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Heat Transfer Enhancement due to Acoustic Fields: A Methodological Analysis

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Abstract: The aim of this paper is to expose the main involved physical phenomena underlying the alteration of convective heat transfer in a heat exchanger subjected to imposed vibrations. This technique seems to have interesting features and industrial applications, such as for efficiency increases, heat transfer rate control and cleanliness action. However, a clear description and comprehension of how vibrations may alter the convective heat transfer coefficient in a heat exchanger has still not been reached due to the complexity of the involved physical mechanisms. For this reason, after a presentation and a schematization of the analyzed thermodynamic system, the fundamental alterations of the thermo-fluid dynamics fields are described. Then, the main involved physical phenomena are exposed for the three cases of gaseous, monophasic liquid and boiling liquid mediums. Finally, on the basis of the characteristics of these described phenomena, some considerations and indications of general validity are presented.

Keywords: heat exchangers; heat transfer enhancement; acoustic fields; vibrations; thermo-fluid dynamics; fouling mitigation

1. Introduction

The influence that the acoustic field has on convective heat transfer has attracted the interest of the scientific and technical community since the 1930s, with the pioneering works of important authors such as Martinelli and Boelter [1]. Starting from the 1960s, intense research activity, mainly experimental, has been carried out.

The aforementioned research activity led to contributions that can be subdivided in two different categories of works.

The first category deals with the study (almost completely experimental) of the physics of phenomena in very simplified configurations, with the primary purpose of clarifying which are the mechanisms underlying the convective heat transfer alteration. A lot of cases are available that involve different fluids in different regimes of flow, for example: gas in natural convection [2–8], gas in forced convection [9–12], liquid in natural convection [13–18], liquid in forced convection [19–23] and liquid in pool-boiling [24–28]. The results obtained are very interesting.

Considering the results exposed in the different papers it is possible to observe that the increase of convective heat transfer coefficient can reach maximum values close to 1000%, but this value is largely dependent on the experimental conditions (for example frequency and amplitude of oscillations, temperature and pressure of work, speed of the fluid etc.) and can reach minimum values under 10%.

From a general prospective, it is possible to observe that the liquid, in particular in subcooled conditions, is the medium for which the maximum increments are reached, though not negligible results have been gained for air and boiling; the lower the speed of the fluid, the higher the measured increments (so that the best conditions are for, in the order, natural convection, laminar regime and turbulent regime); the highest increments are reached giving vibrational energy directly to the heating surface rather than to the fluid in convection. Even though this achieves good results, some problems are still present: there is a great variability in results among the different articles considered in the paper [2–28], indicating that similar experimental conditions may lead to very different convective heat transfer enhancements; there is not agreement on what is the fundamental physical mechanism of alteration, while each author tries to give their own explanation of involved physics; no mathematical model able to quantitatively predict the convective heat transfer has been developed yet. A possible practical application of the enhancement of heat transfer using ultrasounds is observed in the cooling of electronic components.

The second group of papers deals instead with the experimental study of the effects that voluntary vibrational exiting of a heat exchanger can have on its global operation. In these studies, a preexisting heat exchanger is subject to excitation forces giving energy to its structure, and its behavior is then compared with that in absence of vibrations. There are two main lines of investigation. First of all, the increase of the global efficiency of the heat exchanger is measured in some papers by Legay and coworkers [29–32]: the results are very interesting, because in some configurations an increase close to 300% of the heat transfer coefficient is observed in typical configurations of heat exchangers. However, there is still no a clear understanding of the fundamental physical mechanism of alteration in the heat exchanger, and therefore which are the most favorable working and transducing conditions necessary for gaining a good enhancement.

The second line of investigation is concentrated instead on the possibility of cleaning up a fouled liquid to liquid heat exchanger employing the effects of acoustic cavitation [33–35].

Once again, the results are very interesting: almost a complete cleaning of the heat exchanger is possible without stopping and opening the device. Summarizing, the use of vibrational excitation in the heat exchangers seems to be an interesting engineering application. It could be used for:

(1) increasing the global efficiency of the heat exchanger;
(2) controlling the heat exchanging rate (by varying the power of transduction);
(3) keeping clean the heat exchanger without the need of frequent stops.

Nevertheless, it's still not clear how to choice position, frequency and energy of vibration to get a good and efficient action.

