

Review Article

Enhancement of Heat Transfer by Ultrasound: Review and Recent Advances

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This paper summarizes some applications of ultrasonic vibrations regarding heat transfer enhancement techniques. Research literature is reviewed, with special attention to examples for which ultrasonic technology was used alongside a conventional heat transfer process in order to enhance it. In several industrial applications, the use of ultrasound is often a way to increase productivity in the process itself, but also to take advantage of various subsequent phenomena. The relevant example brought forward here concerns heat exchangers, where it was found that ultrasound not only increases heat transfer rates, but might also be a solution to fouling reduction.

1. Introduction

In engineering applications, ultrasound is helpfully used to improve systems efficiencies. Intensifying chemical reactions, drying, welding, and cleaning are among the various possible applications of ultrasonic waves [1]. An analogous observation can be made for heat transfer processes, which are omnipresent in the industry: cooling applications, heat exchangers, temperature control, and so forth. It is somewhat logical and natural to wonder what could be the influence of ultrasound upon heat transfer systems. Strangely, it has not been a research topic deeply investigated until recently.

It appears that researches undertaken in the past concerned basic systems, usually with a single fluid, such as heating rods or walls in a volume of water subjected to ultrasonic vibrations. The tendency goes toward systems getting more complicated (e.g., cooling of tiny components, vibrating structures for heat exchangers) and models becoming more accurate with powerful numerical simulations for example.

The objectives of this paper are to provide scientific and historical backgrounds to the future studies concerning heat transfer enhancement by ultrasonic vibrations and to bring forward the evolution of this domain with several examples of applications. The first part describes an overview of ultrasound, induced phenomena, and how they positively influence heat transfer processes. Then, examples drawn from various fields of interest are analysed (thermal engineering, food industry, experimental and numerical simulations). Emphasis is made on the best improvements and results obtained. Finally, recent adaptation of ultrasonic technologies to heat exchanger devices is discussed thoroughly, with examples drawn from new patents and current laboratory work.

2. Generalities about Ultrasound

2.1. Standard Classification by Power, Frequency, and Use. Acoustic waves of which frequencies are higher than the

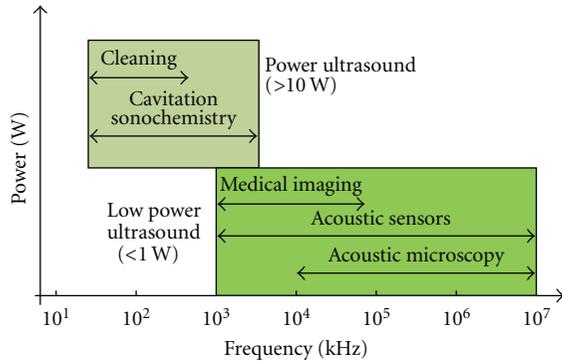


FIGURE 1: Utilizations of ultrasound according to frequency and power.

upper limit of the human hearing range, usually around 16 or 20 kHz, are called ultrasound. These waves are often classified according to their frequency or power.

Between 20 and about 100 kHz, waves are defined as “low frequency ultrasound” or “power ultrasound”. Indeed, it is usually transferred at a high power level (a few tens of Watts), and therefore, ultrasound is able to modify the medium where it propagates. Power ultrasound can disrupt a fluid bulk to create cavitation or acoustic streaming, two phenomena with powerful macroscopic effects for heat transfer enhancement. Therefore, power ultrasound finds uses in various processes like cleaning, plastic welding, sonochemistry [1], and so forth. It is also generally used for heat and mass transfer processes intensification.

Further in the frequency spectrum, above 1 MHz, is found “low power ultrasound” (usually less than 10 W), at a “very high frequency” which does not affect the medium of propagation. Consequently, it is especially used for medical diagnosis or nondestructive material control, and references regarding heat transfer enhancement are very scarce in the literature.

In the intermediate range 100 kHz–1 MHz, “high frequency ultrasound” is found. It is less used than power ultrasound to promote heat transfer. Figure 1 shows some typical uses of ultrasound according to frequency and power. Thorough description of the development of ultrasonic technologies can be found in the literature [1, 2].

2.2. Ultrasound Propagation and Induced Effects. Many phenomena may ensue from propagation of an ultrasonic wave into a fluid and more particularly into a liquid medium. Two of them, of major importance for heat transfer enhancement, are acoustic cavitation and acoustic streaming. There exist other subsequent effects such as heating of the medium due to dissipation of the mechanical energy. This phenomenon is used for the determination of the ultrasonic energy supplied to the medium in an ultrasonic reactor, well-known as the calorimetric method [1]. With high-frequency ultrasound, an acoustic fountain at the liquid-gas interface may also appear. Temperatures up to 250°C can be reached precisely at this interface [3]. Laborde et al. [4] provided a general description and mathematical modelling of some

phenomena resulting from propagation of ultrasound into a liquid. Figure 2 illustrates some of these important effects that may occur in a liquid.

These phenomena have always been a subject of interest since their discovery, and even though research is still ongoing, some comprehensive descriptions have been made by several authors and are frequently updated [1, 4]. Therefore, this paper focuses only on two significant phenomena: acoustic streaming and acoustic cavitation, tackled from a heat transfer point of view.

2.2.1. Acoustic Streaming. Acoustic streaming can be considered as a well-known phenomenon since its comprehensive mathematical description by Lighthill in 1978 [5]. He explained that acoustic streaming ensues from the dissipation of acoustic energy which permits the gradients in momentum, and thereby the fluid currents. Riley [6] also makes the distinction between the quartz wind streaming happening in the fluid bulk, and the Rayleigh streaming located at the boundary layers and solid-liquid interfaces. The speed gained by the fluid allows a better convection heat transfer coefficient near the solid boundaries, sometimes leading to turbulence and promoting heat transfer rate (Figure 3).

Fand and Kave [7] foresaw in 1960 the possible effect of acoustic streaming on heat transfer intensification and studied what was named “thermoacoustic streaming”, a stronger flow phenomenon than isothermal acoustic streaming.

Acoustic streaming (forced air current) was created in the air above a vibrating beam [8, 9]. It was sufficient to levitate small objects and make them spin around themselves, and thereby computing the flow velocity. The temperature of the object above the beam was decreased sensitively, and the convection heat transfer coefficient around it was increased proportionally to the stream velocity. This is an interesting first example of how acoustic streaming can modify heat transfer coefficients.

Acoustic streaming is also a factor that reduces the melting time of paraffin [10]. Its influence was studied apart and described as analogous to forced convection, whatever the profile of the standing waves field is. Nakagawa [11] even managed to simulate and control a streaming flow caused by 4 vibrators, allowing the selection of a zone that needs to be cooled down by the acoustic jet.

A type of configuration often studied is heat transfer occurring in a channel made by two plates or beams at different temperatures with vibrations applied either to the fluid between or to one of the walls [12–14].

The typical order of magnitude of acoustic streaming velocity is usually a few centimetres per second (between 1 and 100 cm s⁻¹) [9, 15], but it also appears to vary slightly with ultrasonic power and frequency [16].

