Advances in Chemical Engineering

Chapter 2

Ultrasonic Assisted Heat Transfer and its Application in Chemical Engineering

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1. Introduction

Sonochemistry is considered to be a general technique like thermo chemistry (heat) and piezochemistry (pressure). The sound frequency which is higher than 16 kHz is called as ultrasound. Some animals utilize ultrasound for navigation (dolphins) or hunting (bats) using the information carried by back-scattering sound waves. Ultrasound is one of the emerging technologies that were developed to minimize processing, maximize quality and ensure the safety of food products. The ultrasound and cavitational effects were found 100 years before. The cavitation was first reported by Thornycroft and Barnaby in 1895 [1]. They noticed that the propeller of the submarine was pitted and eroded. They observed the consequence of collapsing bubbles due to hydrodynamic cavitation that generated intense pressure and temperature gradients in the local vicinity. In 1917, Lord Rayleigh [2] published the first mathematical model describing a cavitation event in an incompressible fluid. After 1927, when Richards and Loomis [3] reported the first chemical and biological effects of ultrasound, the workers recognised that cavitation could be an useful tool in chemical reaction processes. One of the first applications reported in the literature was the use of ultrasound induced cavitation to degrade a biological polymer [4]. Since then, applications of ultrasound induced cavitation have increased in popularity, particularly as novel alternatives to processes such as the production of polymer [5], for the enhancement of chemical reactions [6], emulsification of oils [7] and degradation of chemical or biological pollutants [8]. The advantage of using acoustic cavitation for these applications is that much more mild operating conditions are utilized in comparison to conventional techniques and many reactions which may require toxic reagents or solvents are not necessary [9].

Ultrasound induced cavitation is an extremely useful and versatile tool to carry out chemical reactions. Sonochemistry refers to the area of chemistry where chemical reactions are induced by sound. Sonication is also useful in Nanomaterial synthesis, shear and mechanical mixing, medical applications, food industry and Sonochemical degradation of pollutants. Ultrasound is also helpful to improve and enhance the efficiency of the process. Enhance the chemical reaction, mass transfer and heat transfer process such as drying, mixing etc [10-12]. Some of the potential application of ultrasound where it finds vital role are listed below [13].

Table 1: Application of ultrasound

S. No	Application	Examples
1	Machining of materials	Welding; cutting; drilling; soldering
2	Cleaning	General surface cleaning; washing of soil and ores
3	Homogenization / Spraying	Emulsification and atomization of liquids
4	Separation	Crystallization; sieving; filtration
5	Degassing	Treatment of HPLC eluents
6	Water treatment	Removal of chemical and biological pollution
7	Biological uses	Cell disruption
8	Medical uses	Dental descaling; scalpels; lithotripsy; HIFU; preparation of protein microspheres; nebulizers

Heat transfer enhancement is an important area of thermal engineering. Although it is understood that ultrasound can enhance the heat transfer in the thermal system. The heat transfer can be increased by the passive or active methods. Passive method consists of roughing the tube inner surface, inserting the swirl-flow devices into the tube, and adding the solid-particles into the fluid. Traditional active method is the application of mechanical aids, vibration, and electrostatic fields on the tube. Imposing acoustic vibration onto a liquid pool has been proven to enhance natural convection and boiling heat transfer for several decades. In acoustic vibration the frequency is ranging from 20Hz to 20kHz, but in the ultrasound, the frequency is above 20kHz.

F and [14] and Li and Parker [15] reported enhancement of natural convection heat transfer by virtue of ultrasonic waves. Wong and Chon [16] and Iida and Tsutsui [17] investigated the effects of ultrasonic vibration on pool boiling heat transfer as well as natural convection heat transfer. They found that the natural convection heat transfer is enhanced more than pool boiling by ultrasonic vibration. Park and Bergles [18] and Bonekamp and Bier [19] studied the influence of ultrasound on nucleate boiling heat transfer, to find that the stronger enhancement is achieved at lower heat fluxes. Yamashiro et al. [20] showed enhanced quenching behavior for a hot wire in water when ultrasonic vibration is imposed.

The article focused overview of ultrasound and particularly attempted to influence of heat transfer processes and its application in chemical engineering field. The recent adaptation of ultrasonic technologies to heat exchanger devices is discussed thoroughly, with examples drawn from new patents and current laboratory work.

