The ultrasounds as a mean for the enhancement of heat exchanger performances: an analysis of the available data

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Abstract. The aim of this paper is to investigate the potential use of ultrasounds for improving the performances of heat exchangers. In a heat exchanger, the effect of ultrasonic vibrations is important both for heat transfer intensification and for the possibility of obtaining fouling reduction: the cumulative effect can determine an interesting advantage in term of overall heat transfer coefficient increase. After a general analysis of the topic, the paper analyse the results recently obtained in the two main fields of analysis, heat transfer coefficient enhancement and fouling reduction. The perspective of the use of acoustic fields and ultrasound for optimization of heat exchangers operation is some particular fields of application are discussed.

1. Introduction

The positive effect of ultrasonic vibrations on heat transfer enhancement was reported by several authors; the topic has been recently reviewed in [1]. Free convection [2], boiling [3,4] and also melting [5] were deeply studied and the consequences of ultrasound upon these phenomena are known. At first, the use of ultrasonic vibration concerns only convection heat transfer; but results obtained did not seem promising enough. So, the use of ultrasound was then extended to phase change phenomena. Boiling heat transfer is another important research field, where ultrasonic vibrations promote bubbles formation and therefore delay the onset of the critical heat flux. The influence of ultrasound on heat transfer has been experimentally investigated with reference to particular specific conditions and geometries: the collected results are reported in some papers, like [6–8]. One of the authors of the paper was involved during past years in the field of intensification of heat transfer in boiling and subcooled boiling using refrigerant fluids by means of ultrasounds too, [9-10]. The positive effect of ultrasound can be remarked mainly for fluids operating in subcooled conditions, while ultrasounds seem to lose their influence in saturated boiling conditions.

A possible practical application of the enhancement of heat transfer using ultrasounds is observed in the cooling of electronic components. Even if the physical problem is investigated, less attention seems to be connected with practical application and in particular to heat exchangers. The effect of ultrasonic vibrations on natural convection or phase-change heat transfer has been considered in many fundamental studies but till some years ago, only a few publications analyzed the influence of ultrasound on heat exchanger performances [11, 12].

Recently, investigations began to head toward fouling reduction for heat exchangers. An undeniable advantage of ultrasound is its cumulative effects leading to several improvements on a single system. Heat exchangers are perfectly suited examples to illustrate this doubly favourable factor, with both heat transfer enhancement and cleaning possibilities [13]. An important side-effect of ultrasound to heat exchangers is surface cleaning which essentially thanks to acoustic cavitation. This may be a promising...
solution to reduce the fouling process in heat exchangers. Some authors have studied specific aspects of ultrasounds connected with the operation of heat exchangers, [14, 15]. Considering this a topic of specific interest and not so much systematically investigated by various research groups, the aim of this paper is to investigate the potential use of ultrasonic waves for improving the performances of heat exchangers. In a heat exchanger, the effect of ultrasonic vibrations is important both for heat transfer intensification and for the possibility of obtaining fouling reduction: the cumulative effect determines an undeniable advantage in term of efficiency increase. After a general analysis of the topic, the results recently obtained in the two main fields of analysis, heat transfer coefficient enhancement and fouling reduction are analyzed and the perspective of the use of ultrasound for optimization of heat exchangers operation is some particular fields of application are discussed. This paper is organized in two main parts. The first one deals with a theoretical background on heat transfer intensification by means of ultrasounds. The second part is devoted to the perspective of the use of ultrasounds with application to heat exchangers.

2. Heat transfer with ultrasounds: theoretical background

Sound, as a special form of energy, propagates through pressure fluctuations in elastic media. It can be classified as infrasound (f < 20 Hz), sound (audible) (20Hz < f < 20 kHz), and ultrasound (f > 20 kHz) according to the frequency of pressure pulsation. Over the frequency of 20 kHz, low frequency, high frequency and very high frequency ultrasounds can be observed as schematically described in figure 1. Ultrasonic applications are rigidly classified into low-and high-intensity applications. The low-intensity ultrasound is typically in the megahertz frequencies with acoustic power up to milliwatts. Figure 2 provides a qualitative summary of the various application of ultrasounds at medium power range. The power of 10 W can be considered as a reference level for distinguishing between low and high power ultrasounds. The high-intensity ultrasound is of low frequencies (from 20 to 40 kHz).

