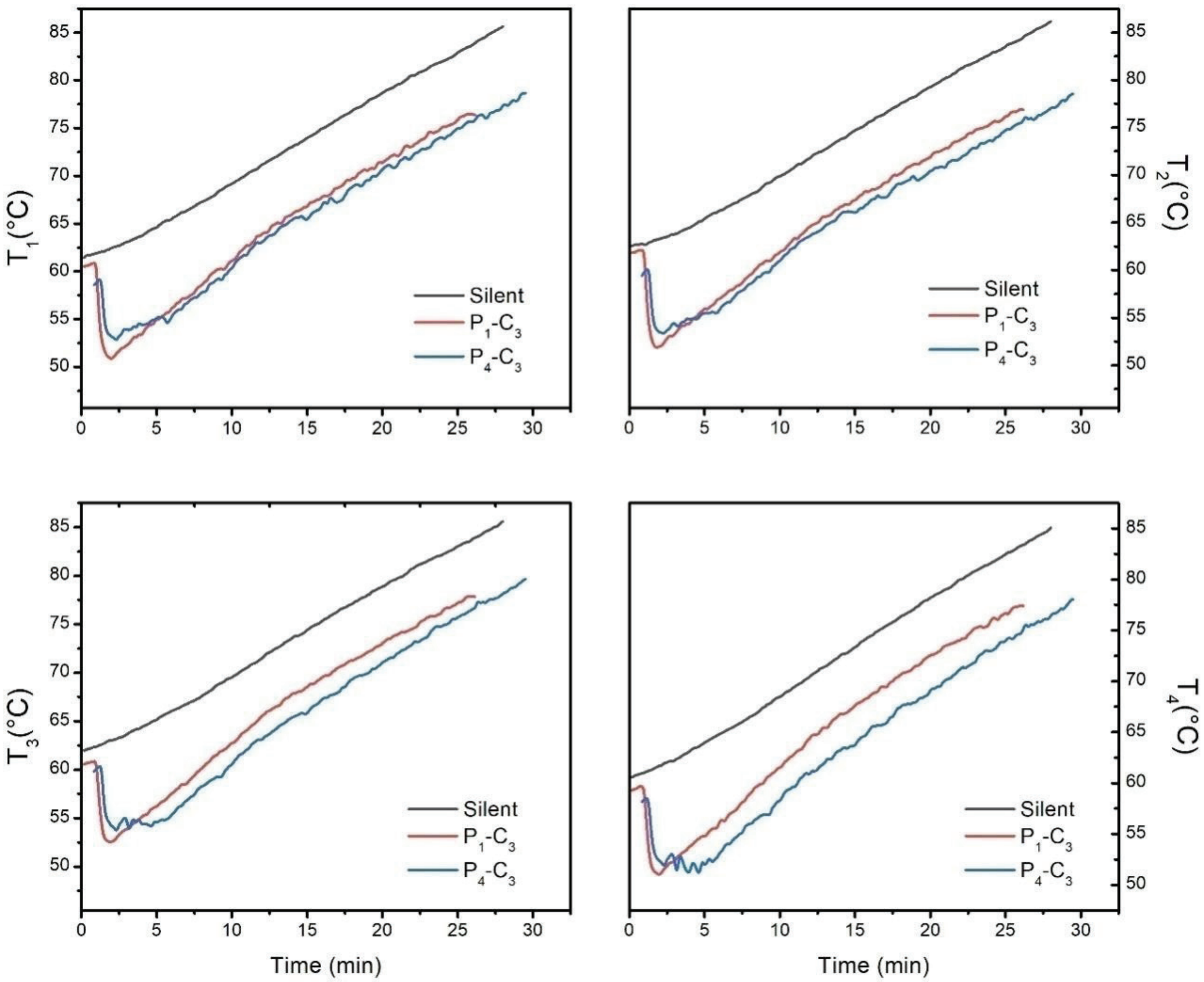


Figure 9. Temporal evolution of the wall temperatures in the C3 configuration case.