2. Cavitation

Generally, cavitation is classified into four types based on the mode of its generation: Acoustic cavitation; Hydrodynamic cavitation; Optic cavitation; Particle cavitation [21,22].

2.1. Acoustic cavitation

The main effects of ultrasonication in liquids are acoustic cavitation and acoustic streaming. In the acoustic cavitation, the sound energy creates the bubble and sudden collapse of this bubble under ultrasonic irradiations which can release high amount of energy in a small location. Ultrasound occurs at a frequency above 16 kHz, higher than the audible frequency of the human ear and is typically associated with the frequency range of 20 kHz to 500 MHz. Cavitation can be generated within fluid using transducers, which convert one form of energy to another. In addition to this phenomenon, propagation of ultrasonic waves in the liquid medium generates local turbulence and micro-circulation in liquid which is known as acoustic streaming. Acoustic streaming can mainly cause physical effects and also influence chemical processing limited by mass transfer.

2.2. Hydrodynamic cavitation

Cavitation can also be generated by forcing the fluid through an orifice, resulting in a pressure drop in the fluid. When the pressure falls below that of the vapor pressure of the fluid stream, cavitation sites are created. The magnitude of the pressure drop is dependent upon the flow rate of the fluid and the size of the orifice. Usually it occurs in ship propellers, pumps, turbines, hydrofoils and nozzles. For most cases, cavitation can cause severe damage to the materials and should be avoided in hydraulic machinery. If the cavitation phenomenon occurs in the centrifugal pump, it can damage the pump.

2.3. Optic cavitation

When the medium is radiated by high-intensity of laser pulses optic cavitation is occurred. Under this condition break down of liquid medium and bubbles are formed. High speed camera is used to record the single and multiple bubbles formed during the behavior.

2.4. Particle cavitation

In addition to photons in optic cavitation, other elementary particles such as protons, neutrons can also be generating the cavitation bubbles. A small fraction of medium will be ionized and rapidly heated when the high energy particle pass through the medium results in the formation of tiny bubbles.

3. Types of Sonoreactors

3.1. Ultrasonic bath

In bath type sonicator is shown in the figure1, the transducers are located at the bottom of the reactor and the ultrasound irradiations transmit into the system indirectly. Bath systems are widely used in sonochemical research because they are readily available and relatively inexpensive. Generally, bath type sonicator should be used where a specific power number or ultrasonic intensity is not required, because ultrasonic power does not change in this type of reactors. It is not easy to obtain a uniform distribution of ultrasonic energy with ultrasonic bath and use of more than one transducer is mandatory for large scale applications [23,24].

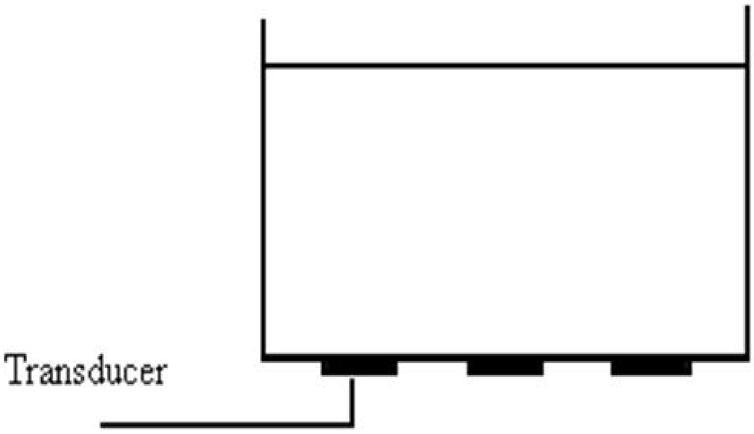

Figure 1: Bath type sonicator

3.2. Ultrasonic horn

In ultrasonic horn or probe type (**figure 2a**) consist of cylindrical probe which submerges in the liquid and transmits the wave in to the medium directly. The horn is usually made of transition metals such as titanium which has the diameter range between 5mm and 1.5cm. In the probe type, erosion and pitting of the probe tip may contaminate the solution medium. Ultrasonic horn is applied in many experimental studies such as micromixing, transesterification of biodiesel, saccharification, microfiltration, etc. Ultrasonic horn can also be used longitudinally in the vessel for different applications. The longitudinal horns usually have higher surface area of irradiation in the medium and the magnitude of energy efficiency in this type of ultrasonic is higher than the convention alone . Furthermore, the large irradiation area of longitudinal ultrasonic horn (**figure 2b**)leads to uniform distribution of cavitational activity in the whole reactor volume which can be more beneficial in pilot scale in comparison with simple ultrasonic horn [23,25].