![Figure 1. Classification of ultrasounds](image1)

![Figure 2. Utilizations of ultrasound according to frequency and power.](image2)
Ultrasound are usually employed for communication, medical diagnosis, fetal imaging, underwater finding (SONAR) and non-destructive testing. Some special effects are induced by power ultrasound during its transmission through media. Pressure waves caused by ultrasound transmitted in a medium cause an oscillation of the molecules around their mean position determining alternating compression and decompression of the medium. Considering the heat transfer intensification, in the specific literature on the subject, three main kinds of fluids have been taken in consideration:

1. **gas or a mixture of gasses**, for example oxygen, nitrogen, air etc.;
2. **single phase fluid**, for example liquid water in standard conditions;
3. **two phase fluid**, for example liquid and vapor (as in boiling and condensing regimes).

In the cases of liquid or two-phase fluid it is also important to take in consideration the presence of dissolved gases in the liquid (in particular air); these dissolved gases may cause the insurgence of a specific convective transfer alteration mechanism. The mechanical effects induced by ultrasound when it transmits through medium are typically cavitation in liquids and acoustic streaming in liquid or gas. But different secondary effects can be also observed. In liquid medium, when ultrasonic power attains a threshold, the rarefaction cycle may exceed the attractive forces. In such a case, cavitation bubbles could appear from existing gas nuclei. Propagation of high-frequency acoustic wave waves, especially in a liquid results in cavitation and acoustic microstreaming which improves the heat transfer conditions substantially (figure 3).

Cavitation is the formation of small bubbles due to local pressure decrease and their subsequent growth and collapse. The implosion of these bubbles results in microscopic hydrodynamic phenomena such as micro-jet formation, shockwave propagation and thereby micro-mixing of the liquid that induce positive effects on the local heat transfer coefficient. The intensity of cavitation and its effects depend on the characteristics of the medium, such as viscosity, and process variables, like ultrasonic intensity, ultrasonic frequency or pressure. In gas media, power ultrasound can produce intense effects on the interfaces, such as pressure variations or micro-stirring, which can affect the mass transfer even if more limited effect on the intensification of heat transfer can be observed. The influence of several factors (amplitude of ultrasonic waves, external static pressure, temperature and viscosity of medium) acting, either individually or in combination can influence in an important way the amount of power transferred from the surface to the fluid. Analyzing the various studies in the literature, it might be concluded that, mainly in case of liquids, both in single phase and in two-phase conditions, the ultrasonic field often results in overall heat exchange transfer coefficient enhancement.

![Figure 3. Four effects resulting from ultrasound propagation in a liquid](image)

In order to quantify the effect of ultrasound on the heat transfer coefficient, an enhancement factor $EF$ is usually defined. This can be considered as the ratio of the value observed with ultrasound divided by the value under silent conditions. In the case of a thermal control system, it corresponds to the ratio of the overall heat transfer coefficient in the presence of ultrasonic waves divided by the overall heat transfer coefficient without ultrasound $U$ for the same hydrodynamic configuration:
A theoretical prediction of the effects of ultrasound on heat transfer is not fully available and a lot of analysis in the literature are based on experimental results. In general, it can be observed that ultrasound is an efficient way to enhance heat transfer performances of liquid flow in laminar regime up to that usually observed for turbulent flow conditions. On the other hand, a theoretical analysis of the problem and the definition of the heat enhancement effect of ultrasounds appear to be really complex: the extremely fast and small-scale phenomenon have interaction with turbulence inside the fluid. Moreover, the problem can be complicated by the fact that the acoustic field propagations could be sensitive to fluid property variations and by the complex geometry involved. Anyway, the heat transfer enhancement factor surely depends on the following elements:

- the fluid under analysis and its phase (liquid, gas, vapour);
- the operating conditions of the fluid (subcooled, saturated, subcooling degree etc.);
- the ultrasonic frequency of the generator, f;
- the ultrasonic generator power, $P_{\text{gen}}$;
- the heat transfer surface characteristics;
- the geometry of the system;
- the material of the surface determining the possible formation of chemical substances.