2.2.2. Acoustic Cavitation. Acoustic cavitation is the major phenomenon that may arise from the propagation of ultrasonic waves into a liquid. Many authors have described cavitation process thoroughly but not always appearing in an oscillating pressure field, in which particular case is called

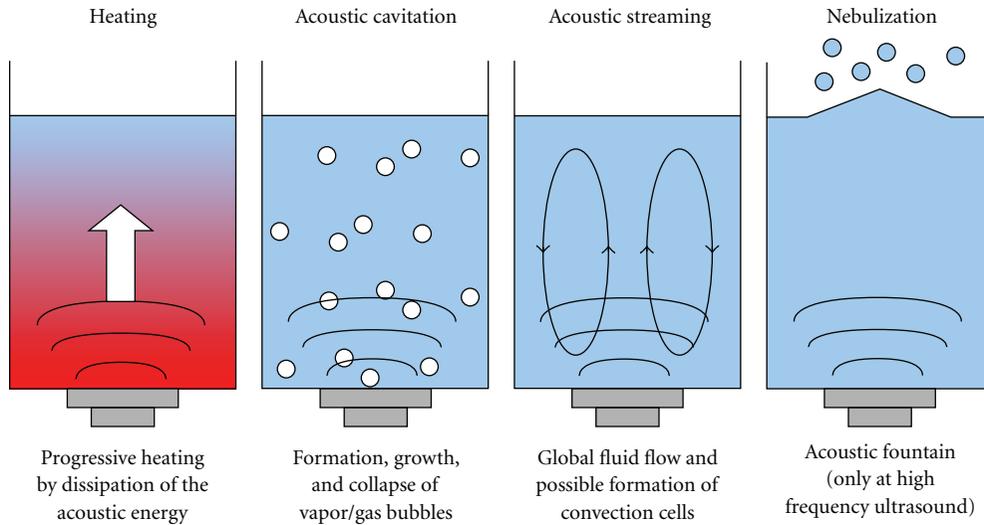


FIGURE 2: Four effects resulting from ultrasound propagation in a liquid.

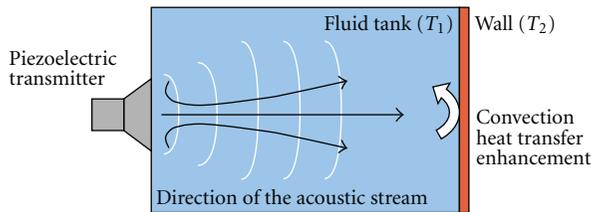


FIGURE 3: Acoustic streaming—enhancement of convection heat transfer.

acoustic cavitation [17, 18]. It is the formation, growth, oscillations, and powerful collapse of gas bubbles into a liquid. When defining acoustic cavitation, one must also describe precisely the experimental conditions at which it occurs (gas dissolution, temperature, pressure, etc.), because it depends on several parameters. When the local pressure is decreased sufficiently below the vapour pressure during the rarefaction period of the sound wave, the static pressure and the cohesive forces are overcome and gas bubbles are formed. They will generally oscillate, grow, and then collapse violently [19, 20].

There are many other ways to create cavitation into a liquid, for instance, hydrodynamic cavitation using microchannels which can also promote cooling heat transfer [21]. Comprehensive details about acoustic cavitation in pure water can be found in [22].

There exist two types of acoustic cavitation: stable and transient [18, 23, 24]. When bubbles oscillate around an equilibrium size, this is called stable cavitation. When they exist for less than one cycle, they are transient cavities. Another important fact is that the implosion of a vaporous cavity is more violent than a gas-filled one because when vapour is turned into liquid, there is no residual gas to cushion the collapse of the bubble. Some experimental results and photographic studies showed that the impact of a collapsing cavitation bubble could last 10^{-7} s, reaching a local pressure up to 193 MPa [23]. This explains many phenomena involved

in chemistry, biology, engineering, [25] and so forth. It also explains why acoustic cavitation is believed to be the major effect of ultrasonic heat transfer enhancement. Indeed, a bubble implosion near a solid-liquid interface disrupts thermal and velocity boundary layers, reducing thermal resistance and creating microturbulence, as schematically explained in Figure 4.

Usually the bubble implosion is assumed to be of the order of the microsecond, and the bubble size is about 10^{-4} m (but also depending on frequency) [1]. So, the order of magnitude of particles displacement velocity during bubble implosion can be estimated at about 100 m s^{-1} . There are approximately between 2 or 3 orders of magnitude between the acoustic streaming and the microturbulence velocities. This is one of the reasons why acoustic cavitation is often considered as the main reason for heat transfer enhancement by ultrasound. It can also be used as a way to promote or control turbulence, which already suggests some possible use in heat exchange devices. Flow friction near the boundaries could be reduced [26].

3. Influence of Ultrasound on Heat Transfer

3.1. History. It is necessary to go back to the 60s to find the first reported studies dealing with heat transfer intensification involving ultrasonic vibrations. These very pioneer studies (see also Section 3.3.1) often gave interesting results but unfortunately, not promising enough to lead to deeper enquiries. Completely different techniques have probably been developed at the meantime (e.g., channel size reduction). Therefore, the subject was quite forgotten until the 90s, where it regained interest with the growing tendency to make more and more efficient devices for energy management. The graph proposed in Figure 5 shows the number of publications dealing with heat transfer enhancement using ultrasound, found in bibliographic databases such as Scopus and Google Scholar for 10-year periods since 1960.

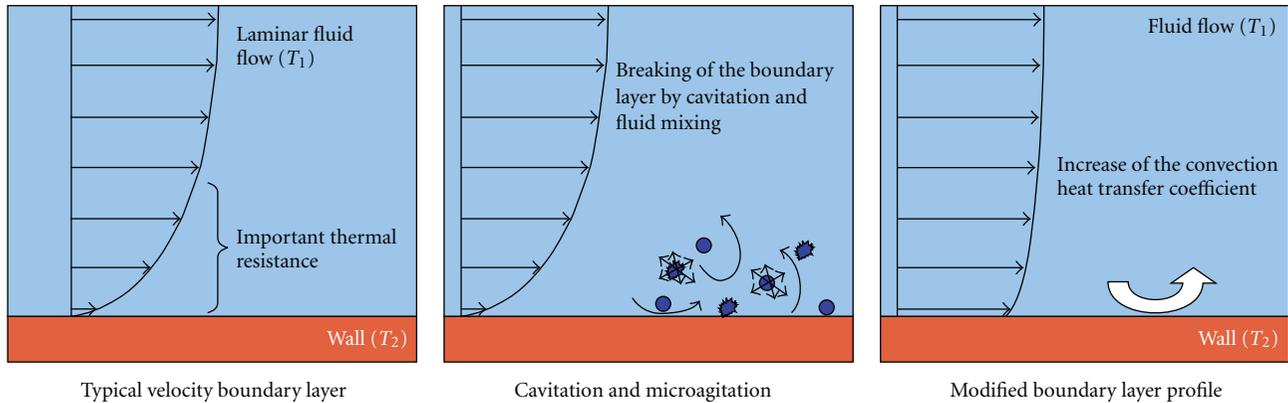


FIGURE 4: Explanation of heat transfer enhancement by acoustic cavitation.

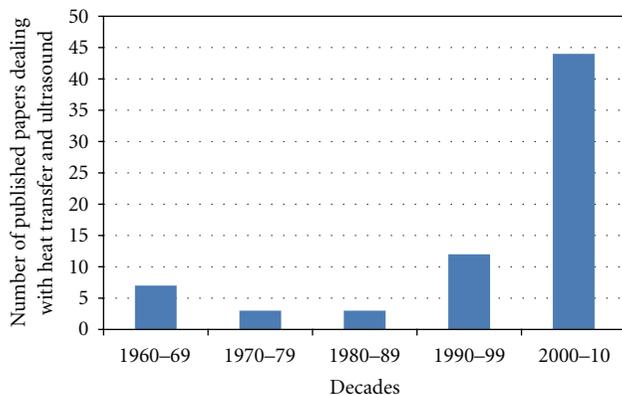


FIGURE 5: Evolution of the number of published papers per decade dealing with heat transfer enhancement by ultrasound.

References taken into account are those reported in all the tables of this document. Earlier than this date, they are hard to find even if some may exist.