3.3. Low power and high power ultrasound

The power is inversely proportional to frequency of the sonication. There are two category, “low frequency ultrasound” or “power ultrasound” and “high frequency ultrasound” or “low power ultrasound”. Ultrsound waves between 20 kHz to 100 kHz, are defined as “low frequency ultrsound”; between 100 kHz–1MHz, waves are defined as “high frequency ultrasound”. Low-frequency ultrasound does alter the state of the medium and is the type of ultrasound typically used for sonochemical applications. High frequency ultrasound (in the megahertz range) does not alter the state of the medium through which it travels and is commonly used for nondestructive evaluation and medical diagnosis. **Figure 3** shows some typical uses of ultrasound according to frequency and power [26].

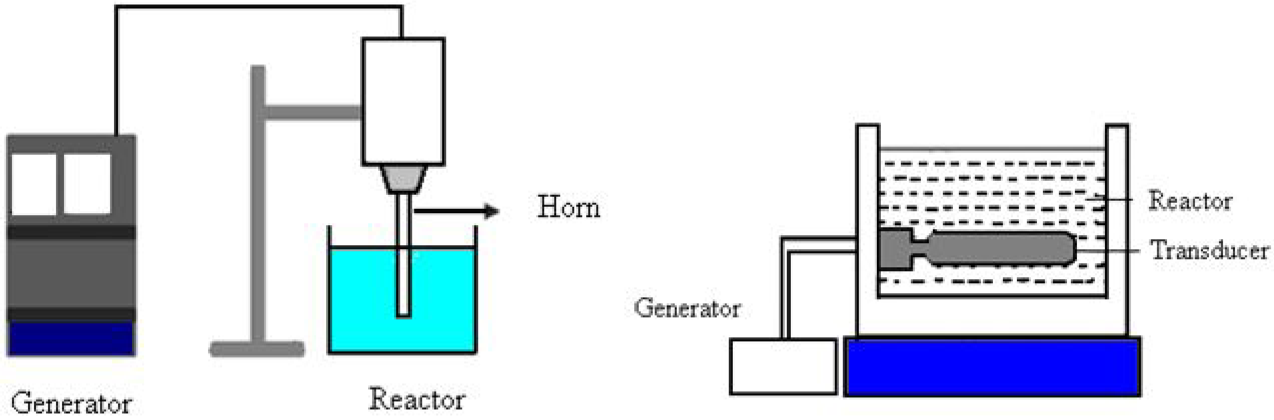

Figure 2: (a) Probe type sonicator (b) longitudinal horns

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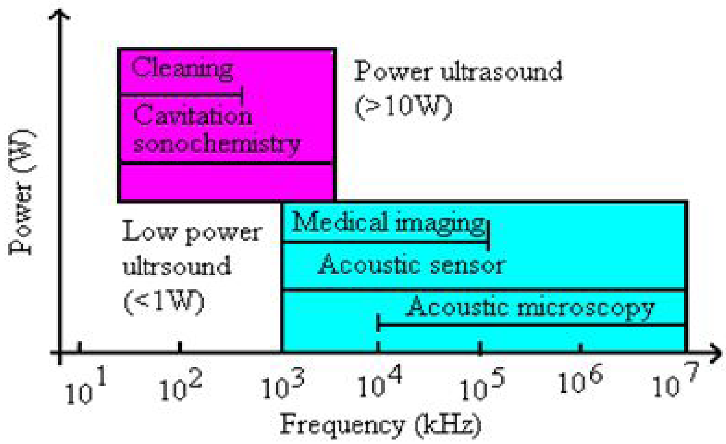

Figure 3: Power versus frequency

3.4. Acoustic power measurement

Several methods are available to determine the acoustic power dissipated to the system by sonication. The most commonly used approach to determine the ultrasonic power is calorimetry, which assumes that all of the energy delivered to the system is dissipated as heat, as shown by equation (1) [27].