### 3. Heat transfer enhancements by means of ultrasounds: available experimental results

Several authors have investigated the heat transfer enhancement due to ultrasonic waves using different fluids and in different operating conditions. The studies on the heat transfer enhancement by means of ultrasounds, mainly focused on measuring the heat transfer rate change with such experimental parameters as the vibration frequency, the distance between the vibration transducer and heat source. Moreover, the heat transfer enhancement depends on a great number of conditions, such as ultrasonic wave power and frequency, dimension of heated wire, chamber dimension and liquid properties, affect the heat transfer enhancement degree. In each experimental analysis, exposed in the literature since the 60s, considerable efforts to investigate the effects of individual parameter changes, like the fluid have been made. Furthermore, without generalization of those observations into reduced or dimensionless parameters, the collection of experimental data showing the influence of the factors above is severely limited unless the same conditions are realized in applications. Obviously they affect flow in a variety of ways depending on the liquid conditions. In the following sections some details about different combinations of fluid and operating conditions are discussed.

#### 3.1. Enhancement of natural convection heat transfer

The effect of ultrasounds on heat transfer enhancement in natural convection is the first topic covered in the literature. The cases of gas and liquid can be considered. In the case of gaseous medium, the scientific literature reports three main phenomena of convective heat transfer alteration caused by an acoustic field: thermo-viscous dissipation of acoustic field, acoustic streaming and acoustic alteration of thermal boundary layer. In the case of liquid, all three phenomena described above for the gas medium are still present, with the only difference that, cause to their low compressibility, the acoustic alteration of thermal boundary layer is less important. Moreover, in this case are involved phenomena which are not present in the case of gas: vaporous and gaseous acoustic cavitation and anti-fouling effect of acoustic cavitation. General analysis on the topic are reported in [16, 18].

Even if the case of fluid in a single phase could be evaluated by means of theoretical calculation, the case is not particularly considered in experimental investigation except that in some specific papers, as [19, 20]. In the papers the authors report an average percentage increase of the heat transfer coefficient between a minimum of 18% and a maximum of 24%. This could not be considered too significant from the point of view of the heat transfer enhancement, because the calculated error on the evaluation of the heat transfer coefficient is around 12%.
3.2. Enhancement of subcooled boiling heat transfer
A paper by Li et al. [21] represents a good reference work for the topic. The experimental analyses remark that increase of the heat transfer coefficients up to 2.5-2.6 times can be observed for liquid in subcooling conditions both with water and refrigerants. Interesting heat transfer enhancements can be observed in case of evaluation of convection heat transfer of liquid flowing inside pipes, as in [22].
Yamashiro et al. studied experimentally the rapid quenching of a thin platinum wire 0.5 mm in diameter to water, in sub-cooling boiling conditions. They clarified the influence on the heat transfer rate of the sound pressure level, the cavitation phenomenon, and acoustical streaming. They varied the heat flux per unit surface, the ultrasonic generator power, the ultrasound frequency, and the working fluid level inside the ultrasonic tank, [23]. Bartoli et al. [9-10] consider the water sub-cooling degree (ΔT_{sub}) as the most important variable. Considering distilled water, the average percentage heat transfer enhancement started from 41% at ΔT_{sub} equal to 45 C, reached the maximum point, corresponding to 57% at 25 C, and then started to decrease dramatically up to 15% at 10 C. The best conditions occurred at T_{sub} equal to 25 C, f = 40 kHz and P_{gen} = 500 W: at the heat flux per unit surface equal to 1.2x10^5 W/m^2 the heat transfer coefficient enhancement is equal to 62%. These results seem to be promising about the use of ultrasounds in thermal problems. Before of their practical application, the working fluid will be replaced with a dielectric fluid, commonly used in electronic cooling.

3.3. Enhancement of saturated boiling heat transfer
The case of boiling liquid medium is the most complicated one: with this kind of fluid all the typical phenomena are present. The tests in saturated pool boiling, exposed in some basic works like [2] and [6] shows as the ultrasounds does not really increase the heat transfer coefficient, even if the critical heat flux can be reached at higher heat flux than in the absence of ultrasonic waves. Heat transfer coefficient doesn’t change significantly with or without ultrasound in saturated boiling even some effect can be observed. A detailed analysis of the problem is provided in a paper by Park and Bergles, [24] and more recently by Kim et al, [25] that compare the effects of ultrasounds in pool boiling with the same in natural convection.