a

b

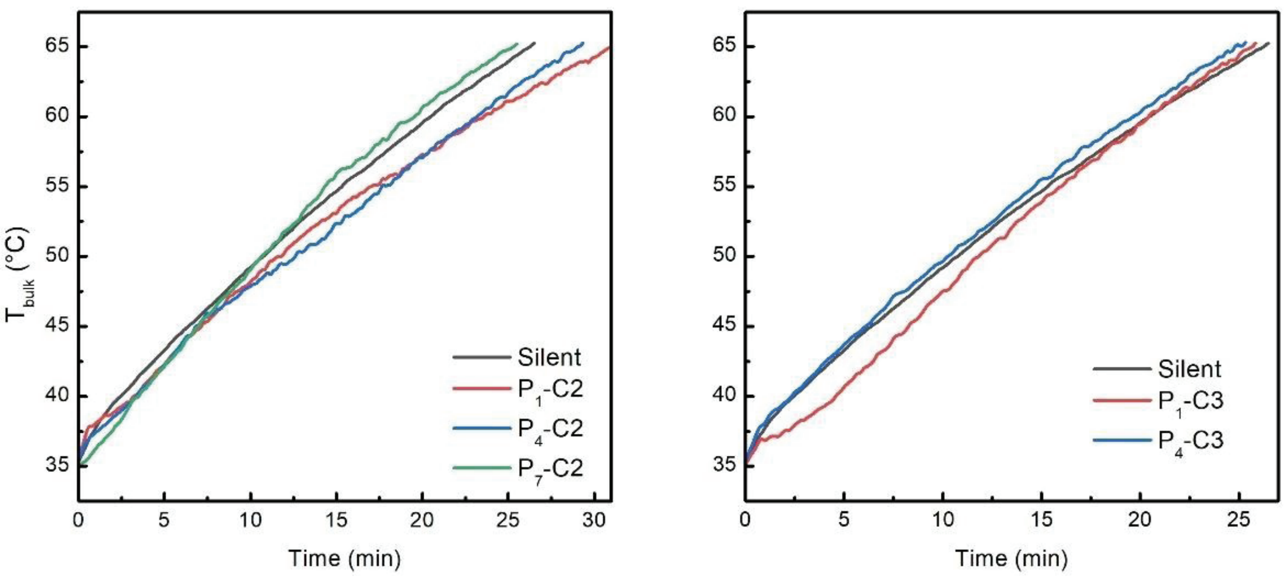
Figure 10. Propagation of the ultrasonic jet in the tank. a-position 4, b-position 1.

the temperature T1 is nearly the same for P1 and P7, which is remarkable knowing that for this last position the distance is highest. Around 15 min, the temperature becomes lower in P1 than that of P7 denoting the positive effect of the ultrasound on heat transfer. When the heated block is centered, temperature T1 exhibits the highest value as long as approximately the time is lower than 7.5 min. Indeed, as the heat source is moved away from the transducer, the cooling effects of the cavitation outweigh the heating. Once again, around 17 min the temperature T1 becomes higher than that obtained with position P1 but lower than that of position P7. This behavior, at first sight, unexpected can be explained by a balance achieved between the effects of the ultrasonic field and heating. The other temperature readings show a similar trend with higher values inside the block.

The variation of the temperature of the heat source as a function of time for the C3 configuration is shown in Figure 9 for different positions. A similar trend emerges from that observed for the previous configuration. Once the transducers are activated, the temperature begins to fall sharply before starting to increase after 2 minutes have passed. For this configuration, the distance separating the block and the transducers affects the temperature T1 and T2 weakly. For T3 and T4, the gap in temperature is about 2°C with lower values when the block is centered. This behavior is explained by the influence of the acoustic cavitation created by the ultrasonic waves into water. The cavitation, particularly visible in the water tank (Figure 10), creates microbubbles of vapor in the water that will grow to ultimately implode near the heat sink. This implosion creates a local agitation close to the walls of the heat source which improves the convection heat transfer.

Average water temperature

The mean water temperature profile is illustrated in Figure 11. In the case of the C2 configuration (Figure 11a), it is noticed that during the first ten minutes after the transducer activation, the temperature evolvement is nearly the same whatever the position of the heat source is. After, approximately, 13 minutes, the increasing trend



a) **b)**

Figure 11. Evolution of bulk temperature in: a) C2 configuration, b) C3 configuration.

continues with higher values as the block is moved away from the transducer. It is also noticed that overall, the water temperature is reduced with the use of the ultrasound. This difference is due to the propagation of the ultrasonic waves into the water. When, the heat source is close to the transducer, the amount of the fluid affected by the ultrasound is low while the rest of water is not significantly affected causing a diminution in the water temperature compared to the silent mode. Concerning the configuration C3 as illustrated in Figure 11b, it is observed that the average water temperature obtained for the different positions increase in the same way.