$$P_{diss} = \left(\frac{dT}{dt}\right)_{t=0} m_{solvent} C_{P,solvent} \qquad (1)$$

$m_{solvent}$ $Cp,_{solvent}$ are the mass and heat capacity of the solvent, respectively, and $\left(\frac{dT}{dt}\right)_{t=0}$ is the initial slope of the temperature rise of the solution versus time of exposure to ultrasonic irradiation. The initial temperature rise of the system is independent of the initial bulk liquid temperature. Equation (1) is used to estimate the power dissipated in the reaction system and it is found it to be inadequate. It predicted that only 33% of the power delivered by the transducer was dissipated as heat, which would indicate that the other 67% of the power was lost in the transfer process, or by other means. Hence that the Equation (1) needed to be modified to account for the heat absorbed by the vessel as well as the solvent, as shown by equation (2)

$$P_{diss} = \left(\frac{dT}{dt}\right)_{t=0} (m_{solvent} C_{P,solvent}) + \left(\frac{dT_v}{dt}\right)_{t=0} (A_{WS} X_W) \rho_{Vessel} C_{P,Vessel} \qquad (2)$$

where T_v is the temperature of the inner vessel wall, A_{ws} is the area of the wetted surface of the vessel, and X_w is the thickness of the inner wall. This provides a much more reasonable result. It was found that 51.5% of the power delivered by the probe was dissipated as heat, more closely agreeing with the manufacturer's information. The other methods to determine the power dissipated in a reaction system are by using chemical dosimeters (such as the generation of HNO_3 from NO_3 in water) and the Weissler reaction (which measures the liberation of iodine from potassium iodide). The comparison of calorimetry and the Weissler reaction as measures of ultrasonic power showed that the two methods provided similar predictions.

4. Enhancement of Heat Transfer Rate

Heat transfer processes has broad application in processing industries like chemical, gas, oil and food industries and also in the functioning of various devices and systems. In a wide variety of situations, heat transfer principles are used to increase, decrease or preserve temperature to achieve desired process at a controlled rate. The enhancement of heating or cooling in an industrial process may save energy, reduce process time, raise the thermal rating and lengthen the working life of equipment. Thus, the advent of high heat flow processes has created significant demand for new technologies to enhance heat transfer [28,29].

There are three methods widely used to increase the rate of heat transfer. The methods are (1) active method (2) Passive method (3) combined method. Following three methods are discussed in detail [30-32].

4.1. Active method

In the active method, some external power input enhances the heat transfer rate. The active method including mechanicals aids, surface vibration, fluid vibration, electrostatic fields, suction or injection and jet impingement requires an external activator/power supply to bring about the enhancement.

Mechanical aids: Stirring or agitating of the fluid by means of mechanical force to increase the heat transfer rate. Generally used for viscous liquids in the chemical process industry.

Surface vibration: High or low frequency surface vibration has been used to increase the single-phase heat transfer. In this case a piezoelectric device is used to vibrate a surface to enhance the heat transfer rate.

Fluid vibration: It is more practical type of vibration enhancement because of the mass of most heat exchangers. The vibrations range from pulsations of about 1 Hz to ultrasound. Single phase fluids are of primary concern. They are applied in many different ways to dielectric fluids. Electrostatic fields : Can be directed to cause greater bulk mixing of fluid in the vicinity of the heat transfer surface.

Injection: It is utilized by supplying gas through a porous heat transfer surface to a flow of liquid or by injecting the same liquid upstream of the heat transfer section. The injected gas augments single-phase flow. Surface degassing of liquids may produce similar effects.

Suction: It involves vapor removal, in nucleate or film boiling, or fluid withdrawal in single phase flow through a porous heated surface.

Jet impingement: It forces a single-phase fluid normally or obliquely toward the surface. Single or multiple jets may be used and boiling is possible with liquids.

4.2. Passive method

This method generally uses surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. For example, inserts extra component, swirl flow devices, treated surface, rough surfaces, extended surfaces, displaced enhancement devices, coiled tubes, surface tension devices and additives for fluids.

Coated surfaces: They involve metallic or nonmetallic coating of the surface. Examples include a nonwetting coating, such as Teflon, to promote drop wise condensation, or a hydrophilic coating that promotes condensate drainage on evaporator fins, which reduces the wet air pressure drop. A fine-scale porous coating may be used to enhance nucleate boiling.