Very few works were published in the 70s–80s but an important increase has taken place since the 90s. According to this tendency, one can expect that in the forthcoming years, this subject is likely to know a substantial development.

Among the three heat transfer modes, conduction and radiation assisted by ultrasound are the less studied. Strangely, only a few authors have investigated them although promising results were already reported in 1979 by Fairbanks [27]. He found that the combination of radiation (artificial or natural) and ultrasound to heat a flowing liquid led to better results than the sum of each process taken separately; besides, metal conduction could be enhanced between 2.25 and 5.55 times. Conversely, during melting of paraffin, when conduction was dominating over convection, Oh et al. found little influence of ultrasound [10]. This difference may be due to the nature of the materials (paraffin and metals) that have a completely different response to the vibrations. Nomura and Nakagawa [15] studied heat transfer enhancement with cavitation and acoustic streaming on a narrow surface where conduction had also a great importance. To quantify

cavitation intensity, they measured the mass loss rate of a $15\ \mu\text{m}$ thick aluminium foil. Microjets induced by cavitation increased the apparent thermal conductivity but they were so powerful that erosion would be a problem (e.g., for microelectronic components cooling). On a very narrow surface, conduction was always dominating over convection.

3.2. Heat Transfer with Phase Change

3.2.1. Melting and Solidification. Power ultrasound is a method to reduce the size of ice crystals on the frozen products and gain in quality [28]. This leads to finest ice crystals and shortens the time between the onset of crystallization and the complete formation of ice, mainly due to acoustic cavitation. Birth of nucleation sites, microstreaming, and some cleaning action of heat exchangers are among the subsequent advantages. Besides, ultrasound is a noninvasive technique. Comprehensive reviews of the uses of ultrasound in food technology exist [29, 30], with many examples of processing, crystallization, and freezing.

The freezing temperature of supercooled water can also be controlled by ultrasonic vibrations to make ice slurry, a solid-liquid mixture very interesting to store and transport cold thermal energy. The probability of phase change is increased with the total number of cavitation bubbles, acting as nuclei for solidification inception [31, 32]. Conversely, to store warm thermal energy, ultrasound allows a melting time reduction (e.g., to take advantage of the sunlight period) without excessive electricity consumption [10]. Table 1 sums up some references where ultrasound was used for phase change applications.

3.2.2. Boiling. Boiling heat transfer in the presence of an ultrasonic field is described apart for being a very active research field. Ultrasound allows improvement of boiling heat transfer almost systematically. The first bubbles appearing in the nucleation sites are swept away by the vibrations, and the apparition of film boiling is therefore delayed so that higher heat fluxes are reached (see Figure 6).

According to several authors, this is still due to acoustic cavitation, which helps the creation and growth of

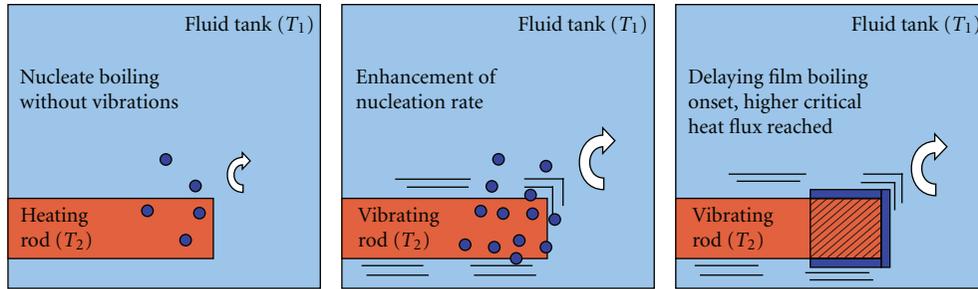


FIGURE 6: Enhancement of boiling heat transfer by ultrasonic vibrations.

the bubbles, whereas their oscillations enable to create microstreaming and local agitation near the surfaces to sweep them away [20, 33–36]. But part of this explanation was called into question [37] because heat transfer was not enhanced at saturated liquid temperature as it should have been.

Heat transfer enhancement of saturated pool nucleate boiling was studied using a combined method: ultrasonic vibrations and glass beads ($49\ \mu\text{m}$ mean diameter, 120 ppm) mixed into distilled water [38]. The convection heat transfer coefficient was found up to 4 times greater.

It was reported several times that the distributions of the sound pressure and of the local heat transfer enhancement were in phase [39–43].

The critical heat flux of subcooled boiling in water in the presence of ultrasound is influenced by several parameters [44, 45]. The effect of plate inclination is reported and the optimum parameters are a surface facing the incident acoustic wave, an elevated ultrasonic power delivered and a low subcooling temperature. The critical heat flux enhancement was closely related to bubble departure from the surface, either by acoustic streaming or by microstreaming caused by cavitation. In [46], the same observation about water subcooling was made (increase of critical heat flux when subcooling temperature decreases) but a different one for the plate inclination. Park and Bergles [47] found very small increases in burnout heat flux compared to the literature with only 10 and 5%, respectively, for saturated and subcooled pool boiling. Vibrations, though not ultrasonic but induced by the flow, also allow a shifting of the critical heat flux, which strengthens the results obtained with ultrasonic vibrations [48, 49].

Table 2 summarizes some studies concerning boiling heat transfer enhancement with ultrasonic vibrations.

3.2.3. Food Industry/Drying. For being particularly adequate (noninvasive, nonchemical, etc.), ultrasonic technologies are intensively developing in food industry. Food drying is one of the best examples. If there is a good acoustic match between the transducer and the food material, ultrasonic vibrations can be directly applied to the material to be dried [55, 56]. This can produce a sponge effect, as illustrated by Figure 7: contraction and expansion cycles, leading to a better drying result. The effect is much more pronounced for very porous products, as explained in [57], which is why the porosity of the product to be dried is an important

parameter to take into account before applying ultrasonic waves.

Power ultrasound mainly affects the external thermal resistance. If the transducer is not in contact with the material and ultrasound is air-borne, it is reported that high air flow rate may introduce modifications in the acoustic field, decreasing also the acoustic energy transmitted to the medium. Power ultrasound increases the effective moisture diffusivities at low air velocities but the improvement becomes negligible at high air velocities [58]. A prototype of an ultrasonic dehydration system has been built and studied in [59]. An impedance matching unit was added to the vibrator to be in direct contact with the food. Applying a sufficiently high acoustic intensity, this technology would permit to save thermal energy in drying processes and to pre-serve the food quality.

With the aim of sterilizing food, the influence of particle size and power input on heat transfer between fluid and food size particles was investigated [60]. These parameters had little influence since the convection heat transfer coefficient was already approximately doubled every time in the presence of ultrasound. Comprehensive review of the uses of ultrasonic technology in the food industry can be found in the literature [29, 30]. A summary of some studies regarding the use of ultrasound in food industry can be found in Table 3.