4. Applications of ultrasound to heat exchangers: analysis of the available results
Heat exchangers have at least two fluids (flowing or at rest), which makes systems sometimes a more difficult task to study the effect of ultrasound as enhancement factor. The vibrational energy could be provided in the heat exchanger by two ways: directly to the fluid, that is the acoustically exited system; to the solid structure of the heat exchanger, that is the mechanically exited system.
Indeed, it must be observed that they are subjected to several constraints, and ultrasonic vibrations have influence on various parameters (e.g., heat transfer, fouling, and charge losses). But the presence of two fluids made possible a more remarkable enhancement effect as it can be observed in Table 1, showing the enhancement obtained for two particular water-water heat exchangers. The heat transfer coefficient intensification is surely the first element that need to be considered in order to evaluate the effect of ultrasound if applied to the heat exchangers. As previously reported, it was shown that concerning a single fluid, the overall heat transfer coefficient can be increased up to 2.5 times with ultrasounds.

Table 1. Enhancement factor of the heat exchangers versus cold water flow rate: influence of the hot water flow rates for a double-tube heat exchanger (a) and for a shell-and-tube heat exchanger (b). [26]

| Cold water flow rate [L/min] | Enhancement factor (Double tube heat exchanger) | Enhancement factor (Shell and tube heat exchanger) |
|-----------------------------|-----------------------------------------------|-----------------------------------------------|
| 0.15                        | 2.10 – 2.60                                   |                                               |
| 0.20                        | 2.05 – 2.40                                   |                                               |
| 0.25                        | 1.80 – 2.30                                   | 1.95 – 2.20                                  |
| 0.40                        | 1.60 – 2.20                                   |                                               |
| 0.50                        | 1.55 – 2.00                                   | 1.60 – 1.80                                  |
| 0.60                        | 1.60 – 2.05                                   |                                               |
| 0.75                        | 1.45 – 1.90                                   | 1.35 – 1.50                                  |
| 1.00                        | 1.50 – 1.60                                   | 1.15 – 1.30                                  |
Considering a system like a conventional heat exchanger, in which two fluids operates, combining the increased effect on both the side an enhancement of more than two times can be easily pursued. In the recent literature analysis of three different heat exchanger configuration can be evidenced: double-tube heat exchanger [26, 27], shell and tube heat exchanger [28] and brazed plate heat exchanger [29]. In all the cases the authors demonstrate that the increase of overall heat transfer coefficient could be remarkable, mainly if some particular conditions are maintained. It was observed that the use of ultrasonic vibrations be a powerful technique to enhance the heat transfer rate both for a double-tube heat exchanger and for a shell-and-tube heat exchanger. In order to compare heat transfer, with and without ultrasounds, energy balances are used being the tested heat exchanger in steady state condition. Without ultrasounds, the energy balance is classically given by Eq. (2), in which the pédices identifies cold (c) and hot fluid (h), taking into account an additional term $q_{env}$ corresponding to heat losses to the environment, negligible if the heat exchanger is well insulated:

$$q_c + q_{env} = q_h$$  \hspace{1cm} (2)

In the presence of ultrasound, the energy balance takes into account the ultrasonic power $P_{US}$ supplied to the system to generate ultrasounds; therefore, the energy balance is written as in Eq. (3):

$$q_c + q_{env} = q_h + P_{US}$$  \hspace{1cm} (3)

4.1. Double-tube heat exchanger

The first system of interest is the double-tube heat exchanger of the typical schematic configuration presented in figure 4. It can be operated in parallel flow configuration and/or in vertical position. This kind of configuration is object of attention of papers, like [26, 27]. According to the balance equation, typical heat transfer intensification can be illustrated by values of heat flowrates according to data of Table 2. Analyzing the data obtained by the authors, it can be observed that an increase of the heat transfer coefficient up to 100% can be obtained and this mainly for a quite low mass flow rate.

![Figure 4. Sketch and dimensions of the vibrating double pipe heat exchanger (dimensions in mm)](image)

Table 2. Examples of heat flowrates with and without ultrasound at both sides of the double-tube heat exchanger for a hot water flowrate in the inner tube of 2 L/min in a counter-flow configuration. [26]

| Cold water flowrate [L/min] | $q_c$ [W] | $q_{c, us}$ [W] | $q_h$ [W] | $q_{h, us}$ [W] | $P_{us}$ [W] |
|-----------------------------|-----------|-----------------|-----------|-----------------|------------|
| 0.20                        | 95        | 216             | 95        | 153             | 70         |
| 0.40                        | 136       | 285             | 135       | 210             | 79         |
| 0.60                        | 163       | 332             | 158       | 254             | 85         |
| 1.00                        | 201       | 400             | 197       | 310             | 109        |
| 1.50                        | 243       | 428             | 237       | 324             | 108        |
| 2.00                        | 268       | 462             | 269       | 355             | 106        |
| 2.50                        | 295       | 479             | 291       | 376             | 101        |
| 3.00                        | 318       | 499             | 312       | 392             | 103        |
| 3.50                        | 337       | 512             | 331       | 426             | 100        |
| 3.75                        | 345       | 515             | 334       | 436             | 99         |
The comparison of the overall heat transfer coefficient without and with ultrasound indicates important increase due to ultrasounds, at least in the fluid flowing in the annular space.