Swirl flow devices: They produce and super impose swirl flow or secondary recirculation on the axial flow in a channel. These devices include helical strip or cored screw type tube inserts, twisted tapes .They can be used for single phase or two-phase flow heat exchanger.

Treated Surfaces: They are heat transfer surfaces that have a fine-scale alteration to their finish or coating. The alteration could be continuous or discontinuous, where the roughness is much smaller than what affects single-phase heat transfer, and they are used primarily for boiling and condensing duties.

Rough surfaces: They are generally surface modifications that promote turbulence in the flow field, primarily in single-phase flows, and do not increase the heat transfer surface area. Their geometric features range from randoms and-grain roughness to discrete three-dimensional surface protuberances

Extended surfaces: They provide effective heat transfer enlargement. The newer developments have led to modified fin surfaces that also tend to improve the heat transfer coefficients by disturbing the flow field in addition to increasing the surface area.

Displaced enhancement devices: These are the insert techniques that are used primarily in confined force convection. These devices improve the energy transfer indirectly at the heat exchange surface by displacing the fluid from the heated or cooled surface of the duct/pipe with bulk fluid to the core flow.

Coiled tubes: These techniques are suitable for relatively more compact heat exchangers. Coiled tubes produce secondary flows and vortices which promote higher heat transfer coefficient in single phase flow as well as in most boiling regions. Surface tension devices: These consist of wicking or grooved surfaces, which directly improve the boiling and condensing surface. These devices are mostly used for heat exchanger occurring phase transformation.

Additives for liquids: These include the addition of solid particles, soluble trace additives and gas bubbles into single phase flows and trace additives which usually depress the surface tension of the liquid for boiling systems. Additives for gases: These include liquid droplet or solid particles, which are in traduced in single-phase gas flows either as dilute phase (gas–solid suspensions) or as dense phase (fluidized beds).

4.3. Compound method

Combination of the above two methods, such as rough surface with a twisted tape swirl flow device, or rough surface with fluid vibration, rough surface with twisted tapes .

Among the new possible technologies as discussed above, that could be developed and optimized in order to improve heat transfer processes, the use of ultrasonic waves appears to be one of the most recent and new sustainable technical solutions in the recent years [33].

5. Enhancement of Heat Transfer by Ultrasound

In recent years, ultrasound technology has been used as an alternative processing option to conventional thermal approaches.

Ultrasound has several applications in engineering industries such as improving systems efficiencies, intensifying chemical reactions, drying, welding, and cleaning etc. An analogous observation can be made for heat transfer processes, which are omnipresent in the industry: cooling applications, heat exchangers, temperature control etc. [26]. This chapter details the use of ultrasonication with special attention on enhancement of heat transfer applications in Chemical Engineering.

5.1. Factors affecting the ultrasonic assisted heat transfer

The various factors that affect the ultrasonic assisted heat transfer [34] are given below.

5.1.1. Influence of ultrasound power

The ultrasonic transducer can produce different power levels of ultrasound with 21 kHz in frequency. Experimental Study on Heat Transfer Enhancement of Water-water Shell-and-Tube Heat Exchanger three power levels, i.e. 40W, 60W and 100W, were used. High-intensity ultrasound can induce cavitation bubbles and acoustic streaming in liquid, which makes it possible for power ultrasonic to be applied to the improvement of heat transfer process. In the present work, the experimental study was made on the heat transfer enhancement of water-water heat exchanger in shell-and-tube type assisted by power ultrasonic. An experimental study shows that the power level of 40W brings about 3% enhancement whereas the power level increases to 60 and 100 W, the enhanced ratio increases to 13% and 17% respectively [34]. It is supposed that the enhanced ratio would further increase if the higher ultrasound power level was applied.

5.1.2. Influence of velocity of liquid

The heat transfer rate is influenced by flow rate of fluid passing through the heat exchanger. It is clear that the heat transfer has an obvious increase after 100W ultrasound is emitted into the heat exchanger. Different flow behavior leads to different degree of heat transfer enhancement. The heat transfer rate increases with increase in liquid flow rate. This is due to that the cavitation bubbles and acoustic streaming induced by the ultrasound in liquid will increase the turbulence degree of movement of fluid, which is equivalent to increasing the fluid velocity. Therefore, it is reasonable to suppose that the effect of ultrasound on the heat transfer would increase with the decreasing flow rate.