3.3. Intensification of Convection. Convection, like boiling, is one of the most studied modes of heat transfer under the influence of ultrasonic vibrations. Increases in heat transfer coefficients up to 25 times are reported [61]. Some years ago, a negligible influence of ultrasonic waves on heat transfer had been described [48, 62, 63]. But more recently, interest in this way of intensification is regained and some authors began to analyze the influence of properties of the environment of propagation (gas dissolution, temperature, flow, etc.) and characteristics of the wave itself (amplitude, frequency, etc.) [37, 38, 64]. Others examined geometries to discover new possible uses [65–67], or as in [68], studied the effect of vibrations (not ultrasonic) on the transition to turbulence and buckling flow theory. Researches undertaken in this field are summarized thereafter. When dealing with convection, it is crucial to observe that ultrasound can be considered as an “external help” to heat transfer. Therefore, it is interesting to wonder if it is not more appropriate to speak of forced convection rather than free convection when ultrasound is

TABLE 1: Various uses of ultrasound to promote phase change heat transfer.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Fairbanks [27]	Radiation (Sun and infrared) into water, conduction into metal, melting heterogeneous system	50 kHz, 61 W (radiation); 20 kHz, 250 W (melting); 20 kHz, 75 W (conduction)	Radiation: double heat transfer rate, conduction: 3.55 times thermal conductivity, melting rate doubled
Inada et al. [31]	Experimental, phase change from supercooled water to ice, acoustic cavitation, pure water and tap water	28 kHz, 0–6.5 kW m ⁻²	Important decrease of supercooling with ultrasound for both types of water
Oh et al. [10]	Melting of paraffin in a tank with constant heat flux, acoustic streaming, cavitation, experimental and modelling study	40 kHz, 70–340 W	Melting time 72 min with 340 W ultrasonic power instead of 275 min without ultrasound
Zhang et al. [32]	Experimental study, probability of water phase change with number of bubble nuclei, cavitation, square vessel, transducer at the bottom	39 kHz, 4.4 kW m ⁻²	Probability of phase change increased with number of bubble nuclei and pressure amplitude

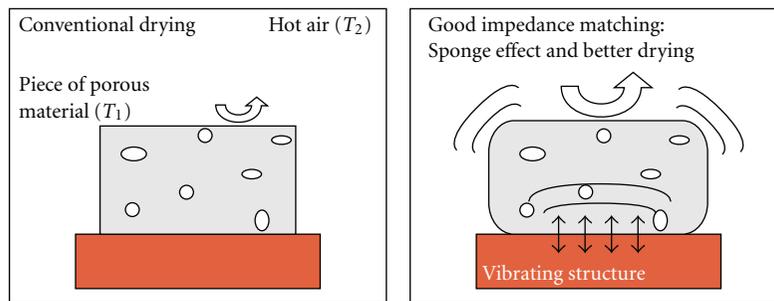


FIGURE 7: sponge effect during vibration and drying of a porous food product.

turned on. This fundamental question still remains opened to discussion.

3.3.1. Pioneer Studies. Fand and Kave [7] are among the pioneers who expected heat transfer enhancement from acoustic streaming forced convection (see Section 2.2.1). Bergles and Newell [50] were probably the first to investigate an annulus-type structure, that is, water flowing between two concentric pipes, with a heating system located inside the central pipe. In this work, up to 40% local increase of the heat transfer coefficient was reported but only 10% in the global coefficient, which was not enough for being profitable. This was in part due to the attenuation of the sound effect, or to a bad contact between the emitter and the tube containing water. Bergles [63] made a survey on the techniques to enhance heat transfer with ultrasonic vibrations. He reported that authors generally found significant increases in nonboiling heat transfer at moderate flow velocity. Improvements were clearly related to cavitation, reported not to be as effective as established boiling. The main restriction came from the attenuation of the ultrasonic energy by the vapour and the difficulties to locate the transducer so as to obtain good coupling with the fluid and suffer minimum attenuation, also reported in [50].

Conversely, in Larson's Ph.D. dissertation [62], natural and forced convection flows over a sphere were investigated. Ultrasonic frequencies, Nusselt and Reynolds numbers were the main variables. Larson claimed that cavitation was responsible for the increase in Nusselt number at the low frequencies, whereas acoustic streaming was the major factor of enhancement at higher frequencies. But he finally reported that no sufficient increase in heat transfer was obtained to warrant the use of ultrasound as a means of heat transfer intensification technique (for Reynolds numbers and ultrasonic intensities tested). Richardson [69] studied the effect of horizontal and vertical acoustic waves (710 and 1470 Hz, not ultrasound) on heat transfer around a horizontal cylinder. He found some local changes in the boundary layer thickness and consequently in convection heat transfer coefficients at high intensity sound levels.

Experiments and numerical results reported by Gould [70] showed that the heat transfer rate increased approximately linearly with the sound amplitude when water was used. Values were increased up to 10-fold with acoustic streaming. When more viscous liquids were used, the relationship between heat flow and sonic amplitude was found to be nonlinear.

TABLE 2: Summary table of boiling heat transfer studies.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Baffigi and Bartoli [45]	Experimental, subcooled boiling, horizontal cylinder, cavitation	40 kHz, 300–500 W	$h/h_{US} \sim 2331/5000 \text{ W m}^{-2} \text{ K}^{-1}$ subcooling temperature: 41 K
Bergles and Newell [50]	Horizontal annulus, subcooled boiling, CHF	70 kHz; 80 kHz, 1.4 W/cm ²	70 kHz, 40% local increase in non-boiling h
Bonekamp and Bier [51]	Pool boiling, pure fluids (R23, R134a), and mixtures of both	42.0 kHz; 69.2 kHz; 84.7 kHz, 4 W	42 kHz, equimolar mixture, $P_{US} > 1 \text{ W}$, 90% increase in h + important hysteresis reduction
Heffington and Glezer [36]	Pool boiling enhancement, VIBE mechanism (vibration-induced bubble ejection)	1.65 MHz	Water/ethanol $\sim 70/30$: 425% increase in CHF (600 W cm^{-2})
Jeong and Kwon [44]	CHF augmentation pool and subcooled boiling, inclination angle	40 kHz	87–126% CHF increase for downward facing surface
Kim et al. [33]	Experimental results, natural convection, pool subcooled and saturated boiling, platinum wire, transducer at the bottom, liquid FC-72	48 kHz	At least 60% global heat transfer increase (natural convection)
Kim and Jeong [52]	Numerical study, water bath, transducer at the bottom, inclination and subcooled boiling	40 kHz	see Jeong and Kwon [44]
Kwon et al. [46]	CHF enhancement pool boiling, variation of inclination angle and pool temperature, transducer at the bottom	40 kHz	CHF increased by 110% at pool temperature 95°C, horizontal downward plate
Park and Bergles [47]	Inert, dielectric liquid typical of those used for immersion cooling of microelectronic components (R-113) to cool small diameters stainless steel tubes power supplied	55 kHz, 75 W, 8000 W m ⁻²	Saturated pool: 10% increase in burnout heat flux; subcooled pool: 5% increase
Serizawa et al. [37]	Horizontal and vertical surfaces in water and vertical round tube under forced circulation of water. Silver rod at 750–800 K into distilled water (film boiling), ultrasound at the bottom	28 kHz, 70 W	Natural convection and pool nucleate boiling augmented for higher liquid subcooling. Temperature change periodically with ultrasonic waves. Quenching time reduced
Wong and Chon [20]	Natural convection and boiling around platinum wire in distilled water and methanol, cavitation, experimental work	20 kHz; 44 kHz; 108 kHz; 306 kHz, 0–200 W (with amplifier)	8-fold increase in heat transfer coefficient in natural convection
Yamashiro et al. [42, 43]	Quenching process, horizontal platinum wires in subcooled water	24 kHz; 44 kHz, 0–280 W	Cooling rate and heat flux increase with cavitation intensity and water subcooling, better effect at 24 kHz
Zhou and Liu [35]	Experimental study, acetone boiling in cubic pool around an horizontal circular tube, acoustic cavitation	?	Heat transfer increased with water subcooling and cavitation intensity
Zhou [53]	Experimental investigations, copper nanofluid, acoustic cavitation, cubic vessel filled with acetone, horizontal copper tube	?	Heat transfer in presence of acoustic field increased with nanoparticles concentration, cavitation intensity, fluid subcooling
Zhou and Liu [54]	Experimental investigations, calcium-carbonate nanoparticles in acetone, acoustic cavitation, cubic vessel with horizontal copper tube	?	Convection and boiling reduced by addition of nanoparticles, but increase with acoustic field intensity
Zhou et al. [34]	Acetone boiling around horizontal copper tube in a cubic vessel, acoustic cavitation effect on boiling heat transfer	?	Higher heat flux at lower wall temperature with acoustic cavitation