With the purpose of giving a clear background of the physics of the phenomenon, in this article the problem is approached by using the fundamental point of view of applied thermodynamics. After initial definitions of the thermodynamic system in analysis, the generic modifications of the different thermo-fluid dynamics variables are presented and discussed both for laminar and for turbulent flows. Then, these generic modifications are used for describing and discussing the main involved phenomena of convective heat transfer alteration for the three mediums of gas, monophasic liquid and boiling liquid. Finally, based on the presented physical phenomena, some general considerations and indications are given for each of the three fluid mediums.

2. Heat transfer Enhancements by Means of Acoustic Fields and Ultrasounds: An Analysis of the Available Experimental Results

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 for the same hydrodynamic configuration:

$$EF = \frac{h_g \; with \; ultrasounds}{h_g \; without \; ultrasounds} \tag{1}$$

As discussed in the introductive section, a theoretical prediction of the effects of ultrasound on heat transfer is not fully available and a lot of analysis in the literature is 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 the level 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, as well as by the complex geometry involved. In any case, the heat transfer enhancement factor surely depends on the following elements:

- the fluid under analysis;
- the phase of the fluid under analysis;
- the operating conditions of the fluid;
- the ultrasonic frequency of the generator, f;
- the ultrasonic generator power, P_{gen};
- the heat transfer surface characteristics;
- the geometry of the system;
- the material of the surface determining the possible formation of chemical substances.

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 1960s, considerable efforts to investigate the effects of individual parameter changes, like the fluid have been made [2–28]. 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 conditions of the fluid. In principle, 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.

The collected data, although in general obtained in experimental apparatuses, appear to confirm, in situations of practical interest, that the enhancement effect of the convective heat transfer coefficient can be remarkable in different specific situations.

In case of gas and liquids the enhancement factor can be very high (average values more than 200%), while being less remarkable in the case of two-phase fluid (average value of about 50%).

High enhancement (average value more than 400%) can be obtained in the case of natural convection, while smaller values (average value of about 120%) can be observed in the case of forced convection. Concerning the type of generation, better results can be observed with mechanical excitation rather than with acoustical excitation.

In Table 1 some details about different combinations of fluid and operating conditions are discussed regarding the various papers considered in the introduction, taking into account only the papers that analyze physical phenomena.

Table 1. An overview of the results obtained in references [2–28].

Reference	Phase	Type of Convection	Type of Generations	Approximate EF Value
[2]	Gas	Natural	Acoustic	75%
[3]	Gas	Natural	Acoustic	100%
[4]	Gas	Natural	Acoustic	1200%
[5]	Gas	Natural	Acoustic	
[6]	Gas	Natural	Acoustic	
[7]	Gas	Natural	Mechanical	400%
[8]	Gas	Natural	Mechanical	
[9]	Gas	Forced	Acoustic	80%
[10]	Gas	Forced	Acoustic	Laminar flow (50%)
[10]	Gas	Forced	Acoustic	Turbulent flow (25%)
[11]	Gas	Forced	Acoustic	25%
[12]	Gas	Forced	Mechanical	130%
[13]	Liquid	Natural	Acoustic	400%
[14]	Liquid	Natural	Acoustic	
[15]	Liquid	Natural	Acoustic	
[16]	Liquid	Natural	Mechanical	
[17]	Liquid	Natural	Mechanical	800%
[18]	Liquid	Natural	Mechanical	30%
[19]	Liquid	Forced	Acoustic	70%
[20]	Liquid	Forced	Acoustic	100%
[21]	Liquid	Forced	Acoustic	90%
[22]	Liquid	Forced	Mechanical	280%
[23]	Liquid	Forced	Mechanical	Laminar flow (450%)
[23]	Liquid	Forced	Mechanical	Turbulent flow (10%)
[24]	Pool-boiling		Acoustic	60%
[25]	Pool-boiling		Acoustic	10%
[26]	Pool-boiling		Mechanical	62%
[27]	Pool-boiling		Mechanical	24%
[28]	Pool-boiling		Mechanical	100%

3. Fundamental Modifications of Thermo-Fluid Dynamics by the Actions of an Acoustic Field

The acoustic field can be imposed with an acoustical transducer, that is a mechanic object which gives vibrational energy to the fluid medium in the control region. In this first case, we would define this ensemble of elements as an acoustically excited system.

The other possibility is the presence of a mechanical transducer, that is a mechanical device which gives vibrational energy to a wall of the control region (and then, from this wall, to the fluid medium). In this case, the ensemble of elements can be defined as a mechanically excited system.

In both the cases the fundamental open question is to understand how the vibrational energy may alter the standard convective heat transfer mechanisms. It's important to observe that, both in the cases of acoustically and mechanically excited systems, there could be more than one inlet or outlet sections, as there could be more than a portion of wall subjected to convective heat transfer.