5.1.3. Influence of inlet temperature of the fluid

Although the water temperature produces little effect on the heat transfer coefficient, it may influence the efficiency of heat transfer. The phenomenon may be explained by the relationship between the acoustic cavitation and the liquid temperature. As mentioned above, cavitation induced by the ultrasound is the main force that intensifies the turbulence of fluid. Therefore, maximizing cavitation of the liquid is obviously very important for ultrasound to enhance the heat transfer process. Temperature may be the most important parameter to be considered in maximizing cavitation intensity. This is because many liquid properties affecting cavitation intensity are related to temperature, such as the viscosity, the solubility of gas in the liquid, and the vapor pressure. Increasing liquid temperature, on one hand, will decrease viscosity of liquid and make it easier to form cavitation bubbles, on the other hand, will be adverse to the formation of acoustic cavitation because of the reduction of dissolved gas in the liquid and the rising of vapor pressure required.

5.2. Application of ultrasonication in heat transfer studies

5.2.1. Preparation of nanofluids

Nanofluids have been considered in various applications as advanced heat transfer fluids for almost two decades. Nanofluids are a new class of fluids engineered by dispersing nanometer-sized materials (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheet, or droplets) in base fluids. Base fluids mostly used in the preparation of nanofluids are the common working fluids of heat transfer applications; such as, water, ethylene glycol and engine oil. In order to improve the stability of nanoparticles inside the base fluid, some additives are added to the mixture in small amounts. Nanofluids have been found to possess enhanced thermo physical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients compared to those of base fluids like oil or water.

Generally, a preparation of nanofluids is an important step in experiments on nanofluids. To achieve a stable nanofluid that exhibits true nano behavior, the particles should be dispersed with no or very little agglomeration. There are mainly two methods of nanofluid production, namely, two-step technique and one-step technique. In the one-step technique, production and dispersion of nanoparticles is carried out simultaneously. In the two-step technique, the first step is the production of nanoparticles and the second step is the dispersion of the nanoparticles in a base fluid. Two-step technique has advantageous when mass production of nanofluids is considered.

The dispersion of the nanoparticles is achieved with the help of any one of the following technologies, intensive magnetic force agitation, ultrasonic agitation, high-shear mixing and homogenizing. Due to the high surface area and surface activity, nanoparticles have the tendency to aggregate. Out of various methods of dispersion described above, the most commonly used technique is ultrasonication.

The heat transfer intensification studies with the use of nanofluids have captured significant attention of researchers across the globe in recent years. Though it is still completely unexplored, there are several works published and continuing in exponential way. In almost all the reported works, the mechanism used for dispersing the nanopowders into base fluids is by ultrasonication.

5.2.2. Heat transfer with phase change

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. According to several authors, this is still due to acoustic cavitation, which helps the creation and growth of the bubbles, whereas their oscillations enable to create micro streaming and local agitation near the surfaces to sweep them away [3538].

Power ultrasound is a method to reduce the size of ice crystals on the frozen products and gain in quality [39]. 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, micro streaming, and some cleaning action of heat exchangers are among the subsequent advantages. Besides, ultrasound is a nonintrusive technique. Comprehensive reviews of the uses of ultrasound in food technology exist [40,41], 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 [42,43].

Ultrasonic technologies have also gaining significant attention 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 [44,45]. This can produce a sponge effect, contraction and expansion cycles, leading to a better drying result. The effect is much more pronounced for very porous products [46], 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.

5.2.3. Enrichment of convection

Convection is also one of the most studied modes of heat transfer like boiling under the influence of ultrasonic vibrations. Increases in heat transfer coefficients up to 25 times are reported [47]. 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 turned on.

Bergles [48] 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 [49].

Kiani et al [50] have experimentally observed that, ultrasound irradiation was able to enhance the cooling process of a stationary sphere immersed in the cooling medium significantly and resulted in increased heat transfer rates. They have identified that, increasing the intensity of ultrasound led to the increase in the cooling rate. Enhancement factors from 1.02 to 4 were detected for different intensities and sphere locations. According to them, the position of the sphere played an important role during the ultrasound assisted cooling due to the position-related cavitation bubble population and acoustic streaming patterns. Closer distances to the transducer surface showed higher cooling rates. Concentrated cavitation bubbles at the interfaces were the main reason for the heating effect of ultrasound. They have developed an analytical solution for the ultrasound assisted heat transfer with regards to the heat generation at the surface.