TABLE 3: Reported uses of ultrasound in food industry.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Cárcel et al. [58]	Drying persimmon cylinders, air velocity change, experiments, and mathematical model	21.8 kHz, 75 W, 154.3 dB	Drying speed increased with ultrasound at low air velocities ($<4 \text{ m s}^{-1}$), affecting internal and external thermal resistances
de la Fuente-Blanco et al. [59]	Drying process with direct contact, vibrating plate	20 kHz, 0–100 W	At 100 W power, after 60 min, sample mass 27% instead of 85%
Gallego-Juárez et al. [55]	Drying process with direct contact, vibrating plate	20 kHz, 100 W	Final moisture less than 1%, speed increase, and better quality product
Li and Sun [28]	Experimental study: potatoes samples freezing into 50/50% mixture water/ethylene glycol at about -18°C	25 kHz, 7.34 W; 15.85 W; 25.89 W	Most efficient power: 15.85 W; exposure time: 2 min; during the phase change period
Mason et al. [30]	Review article (food technology)		
Sastry et al. [60]	Sterilization applications but food particles replaced by metal samples. Effect of size and power input	Power input: 0.139, 0.069 and 0.046 W g^{-1} of liquid	Convection coefficient approximately doubled in all cases
Zheng and Sun [29]	Review article (food freezing process)		

3.3.2. *Influence of Environmental and Wave Characteristics.* Using frequencies below 20 kHz, Komarov and Hirasawa [64] investigated the cooling of a preheated platinum wire. Like in [8], the most efficient effect was obtained using high-amplitude sound waves. Besides, a moderate wire temperature was also necessary, otherwise cooling radiation effect was greater and convection effect diminished. This observation joins the one made in [71], where a better efficiency of ultrasonic waves at low heat fluxes is due to a thinner thermal boundary layer, easier to be disrupted by cavitation bubbles.

At a local scale, in a stationary acoustic field, it was observed that the convection heat transfer coefficient was the highest where the sound pressure was maximal [39–41]. This is due to the effect of buoyancy force coupled to pressure force and to the thermal boundary layer thickness shrinking because of water movement near the surface.

Dissolved gas can also have an influence as illustrated in [72] with gaseous cavitation into CO_2 saturated water. The distinction was between the two types of acoustic cavitation: a low-intensity gaseous cavitation, and a high-intensity vaporous cavitation. Gaseous cavitation was found to be a very good way to enhance heat transfer by increasing turbulence, in a flow where the Reynolds number is not already high. A fluid flow may also be controlled without contact (only by ultrasonic vibrations) [73]. A velocity reduction near the antinodes of the pressure wave was caused by cavitation bubbles. This effect was negligible if the flow velocity was too high because bubbles were carried downstream.

The influence of the fluid characteristics has also some importance, as shown in [74] where convective heat transfer enhancement by ultrasound was analysed into acetone,

ethanol, and water. The best improvement ratio obtained was about 4-fold for acetone. Conversely, the effect of cavitation seemed different for water, brine, and sugar-water [71]. But the most probable reason for heat transfer enhancement still remains the disturbance created by cavitation bubbles and the impingement due to their implosion at the surface, causing a local thinning of the thermal boundary layer.

More unusual studies have also been undertaken like the influence of nanoparticles combined with acoustic cavitation on convection and boiling [53, 54]. Another example can be found in [75], dealing with heat transfer between a molten metal (1520°C) flowing in a tube and water around to cool it down. Convection coefficients were found to be almost doubled in the presence of ultrasound at 20 kHz.

Two graphs have been plotted in Figures 8 and 9 to sum up, respectively, the influence of the ultrasonic power supplied and the wave frequency on the increase of the convection heat transfer coefficient. Each point represents the best result obtained in the corresponding referenced paper.

One can see in Figure 8 that the intensification of convection seems to be proportional to the ultrasonic power supplied, at least for low values ($<200 \text{ W}$, the blue zone). It would have been interesting to plot h_{US}/h as a function of the acoustic intensity (W m^{-2}) or even of the volumetric power (W m^{-3}). Unfortunately, this information is not always put forward in papers, and it is often impossible or very difficult to calculate it precisely afterwards. That is why in the future, it would be interesting and necessary to find a common term to compare studies between them (as it is already possible with frequency). However, for the moment it can be assumed that the sizes of most systems investigated in the literature are at the laboratory scale (few dozens of centimetres in length).

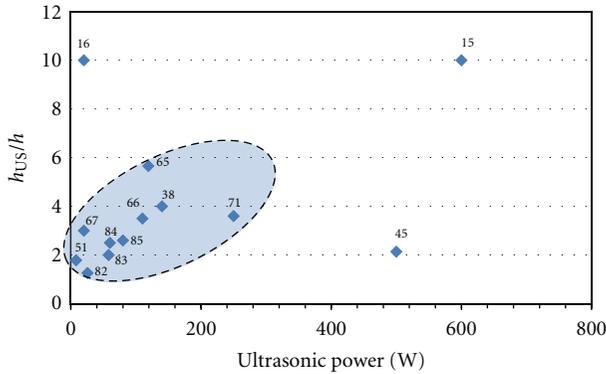


FIGURE 8: Increase in convection heat transfer coefficient versus ultrasonic power.

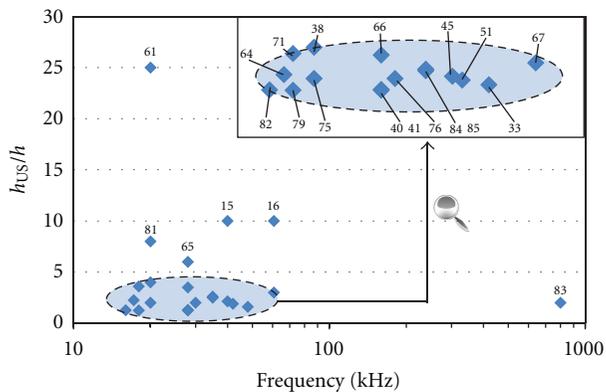


FIGURE 9: Influence of frequency on the increase of convection heat transfer coefficient.

So the plotting as a function of the total power can give a first good approximation. By the way, the 3 points outside the blue zone on Figure 8 probably correspond to references where the acoustic intensity and/or the volumetric power were very different from those in the blue zone.

Concerning Figure 9 and the effect of frequency, it is more difficult to find a tendency. Most works reported are concentrated in a zone between 15 and 60 kHz (low frequency, power ultrasound), but the improvements do not seem to depend on the frequency. More important is probably another parameter such as the system configuration or the ultrasonic power relative to surface or volume. An important point to underline is that frequencies between 60 kHz and 800 kHz (high frequency ultrasound) have not been investigated. Such frequencies would probably bring new interesting results.

3.3.3. Influence of the Geometry of the System. An interesting experimental setup is described in [65] to examine the effect of irradiation angle of ultrasonic waves upon the convective heat transfer rate from an inclined flat plate to water. The plate was oriented downward in front of the transducer and was electrically heated. The effect of angle of inclination on heat transfer coefficient was very low if acoustic cavitation

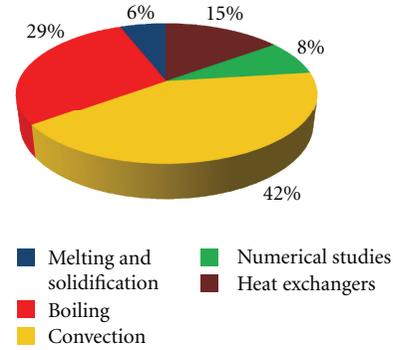


FIGURE 10: Percentage of studies by subject (total: 62 papers from the tables of this document).

was not generated, apart from if the plate was vertical where a small effect of acoustic streaming was detected.