Figure 12 illustrates how the ultrasonic field influences the uniformity of the water temperature. Thus, in the silent mode (Figure 12a) the water temperature is higher in the upper region of the tank than that of the lower region due to the natural convection in water. The use of the ultrasonic transducers reduces the temperature gap existing between the two regions for the both configurations. For the C2 configuration (Figure 12b), when the heated block is at position P1, a constant decrease in the temperature difference is observed over time. However, when the heated block is centered, in configuration C3 (Figure 12c), the decrease is faster. The difference is reduced to 2°C after 15 minutes and remains practically constant. In the latter case, the both sides of the heated bloc were exposed to the acoustic cavitation which explains such results.

Local convective heat transfer coefficients

The variation of the local convective heat transfer coefficients h1 and h2 as a function of time and different positions of the heat source is presented in Figure 13 for cases C1 and C2. For P1 location, it is observed an intensification of the heat transfer on the face in front of the transducer with decreasing intensity as time elapses. As the heater is moved away from the transducer, the heat transfer enhancement is lower, but its intensity increases overtime before decreasing around 12 min with close values as those obtained for

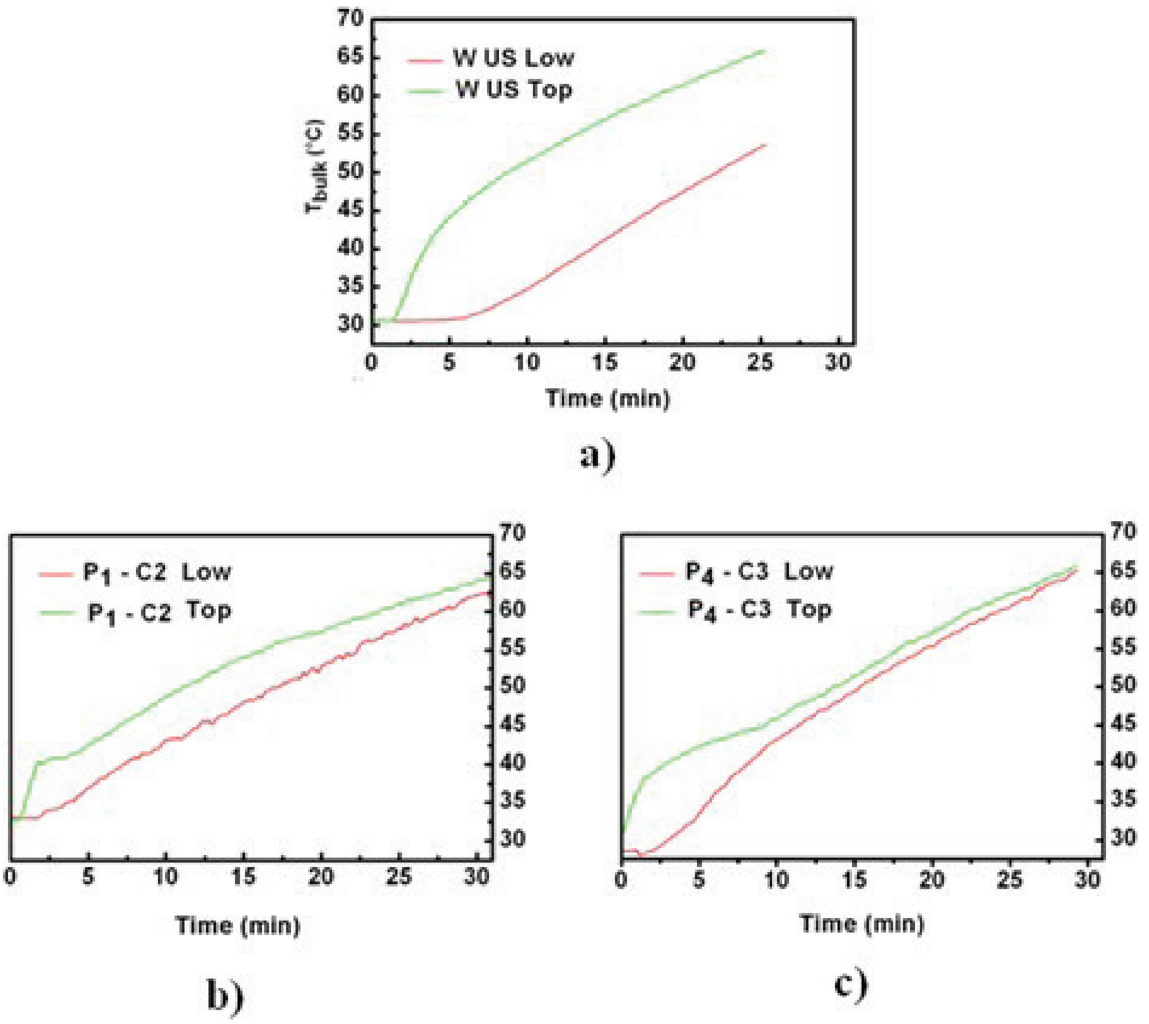


Figure 12. Average water temperature versus time between upper and lower part of the tank, a) Silent mode, b) Configuration C1, c) Configuration C3.

P1. For the farthest position, h1 becomes lower than that obtained with the silent mode. This behavior is due to the competition of the cooling effect of the ultrasounds with the heating. Indeed, as the distance increases the ultrasonic waves attenuate and consequently the cavitation intensity decreases too. On the opposite face, slight differences are observed in the heat transfer coefficient. However, the trend is overall reversed. This shows that the ultrasounds affect also this face even though the attenuation increases.

The comparison of h1 and h2 coefficients on the both sides of the heat source versus the time is shown in Figure 14 for C3 configurations and positions P1 and P4. It is

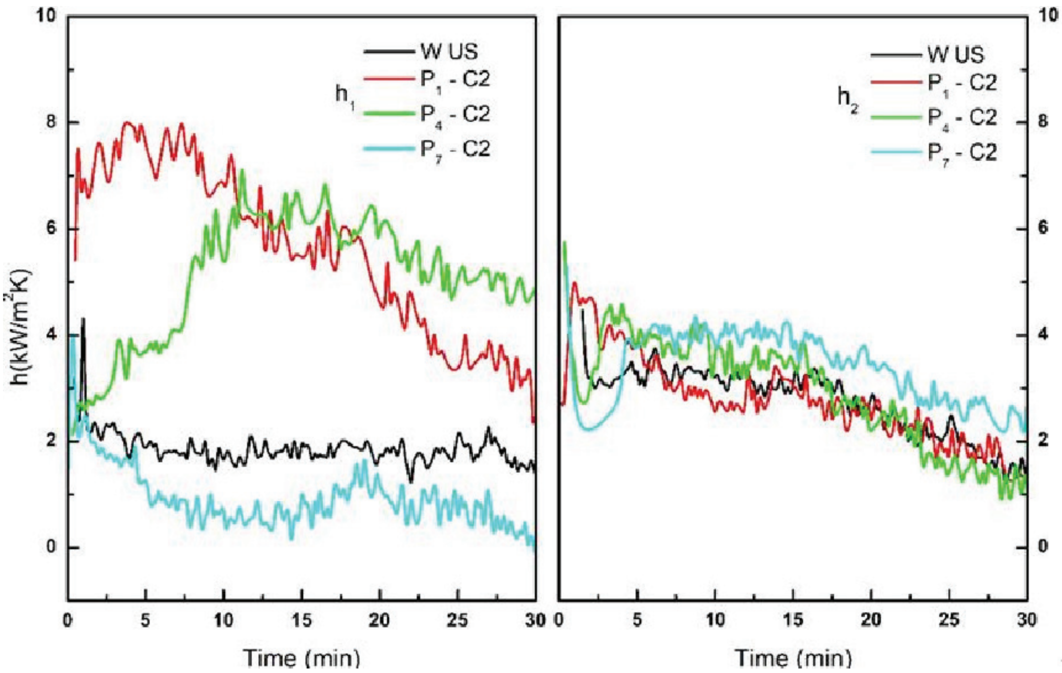


Figure 13. The local convective heat transfer coefficients versus time for the C2 configuration.