5.2.4. Use in Heat Exchangers

One of the first studies was carried out by Kurbanov and Melkumov in 2003 [51]. 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 sub flows 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 performance improvement.

Microstructured heat exchangers show significant advantages in comparison with conventional heat exchangers. But, they are prone to fouling very easily. Benzinger et al [52] studied and exemplified that the use of ultrasound is a useful supplement of micro heat exchangers. Micro heat exchangers could be used for the heating of substances which show a higher tendency of fouling. The combination of micro heat exchanger and ultrasound presents a development, which should improve the performance characteristic. Their investigations indicated that the use of ultrasonic power influences the fouling and opens up possibilities todiminish the fouling in microchannels significantly.

Monnot et al [53] experimentally and analytically analysed the cooling of sonochemical reactors by cold water flowing into a coil, 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. Their observation in 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 by Gondrexon et al [54]. 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. 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.

Legay et al [55] designed, built and studied a new kind of ultrasonically-assisted vibrating heat exchanger. They demonstrated that ultrasound can be used efficiently as a heat transfer enhancement technique, even in such complex systems as heat exchangers. Overall heat transfer coefficients were determined with and without ultrasound. Their results showed that, whatever the heat exchanger flow configurations, the overall heat transfer coefficients in the presence of ultrasound are higher than under silent conditions. It was assumed that the conduction thermal resistance through the thickness of the internal pipe and that the convection thermal resistance inside the internal pipe are not affected by ultrasonic waves. Hence, they have concluded that only the convection thermal resistance in the annular space was decreased, leading to an enhanced exchanged heat flow rate. It is considered that physical effects induced by cavitation as well as vibrations of the walls result in a disturbance of the dynamic boundary layer. They strongly concluded that, ultrasound is an interesting way to improve heat exchanger performances.

Legay et al [56] investigated the potential use of ultrasonic waves directly applied to a heat exchanger structure in order to clean some fouling layers. The heat exchanger was a double pipe configuration in which the central pipe is removable. Glass and stainless steel central pipes were tested after being painted with spraying paint to simulate some fouling layers. After ultrasound exposure at minimal available power, almost all paint can be removed from the zone subjected to structure vibrations. The cleaning process starts at the antinodes of the ultrasonic wave and expands to all the vibrating length. They claimed that the results were very encouraging since the fouling layers can be removed both from the external side of the pipe and, with more difficulties, from the internal side. Therefore, the overall heat transfer coefficient, previously decreased by the thermal resistance of the paint thickness, was found again up to its initial value, corresponding to that of a clean tube.

5.2.5. Some other advantages of sonication

Sonication in a process offers several subsequent advantages and few of its significant advantages are listed below

- Another important phenomenon resulting from ultrasonic vibrations application is surface cleaning (due 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.

- Ultrasound is efficient to reduce hysteresis effect, which is the tendency of a system to remain in its initial state in spite of the cause supposed to produce a change.

- 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.

- 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.

6. Conclusion

Earlier during 20th century, although researches shows ultrasound can play an important role in process industries, lack of knowledge keeps industry from implementing ultrasound in their processes. A recent survey and market study of the possible future applications of new process technologies (like microwave, ultrasound) in the process industries has revealed that many companies are reluctant to apply these new technologies due to poor understanding of these new techniques by professionals. Recently, that is during the last decade, ultrasound has gained a growing interest from industry, resulting in the development of several specific applications. Ultrasonic waves appear as an interesting way to improve processes productivity especially to overcome transfer limitations.

For heat transfer applications, 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. Several well-known factors responsible for heat transfer improvement such as acoustic cavitation, acoustic streaming, and fluid particles oscillations were observed by researchers. But, 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. Literatures demonstrate that the 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 shows the beneficial effect of ultrasound on boiling as well as melting or solidification. A more recent 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 [26].

Overall, it can be concluded that ultrasonication have significant potential for chemical process intensification [57]. But, the scale up of the ultrasonic technology to pilot or industrial scale heat exchangers has not been yet deeply investigated. The combined efforts of the involved stake holders including chemists, material scientists, chemical engineers and instrumentation/electrical engineers would be required to translate the small scale marvel into commercial scale realization

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