Nomura et al. [66] measured experimentally the heat transfer coefficients during natural convection on a downward facing horizontal surface and a vertical surface. This coefficient was periodically changed by the ultrasonic vibrations according to the distance from the oscillator, but could become more uniform when using different ultrasonic frequencies. It also increased with the wave amplitude, as reported in [8, 70]. The distance between the transducer and the device to cool has a great importance [76]. It must be a multiple of the half wavelength used to create a resonating medium, in order to obtain more elevated acoustic streaming velocities and higher heat transfer coefficients. It is also apparently possible to create acoustic streaming behind a wall, for instance to cool the internal components of a system from the outside [67]. In [16], a horn-type transducer produced vibrations to study cooling techniques by natural convection in tap and degassed water. A convection coefficient up to 10 times higher with ultrasonic vibrations than without was calculated and different regions where the enhancement was more or less pronounced were observed.

An interesting and original use of power ultrasound is for wood treatment [77]. Ultrasonic waves could have a very positive effect on the temperature increase speed in the centre of wood cylinders which are either air-dried or fully water-saturated.

3.3.4. Sum Up of Convection Studies. In the domain of ultrasonically improved heat transfer, convection is the most studied area, as illustrated by Figure 10.

This chart was made with all references quoted in the tables except Table 3 (food) because many other studies exist in this domain and it would not have been representative (e.g., see [29, 30]). Convection covers at least half of these studies, and even more because it appears also in heat exchangers and in phase change.

A very important point is the cause of heat transfer enhancement, which is very difficult to determine since many phenomena appear simultaneously during propagation of ultrasound. Figure 11 shows a diagram with these different

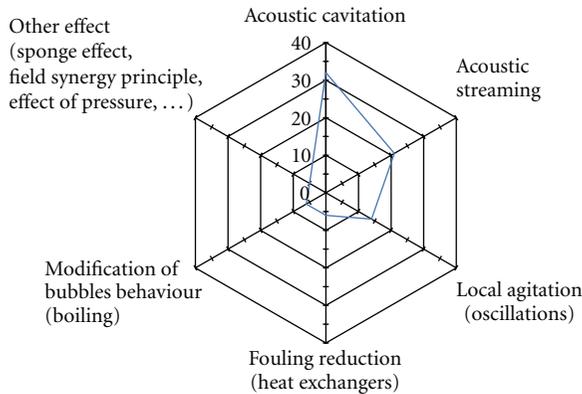


FIGURE 11: Ultrasound effects held responsible for heat transfer enhancement.

phenomena and the number of times these effects are assumed to be the cause of heat (and mass) transfer enhancement. This diagram was made from references of all the tables of this text (except the reviews), but more than one effect can be quoted in one paper (which explains why the number of effects quoted is superior to the number of papers).

According to this statistic chart, acoustic cavitation is the predominant phenomena for heat transfer enhancement. It is followed by acoustic streaming and by local agitation due to oscillations. Other phenomena, such as fouling reduction, hysteresis reduction, change in bubble behaviour, are side effects that could become very important when ultrasound will be used in industrial systems.

Table 4 synthesizes improvements obtained for convection heat transfer assisted by ultrasonic waves.

3.3.5. Numerical Studies, Modelling. Numerical simulation is taking a more and more important place with the growing potential of computational calculation. Even if the systems of interest often remain quite simple (one fluid, one moving part), the level of accuracy of computations can be very high [8, 9, 11, 52]. At least four equations have to be solved when dealing with numerical problems involving heat transfer and acoustic waves: continuity, momentum (Navier-Stokes), energy, and a least one for the streaming forces (from Nyborg's theory [78]). If acoustic cavitation is modelled, equations must be solved for the two fluid phases (liquid, vapour). Vibration is usually represented by a moving boundary and a dynamic mesh modelling (e.g., [52]) or by a sound field distribution inside the liquid (e.g., [79]).

A numerical model of acoustic streaming between two parallel beams separated by an air gap between 0.1 and 2 mm wide is proposed in [80]. The Nusselt number is increased only by 1% under constant heat flux conditions and by 0.5% under heat source condition. The initial purpose was to study the feasibility of cooling computer chips in laptops. The 2D simulation described in [81] showed that a standing waves pattern was necessary to obtain an increase in heat transfer. The reason for heat transfer enhancement invoked in [52] is fluid mixing by ultrasonic vibrations that provided fresh water to the heat transfer surface, increasing the temperature

gradient. Wave and flow patterns can be predicted precisely, which could be a basis of a future tool for the optimization of vibrating heat exchangers [13].

The field synergy principle is also a convincing way to illustrate cavitation-enhanced heat transfer [79]. This principle says that the local temperature gradient vectors should be parallel to the local velocity vectors to obtain the better convection heat transfer effect. And indeed, it is seen on streamlines patterns and temperature gradient patterns that acoustic cavitation helps to reduce in many zones the intersection angle between these two vector fields. Table 5 summarizes enhancements observed by undertaking numerical simulations.

4. Applications to Heat Exchangers

In the previous sections, examples concerned configurations with only one fluid in thermal contact with another solid body at a different temperature. It was necessary to gain a good knowledge of those basic systems before studying more complex ones. Heat exchangers have at least two fluids (flowing or at rest), which makes systems sometimes more tricky to study. Indeed, they are subjected to several constraints, and ultrasonic vibrations have influence on various parameters (e.g., heat transfer, fouling, and charge losses). It is, therefore, more difficult to assess the efficiency of ultrasound on such systems. That is probably one of the main reasons why their development is quite recent. This is the field of research that is currently under development in our laboratory.

4.1. Examples from the Literature. One of the first studies was carried out by Kurbanov and Melkumov in 2003 [82]. They explained comprehensively why ultrasonic vibrations are very well suited to increase performances of liquid-to-liquid heat exchangers. According to them, acoustic waves homogenize the velocity vectors of the subflows in pipes and decrease the surface tension of the fluid near the boundaries. The latter phenomenon is even more interesting if a thin film of lubricant is stuck to the pipes surfaces, which usually happens in refrigeration systems. This thin film induces a thermal resistance and its removal is very interesting for performances improvement.

Cooling of sonochemical reactors by cold water flowing into a coil, as presented in Figure 12, was experimentally and analytically analysed [83]. The cooling time of a certain amount of water, stored in the chemical reactor, was compared with and without high-frequency ultrasonic vibrations. The convection coefficient was enhanced between 135 and 204% in the presence of acoustic waves, reducing effectively the cooling time. Observed improvement was explained in terms of overall agitation due to the combined effects of local mixing (acoustic cavitation) and global fluid motion within the reactor (acoustic streaming).

A shell-and-tube configuration for a fluid-to-fluid vibrating heat exchanger was built and studied [84, 85]. This system is presented in Figure 13.