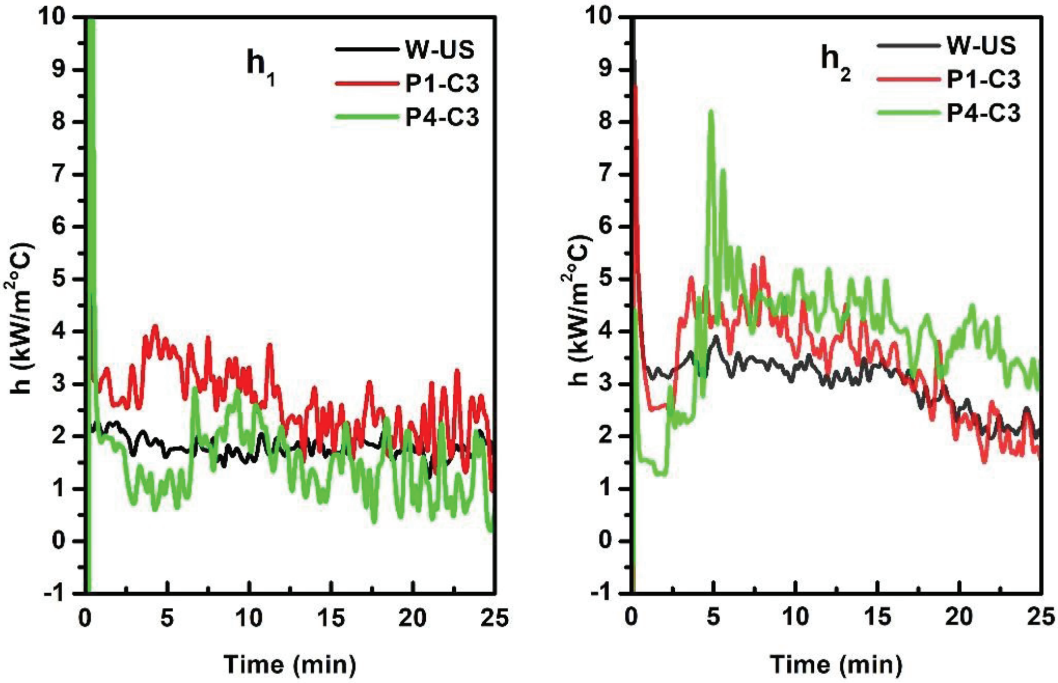


Figure 14. Average temperature profiles versus time for the configurations C1, C2 and C3.

noticed that h1, for the P1 position, instantly increases and starts decrease after 5mn until it becomes lower than that of the silent mode. For the centered position P4, the opposite effect is observed. Indeed, h1 decreases before to increase abruptly after 5 min showing a heat transfer improvement. Then, it decreases over time while remaining lower than that of the previous position and the silent mode. Concerning, the h2 coefficient, it can be noticed that between t=2.5 min and around t=6 min, the positions P1 and P4 show approximately the same heat transfer enhancement then it decreases similarly for the two positions as time passes. After 15 min, the decrease accelerates for P1 position. This is due to the simultaneous triggering of the transducers, which lowers the wall temperature quickly.

Average convective heat transfer coefficients

The average convective heat transfer coefficient for the different positions of the heat source in the acoustic mode (C2) is shown in Figure 15. There is a significant impact on