4.2. Shell-and-tube heat exchanger

A special configuration of shell and tube heat exchanger using ultrasound as enhancement effect has been examined in [28]. The shell side of this exchanger vibrates at a given low ultrasonic frequency (35 kHz) resulting in what might be regarded as a vibrating shell-and-tube heat exchanger.

Experiments carried out in [28] and estimations of the overall heat transfer coefficient based upon the energy balance demonstrates that with ultrasounds, heat flow rates are increased at both sides of the heat exchanger. The authors show that the enhancement of the overall heat transfer coefficient ranges from 120 up to 250%. It is shown that the enhancement of the overall heat transfer coefficient due to ultrasound is not sensitive to the ultrasonic power supplied at the shell side. Low ultrasound amplitude results in a significant enhancement of the heat transfer. Furthermore, the enhancement factor strongly depends on the cold water flow rate at the shell side while it seems not to depend on the hot water flow rate in the tube. Figure 5 provides the results obtained in terms of overall heat transfer coefficients for both double pipe heat exchanger and shell and tube heat exchanger.

![Figure 5. Overall heat transfer coefficient versus cold water flow rate: a comparison of double tube and shell and tube heat exchanger [28]](image)

4.3 Plate heat exchanger and compact heat exchangers

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 [19, 20]. This configuration has a specific application in the plate heat exchangers that has a great interest for a lot of industrial and civil applications (like a district heating systems).

The intensification of heat transfer in plate heat exchanger have been investigated in [29]. In particular, a classical double-tube heat exchanger and an industrial brazed plate heat exchanger have been considered as object of the analysis. Considering the three cases under analysis, the optimal settings for a pronounced enhancement for both configurations appear to be a slow laminar flow. Improvement of heat exchanger operation using ultrasound in compact heat exchangers is reported in [30].

5. Use of ultrasounds for anti-fouling

Fouling usually exists in industrial heat exchangers mainly when water is used as working fluid. Fouling not only decreases heat transfer performance seriously, but also reduces the life of heat transfer equipment. The anti-fouling effect of ultrasound is mainly connected with acoustic cavitation: this is interesting, being indeed an indirect convective heat transfer enhancement mechanism due to acoustic cavitation (both vaporous or gaseous). It is especially remarkable that some recent works on the
application of ultrasound in heat exchanger usually claim improvement not only for heat transfer coefficient but for pressure drop reduction or anti-fouling properties too. Moreover, the hydrodynamic actions originated from bubble implosion induce high mechanical strains in this fouling layer, making possible in some cases its disintegration and removal (and, therefore, a global increase of efficiency).

In a recent work, [31], Legay et al. reports experimental studies about fouling reduction by ultrasound inside a double-pipe heat exchanger. They tested 4 different combination of material geometry of the internal tube (5.6 mm and 6 mm of internal diameter and 10 mm or 12 mm of outer diameter of the internal tube). The results are shown in figure 6: after 20 minutes, a remarkable increase of the overall heat transfer coefficient, meaning a reduction of resistance due to fouling, can be evidenced.

In a recent paper Chen et al. [32] analysed, by means of an experimental analysis, the antifouling effect of ultrasound in a heat exchanger operating with water at different temperatures. The parameters of ultrasound were controlled in the frequency range (28–40 kHz) and power of 25 and 50 W. As exposed in Tables 3 and 4 the fouling resistance appears to be dependent on the ultrasound frequency as well as on the ultrasound power and on the initial hardness of water (expressed in mg/L). The results show that ultrasound has remarkable antifouling effects and propose similar conclusion with those exposed in [31].

Moreover in this case the authors analyse the effects of frequency: it is possible to state that antifouling rate increases with decreasing of ultrasonic frequency. Whereas a contrary trend was observed for ultrasonic power, i.e. a higher antifouling rate was reached with a power of 50W.