TABLE 4: Ultrasonic waves and convection heat transfer improvements.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Bergles [63]	Review article, heat transfer enhancement		
Cai et al. [71]	Experimental, natural convection, acoustic cavitation, circular heated copper tube in water, brine and sugar water	18 kHz, 0–250 W	Heat flux from cylinder: 132 W m^{-2} , ultrasonic intensity: 80 W cm^{-2} , enhancement up to 360%.
Fand and Kave [7]	Acoustic streaming, convection heat transfer, heated cylinder	800 Hz–4800 Hz (no ultrasound)	3-fold increase in heat transfer rate
Gould [70]	Acoustic streaming, convection between metal and water or glycerin-water mixtures	?	Up to 10-fold increase
Hoshino and Yukawa [41]	Experimental investigation, hot and cold cylinders, vertical standing waves, local and global coefficients in degassed water	28 kHz, $0.1\text{--}0.215 \text{ W cm}^{-2}$	Local coefficient $h_{\text{US}}/h \approx 1.3$ at 0.125 W cm^{-2} , maximum at antinode and minimum at node
Hoshino et al. [40]	Free convective heat transfer from a heated wire	28 kHz	Local coefficient $h_{\text{US}}/h \approx 1.25$ at 0.24 W cm^{-2} acoustic intensity, maximum at antinode and minimum at node
Hyun et al. [8]	Experiments and CFD simulations of acoustic streaming induced by flexural vibrations of a beam, cooling of a stationary beam above	28.4 kHz	Temperature drop of 40°C in 4 min, h up to $157 \text{ W m}^{-2} \text{ K}^{-1}$
Iida et al. [39]	Experimental, natural convection heat transfer from a fine cylinder to water, comparison convection coefficient and sound pressure profiles	28 kHz	Augmentation ratio around 1.6 when $\Delta P > 0.02 \text{ MPa}$
Komarov and Hirasawa [64]	Standing and travelling sound waves in tubes, platinum wire	0.3–17.2 kHz	$\text{Nu}_{\text{US}}/\text{Nu} \approx 2.25$ at 17.2 kHz, no gas flow and preheated wire temperature $\sim 675 \text{ K}$
Lam et al. [77]	Experimental study, saturated and air-dried wood cylinders heated in a water bath at 59.8°C with and without ultrasound. Temperature recorded at the centre of the cylinders	50–55 kHz, commercial cleaner	Significant influence of ultrasound on the temperature increase at the centre of cylinders
Larson [62]	Acoustic streaming around a sphere within a cylinder, cavitation, toluene, and water	20–1000 kHz, up to 6 W cm^{-2}	Increase in Nusselt number up to about 4 times, but not sufficient to warrant the technology
Lee and Loh [76]	Acoustic streaming in a gap between heat source and transducer	30 kHz	Heat transfer rate increased up to 75%
Lee and Choi [72]	Acoustic cavitation into CO_2 saturated water	138 W	Up to 369.5% turbulence intensity enhancement
Loh et al. [9]	Experiments and simulations (CFX4), flexural vibrations of a beam, acoustic streaming in air above (open) to cool a fixed beam	28.4 kHz	Temperature drop of 40°C in 4 min, streaming velocity up to 2 m s^{-1}
Markov et al. [75]	Flowing molten metal ($\sim 1520^\circ \text{C}$) in a water-cooled tube	20 kHz	Heat transfer coefficient as much as doubled
Nakagawa [11]	Experimental and computational results (CFX4), 4 vibrators to control acoustic streaming in a vessel containing silicon oil	1 MHz	Maximum streaming velocity measured: 0.07 m s^{-1} , jet position modified

TABLE 4: Continued.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Nakayama and Kano [38]	Experiments, cylindrical glass vessel, distilled water, with or without glass beads	20 kHz, 0–140 W	With glass beads, at saturation pressure 13.3 kPa, h increased up to 4 times
Nomura and Nakagawa [15]	Cooling a narrow surface, acoustic streaming and cavitation effects separated, water tank, experimental investigations	40 kHz, 600 W	Acoustic streaming at 0.4 m s^{-1} , h predicted with forced convection equations. Cavitation: h increased up to about 10 times
Nomura et al. [16]	Downward facing surface, ultrasound from below, experimental, cavitation, and acoustic streaming	60.7 kHz, 5–20 W	Up to 10-fold increase in heat transfer coefficient, tap and degassed water
Nomura et al. [26]	Turbulence intensity measured experimentally, square channel, transducer at the bottom	25 kHz, 0–50 W	Turbulence intensity 3 times larger with ultrasonic vibrations and up to 5 times locally
Nomura et al. [66]	Effect of ultrasonic frequency on downward facing and vertical surface	28 kHz (110 W), 45 kHz (210 W), 100 kHz (25 W)	Around 2 or 3 times average increase in h
Nomura et al. [67]	Experimental, natural convection, obstacle in front of a heating surface (different materials), acoustic streaming	60.7 kHz, 5–20 W	Up to 3 times with acrylic plate at 20 W, obstruction plates placed near the horn tip
Richardson [69]	Horizontal heated cylinder, horizontal and vertical sound fields, shadowgraphs	710 and 1470 Hz (no ultrasound), 120–140 dB	Local changes of boundary layer thickness and heat transfer enhancement
Uhlenwinkel et al. [61]	Experimental, gas vessel (air argon helium), resonant acoustic field, distance between transducers 20–200 mm	10 and 20 kHz	Heat transfer enhancement up to 25 times at ambient pressure at about 0.9 MPa and 20 kHz
Vainshtein et al. [12]	Two horizontal plates at different temperatures, acoustic streaming in longitudinal direction	200 Hz–15 kHz, 140 and 145 dB	Nu from 1 to 10, increase with frequency
Yukawa et al. [65]	Inclined copper plate in water	28 kHz, $0.1\text{--}0.48 \text{ W cm}^{-2}$	Convection coefficient increased 6-fold at inclination 90° , intensity 0.48 W cm^{-2}
Zhou et al. [74]	Horizontal copper tube in water, acetone and ethanol, experimental study	?	Maximum ratio of heat transfer enhancement: 3.95 with acetone, maximum source intensity, and close sound distance

The ratio between the overall heat transfer coefficient with ultrasound and the one without ultrasound for this shell-and-tube heat exchanger was calculated and found ranging from 1.2 up to 2.6 depending on the liquid flow-rate at the shell side [85]. The ultrasonic power had negligible influence on the heat exchange rate and the overall heat transfer coefficient was always higher with ultrasound than without, whatever the liquid flow rates or range of temperatures tested. Further investigations on the same system showed that higher improvements could be expected, especially for slow laminar flows in the shell.

4.2. Other Subsequent Advantages. As shown in [51], ultrasonic vibrations could be interesting to achieve a complete activation of nucleation sites in large evaporators with extended surfaces, normally reached with a sufficiently high

heat flux (and consequently elevated wall temperature). Indeed, ultrasound is efficient to reduce hysteresis effect [86], that is, the tendency of a system to remain in its initial state in spite of the cause supposed to produce a change.