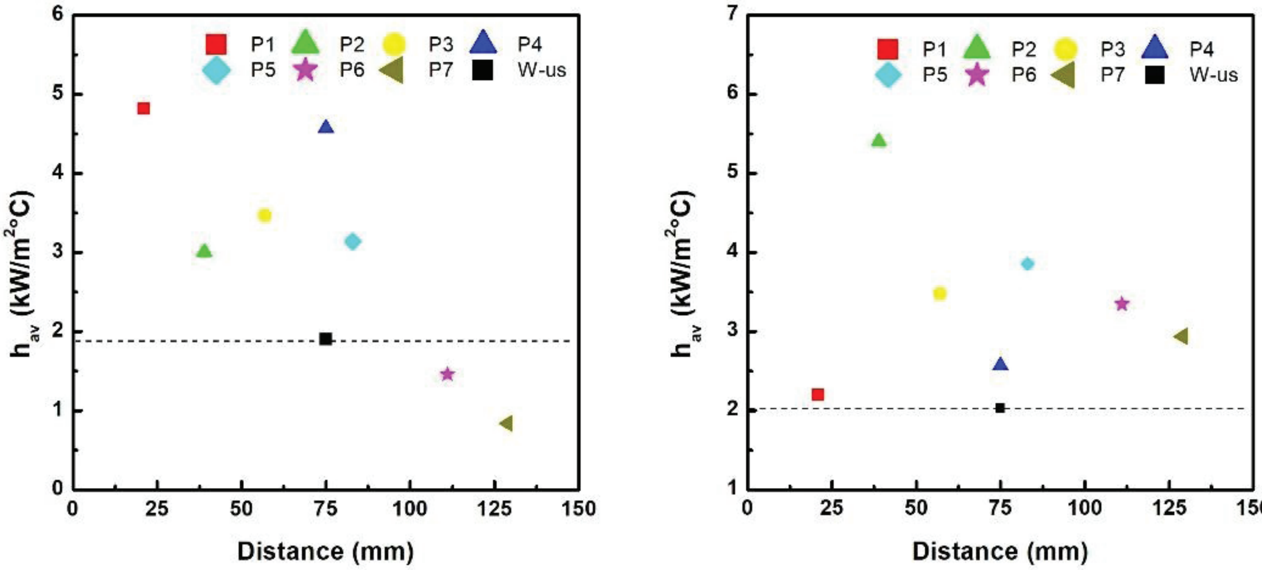


Figure 15. The average convective heat transfer coefficients versus the distance of the heat source in the tank for the C2 configuration.

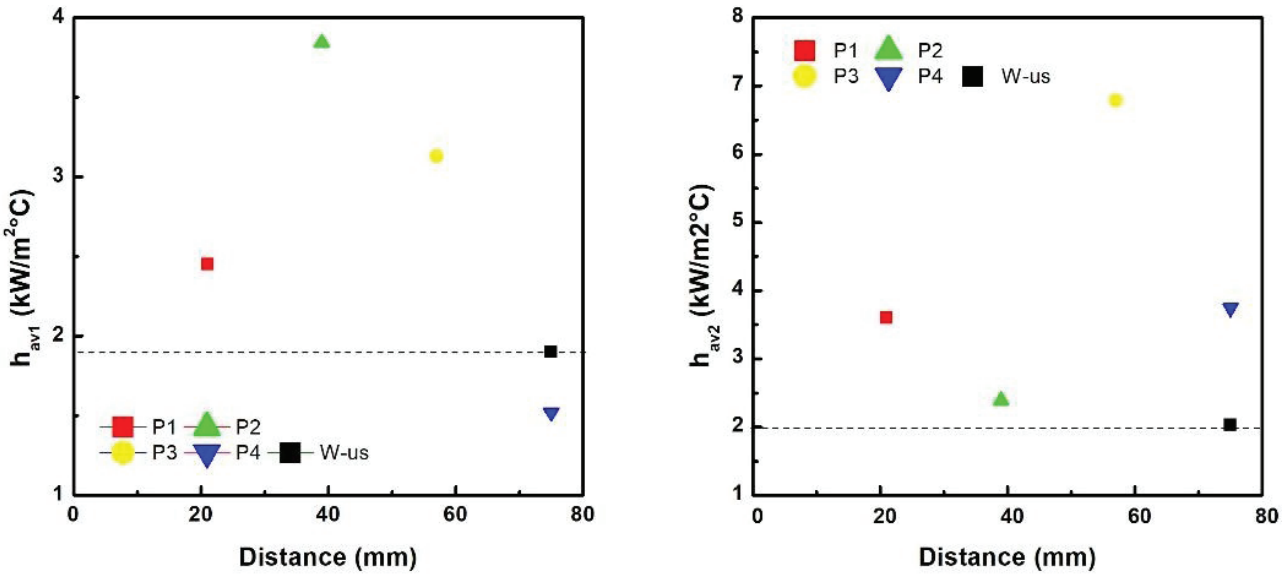


Figure 16. The average convective heat transfer coefficients versus the distance of the heat source in the tank for the C3 configuration.