The use of ultrasound to prevent fouling is discussed with reference to a plate heat exchanger too [33].

![Figure 6](image)

**Table 3.** Fouling resistance at different ultrasound frequencies at T=44 °C [32]

| Time of exposure [hours] | No ultrasound | 28 kHz | 40 kHz |
|------------------------|---------------|--------|--------|
| 5                      | 1.20 10⁻⁴ m²K/W | 1.00 10⁻⁴ m²K/W | 1.10 10⁻⁴ m²K/W |
| 10                     | 1.80 10⁻⁴ m²K/W | 1.40 10⁻⁴ m²K/W | 1.60 10⁻⁴ m²K/W |
| 15                     | 2.00 10⁻⁴ m²K/W | 1.55 10⁻⁴ m²K/W | 1.80 10⁻⁴ m²K/W |
| 20                     | 2.10 10⁻⁴ m²K/W | 1.60 10⁻⁴ m²K/W | 1.95 10⁻⁴ m²K/W |
| 25                     | 2.20 10⁻⁴ m²K/W | 1.70 10⁻⁴ m²K/W | 2.00 10⁻⁴ m²K/W |

**Table 4.** Fouling resistance variation with ultrasound power at the optimal frequency 28 kHz [32]

| Time of exposure [hours] | No ultrasound | 25 W   | 50 W   |
|------------------------|---------------|--------|--------|
| 5                      | 1.10 10⁻⁴ m²K/W | 0.60 10⁻⁴ m²K/W | 0.25 10⁻⁴ m²K/W |
| 10                     | 1.15 10⁻⁴ m²K/W | 0.65 10⁻⁴ m²K/W | 0.30 10⁻⁴ m²K/W |
| 15                     | 1.10 10⁻⁴ m²K/W | 0.65 10⁻⁴ m²K/W | 0.25 10⁻⁴ m²K/W |
| 20                     | 1.05 10⁻⁴ m²K/W | 0.60 10⁻⁴ m²K/W | 0.25 10⁻⁴ m²K/W |
| 25                     | 1.00 10⁻⁴ m²K/W | 0.60 10⁻⁴ m²K/W | 0.25 10⁻⁴ m²K/W |
6. Conclusions
The use of ultrasounds appears to be an effective mean to improve the heat transfer performances of fluids and can attract specific interest for some special applications like heat exchangers. In the case of gas, current literature has identified the occurrence of three phenomena of convective heat transfer modification: the heat dissipation of the introduced vibrational energy (thermo-viscous dissipation of acoustic field); the alteration of the mean flow trajectories (acoustic streaming); the intensification of conductive heat transfer in the thermal boundary layer (acoustic modification of thermal boundary layer). With liquids, other three phenomena can be identified: the alteration and mixing of fluid flow in the thermal boundary layer, through the implosion of low pressure vapor bubbles (vaporous acoustic cavitation), a similar alteration of vaporous acoustic cavitation, but through the implosion of low pressure gas bubble (gaseous acoustic cavitation) and the removing of fouling layers by the mechanical stress inducted by acoustical cavitation (anti-fouling effect of acoustic cavitation).
In the case of two-phase fluid in boiling conditions, all the six phenomena exposed above are still present. Furthermore, a new peculiar phenomena can be identified: the destabilization of the vapor bubble on the heating surface and its facilitated detachment (acoustic release of vapor bubble).
Considering the various phenomena, it is not easy to develop a theoretical analysis of the problem; an adequate mathematical description is very difficult to be obtained due the complexity of the phenomenon and there is also a strong uncertainty about the possibility of using the theoretical results in real application. For the above mentioned reasons the authors that have considered the problem thinks that an experimental backup is highly desirable. But experimental investigation is often limited to quite specific cases and it would take a very long time to cover a meaningful extension of the results. However results obtained in specific conditions indicates that increase of the heat transfer coefficient of 200% in natural convection, 400% in subcooled conditions and of 50% in saturated pool boiling can be reached.
Considering the case of heat exchangers, a promising interesting field of application for ultrasound is represented by the control of heat transfer coefficient in consequence of a reduction of the mass flow rate. In this case the perspective of a possible regulation of the heat transfer coefficient as a consequence of mass flow rate decrease in off-design conditions and the control of fouling effects represents elements of particular interest and suggest the opportunity of further investigations, mainly in case of liquids.

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