Another important phenomenon resulting from ultrasonic vibrations application and not described until here is surface cleaning (essentially thanks to acoustic cavitation). This is very important because it could be part of a solution to reduce the natural fouling process in heat exchangers. Indeed, the environmental conditions in such devices make them prone to corrosion or microorganisms deposition. They induce additional thermal resistances which prevent the system from operating in optimal conditions, adding environmental and economical costs. However, one must pay attention to the powerful erosion capability of cavitation that could damage materials. Benzinger et al. [87] have studied

TABLE 5: Summary of numerical researches on convection increase by ultrasound.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Aktas et al. [81]	Shallow enclosure, vibrating vertical side wall, acoustic streaming	20 kHz and 25 kHz	After 5 ms, $h/h_{US} \approx 40/320$ at 20 kHz, $\Delta T = 10$ K
Cai et al. [79]	Square enclosure—hot bottom, natural convection, acoustic cavitation, ultrasonic beam from the centre	18 kHz	Field synergy principle analysis, 25% increase in h at the centre
Lin and Farouk [13]	Gas-filled square enclosure vibrating side-wall, top-side heated	20 kHz	Heat transfer enhanced with streaming flow velocity (maximum at the middle of the bottom wall)
Wan and Kuznetsov [80]	Acoustic streaming in a gap (0.1–2 mm) between two horizontal beams, the lower vibrating	160 Hz (no ultrasound)	1% increase in Nusselt number for constant heat flux case of the upper beam
Wan and Kuznetsov [14]	Air channel composed of two parallel beams, upper beam vibrating	21 kHz	h from 0.9 to 82 $W m^{-2} K^{-1}$ at constant heat flux, decreasing with channel width

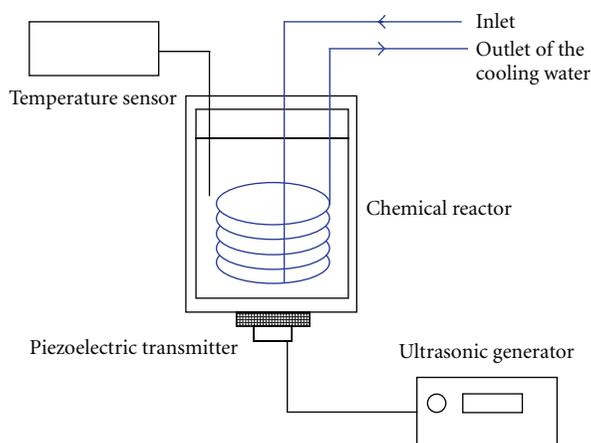


FIGURE 12: Ultrasonically assisted cooling of a chemical reactor.

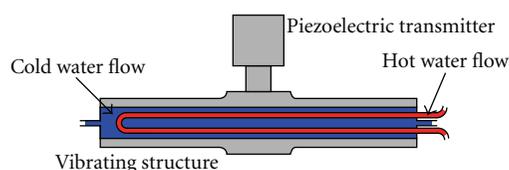


FIGURE 13: Schematic diagram of the vibrating shell and tube heat exchanger.

the effect of ultrasound on a microstructured heat exchanger to avoid fouling. Their results are very promising because the convection heat transfer coefficient increases almost up to the initial value after an ultrasonic pulsation cycle. Biofouling control is a possible application of ultrasound, that is, the prevention of microorganism growth (algae, fungi, bacteria)

on surfaces by application of ultrasonic vibrations [88]. Other examples are the synergistic properties of axially propagated ultrasound and antibiotic on the removal of biofilms in water-filled tubes [89]. An analogous study analysed the combined effect of ozone and ultrasonic vibrations [90]. The result observed was that the use of ozone and ultrasound was more effective than each process alone. But optimal parameters are sometimes difficult to find, for example, concerning scale removal [91] with choice of temperature, distance, and acoustic intensity.

Influence of ultrasound on pressure drop, or charge losses, also seems to be positive although very few studies deal with this subject [26, 82, 92].

Table 6 sums up the different examples of vibrating heat exchangers and of positive effects of ultrasound on these systems encountered in the research literature.

4.3. Patented Devices. Assessments of all these advantages in academic research literature are rare. Nevertheless, several systems (setups) regarding vibrating heat exchangers have been recently patented [93–104]. Almost all of them claim energy consumption savings either by a fouling reduction (or cleaning effectiveness) [93–97] or an improvement of the heat exchange efficiency, and sometimes both of them. These patents may involve different types of structures such as shell and tube heat exchangers [94, 95, 98, 99], water tank and heating coil (batch configuration like in Figure 12) [100], or various heat exchanger devices with applications in chemical engineering (reducing reaction time [101], increasing defrosting speed [102], cryogenic applications [103], and steelmaking applications [104]).

5. Conclusion

Ultrasound has gained a growing interest from industry during the last decades, resulting in the development of

TABLE 6: Review of vibrating structures for heat exchangers and their advantages.

Reference	Description of the study	Frequency, power, intensity	Best and/or interesting result obtained
Benzinger et al. [87]	Microstructured heat exchanger, antifouling investigations	20 kHz, 35 W	Pulses of 1 min to break the fouling layer but fouling speed increased
Bott and Tianqing [90]	Ozone + ultrasound to clean heat exchangers, axially propagated ultrasound	20 kHz, 2357.8 kW m ⁻²	2357.8 kW m ⁻² , 3 × 1 min pulse/day, up to 70% reduction in biofilm thickness
Bott [88]	Control of biofilm formation or biofilm removing in heat exchangers	20 kHz	88% reduction of biofilm growth with 10 treatments/day, 3 × 30 s at 40% amplitude
Gondrexon et al. [85]	Vibrating shell-and-tube heat exchanger, experimental investigation	35 kHz, 80 W	Overall heat transfer coefficient increased up to 257%
Kurbanov and Melkumov [82]	Heat exchanger-type for heating and refrigeration	3 and 16 kHz	27% increase in h but other major advantages
Li et al. [91]	Effects of various parameters on antiscaling and scale removal. Sedimentary speed and scale inhibition rate analysed	14–20 kHz; 0–250 W	Larger acoustic intensity is better for scale removal. 40°C best for antiscaling, 50°C for scale removal. Better effect for small distances to the ultrasonic transducer
Monnot et al. [83]	Cooling of chemical reactor (2.9 L), experimental and modelling	800 kHz; 1.6 MHz; 20 kHz; 0–109 W	Max $h_{US}/h \sim 2.04$ at 800 kHz, 57.6 W
Mott et al. [89]	Experimental investigation, glass tubes filled with water, standing waves	20–350 kHz, 35–45 W	95.3% of biofilm removed by 2 × 30 s treatment at 20 kHz in 7 cm tubes, 87.5% at 3 × 30 s in 50 cm tubes
Tisseau et al. [84]	Shell and tube heat exchanger, experimental investigation	35 kHz, variable power	Overall heat transfer coefficient increase up to 250%

several specific applications. Ultrasonic waves appear as an interesting way to improve processes productivity especially to overcome transfer limitations. For what concerns heat transfer, ultrasound can also be regarded as a possible technical solution for heat exchange enhancement. Hence, a lot of publications dealing with fundamental studies can be found in the literature. But most of these works are performed at the laboratory scale involving academic setups and usually using classical low frequency ultrasound. Well-known ultrasonically induced effects such as acoustic cavitation, acoustic streaming, and fluid particles oscillations are responsible for heat transfer improvement observed. It is also very important to note here that it is very difficult to distinguish the influence of these effects since they often occur simultaneously. One might therefore consider the positive influence of ultrasound as an overall effect. As detailed in this paper, influence of ultrasound on convection remains the major subject of interest. Local heat transfer coefficient was shown to be multiplied between 2 and 5 times in the presence of an ultrasonic field. Phase change heat transfer also covers a great number of studies that demonstrate the beneficial effect of ultrasound on boiling as well as melting or solidification. A more recent and scarce research field that focuses on heat exchangers has shown that the use of ultrasonic waves can

improve overall performances regarding heat transfer and/or fouling.

Although very promising results are reported, the scale-up of the ultrasonic technology to pilot or industrial scale heat exchangers has not been yet deeply investigated. Only few references are available in the literature, illustrating the difficulties to meet such a technological challenge. It is then expected that the combined efforts of acousticians, chemical and mechanical engineers will also help to design a new type of “vibrating” heat exchangers. It might, therefore, result in improved performances as well as antifouling action in the near future.

Nomenclature

Latin/Greek Symbols

- h : Convection heat transfer coefficient W m⁻² K⁻¹
- Nu: Nusselt number
- P : Power W
- T : Temperature K or °C
- ΔT : Temperature difference K

Acronyms/Subscripts

CHF: Critical heat flux
 CFD: Computational fluid dynamics
 US: Ultrasound.

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