Table 3. Heat transfer enhancement factor in ultrasound mode (C2) compared to the silent mode (C1) in position P1.

h_{avg1}W.US (W/m².K)	h_{avg1}US (W/m².K)	HTEF	h_{avg2}W. US (W/m².K)	h_{avg2}US (W/m².K)	HTEF
1878.720	4729.085	2.517	2027.996	2434.632	1.200

Table 4. Heat transfer enhancement factor in ultrasound mode (C3) compared to the silent mode (C1) in position P1.

h_{avg1}W.US (W/m².K)	h_{avg1}US (W/m².K)	HTEF	h_{avg2}W. US (W/m².K)	h_{avg2}US (W/m².K)	HTEF
1878.720	2434.632	1.295	2027.996	4393.409	2.166

the heat transfer of the distance separating the heat source and the ultrasonic transducer. Overall, a clear improvement in heat transfer is achieved compared to the silent configuration. Generally, when h1 increases, h2 decreases. For h1, the highest and lowest values are obtained for the closest and the farthest position respectively. For the positions P6 and P7, the average convective heat transfer h1 drops below that of the silent case despite the presence of ultrasound which attenuate due to the distant. On the opposite face, the highest and lowest values are obtained for the intermediate positions while remaining higher than that of the silent mode. The average values of h1 and h2 coefficients on the both sides of the heat source for different positions in the acoustic mode C3 is shown in Figure 16. There is a significant impact of the distance separating the heat source and the ultrasonic actuator with a non-monotonic evolution which suggest the existence of an optimal position where the transfer is maximized.

Enhancement of average convective heat transfer coefficients

Evaluating the effectiveness of the ultrasound waves as a heat transfer intensification technique is of a great importance. To this end, a heat transfer enhancement factor (HTEF) was defined as the ratio of the average heat transfer coefficient obtained with ultrasounds to that without ultrasounds. The HTEF on the both faces of the heat source (h1 and h2) for the configuration (C2) in the position P4 is shown in Table 3. It is noticed that the HTEF for h1 is equal approximately 2.5 while its value is only 1.2 for h2. This result was expected as the ultrasonic field is greatly attenuated in the solid bloc.

Concerning the configuration (C3), Table 4 shows also a heat transfer enhancement on the both faces of the heated block. However, as the ultrasonic power is equally distributed on the water tank faces, we would have obtained a similar value of the HTEF. This suggests more complicated phenomena due to the ultrasounds.

CONCLUSION

The effect of ultrasonic waves on natural convection heat transfer due to a heat source in a tank filled with distilled water was studied experimentally. For this purpose, piezoelectric transducers were arranged into two different configurations. In the first one, a unique transducer of 40 kHz/60 W was used while in the second configuration, the ultrasound power being shared on the two transducers mounted on two opposite faces of the tank. The obtained results showed that the distance between the heat source and the ultrasonic transducers impacts significantly the heat transfer rate. Overall, a heat transfer improvement is noticed comparatively to the silent mode. This intensification presents a shape close to a sinusoidal with the distance. The ultrasonic cavitation is the main phenomenon leading to a such heat transfer augmentation. The efficiency of this improvement was estimated with the heat transfer enhancement factor. This later was estimated to 2.5 on the surface facing the transducer while it was only about 1.2 on the opposite surface in C2 configuration. In C3 configuration, the heat transfer enhancement factor is nearly the same with however more homogenous water temperature. To conclude, the use of ultrasounds appears to be an effective and promising mean to improve the heat performances of fluids initially at rest. However, further studies should be conducted to explore deeply the potential of this technique.

NOMENCLATURE

C_l	Specific heat for liquid (J kg^{-1}K^{-1})
C_s	Specific heat for solid (J kg^{-1}K^{-1})ure
E	Distance (m)
h	Convective heat transfer coefficient (W m^2 K^{-1})
h_{avg}	Average convective heat transfer (W m^2 K^{-1})
m	Mass of the heat source
P	Power (W)
T	Time interval (s)
T	Temperature (°C)
T_{bulk}	Bulk temperature (°C)

V_1 Volume of water in the left side of the heat sink (m^3)
V_2 Volume of water in the right side of the heat sink (m^3)
ΔT Temperature difference (°C)

Greek symbols
λ Thermal conductivity of the heat source ($W\ m^{-1}\ K^{-1}$)
ρ Fluid density ($kg\ m^{-3}$)

Subscripts
Env Environnement
f Fluid
t Time
s Solid
w Wall of the heat source
x Referrring to side
us With ultrasound
wus Without ultrasound
usr Power delivered by the ultrasonic generator
ust Acoustic energy transmitted to water

AUTHORSHIP CONTIBUTIONS

Abdelmalek Hamadouche: Methodology, Data curation, Investigation,Writing, Original draft preparation. **Rachid Nebbali:** Supervision, Project administration, Writing- Reviewing, Editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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