In the specific literature on the subject, three main kinds of fluids have been taken into consideration:

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

In the cases (2) and (3) it is also important to take into consideration the presence of dissolved gases in the liquid (in particular air): those dissolved gases may cause the insurgence of a specific convective transfer alteration mechanism.

The periodic excitation action of the transducer is assumed to be sinusoidal in time. This action is completely determined if the following two parameters have been specified:

1. the frequency f, i.e., the number of oscillations of the transducer per unit of time;
2. the amplitude δ, i.e., the maximum displacement of the transducer from its relaxed position.

Depending on the frequency of the excitation, the transducer actions may be classified as:

1. infrasounds, if it is $f < 20$ Hz;
2. sounds, if it is 20 Hz $< f <$ 20 kHz;
3. high power ultrasounds, if it is 20 kHz $< f <$ 1 MHz;
4. low power ultrasounds, if it is $f > 1$ MHz.

Infrasounds and sounds are known for generating dangerous acoustic pollution, so it's quite evident that they could not be employed in the majority of applications and that the application of ultrasounds has to be considered [35].

3.1. Laminar Flows

Let's suppose that one of the systems has reached a working condition characterized by a stationary laminar flow. Indicating with ψ the generic scalar thermo-fluid dynamics variable in a generic point $\vec{x}$ of the fluid domain (e.g., ψ could be the temperature, the pressure, a cartesian component of velocity vector etc.), we may imagine the trend of ψ(t) as the one on the left. In this condition, we are saying that the system has reached a laminar equilibrium state.

Let's suppose now that the transducer has been activated for a relatively long time and let's imagine and plot the new trend of ψ(t). In general, the typical trend is represented in Figure 1.

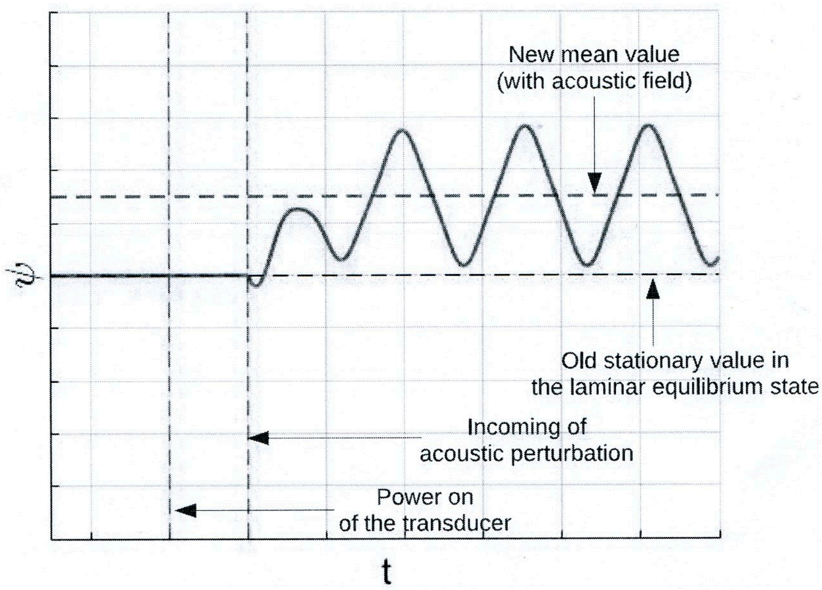

Figure 1. Two different aspects of alteration of the trend of y (laminar flow).

As it's possible to see, there are two different fundamental modifications in the trend of ψ(t):

1. a new mean value of ψ(t), in general different from the old one in the previous equilibrium state can be identified;
2. there is a periodic oscillation of ψ(t), in general (but not always) close to sinusoidal shape.

Each physical phenomenon involved in the alteration of convective heat transfer in a laminar flow may be associated with one of the two above fundamental modifications.

3.2. Turbulent Flows

If the fluid has reached a working condition characterized by a stationary turbulent flow, indicating again with ψ the generic scalar thermo-fluid dynamics variable in a generic point $\vec{x}$

of the fluid domain, it is possible to recall the statistical theory of turbulence of Kolmogorov. According to this theory, the trend of each ψ(t) can be written as the sum of a stationary mean value $\overline{\psi}$ and a randomly fluctuating value $\widetilde{\psi}(t)$:

$$\psi(t) = \overline{\psi} + \widetilde{\psi}(t) \tag{2}$$

so that the trend of ψ(t) is like the one in the Figure 2.

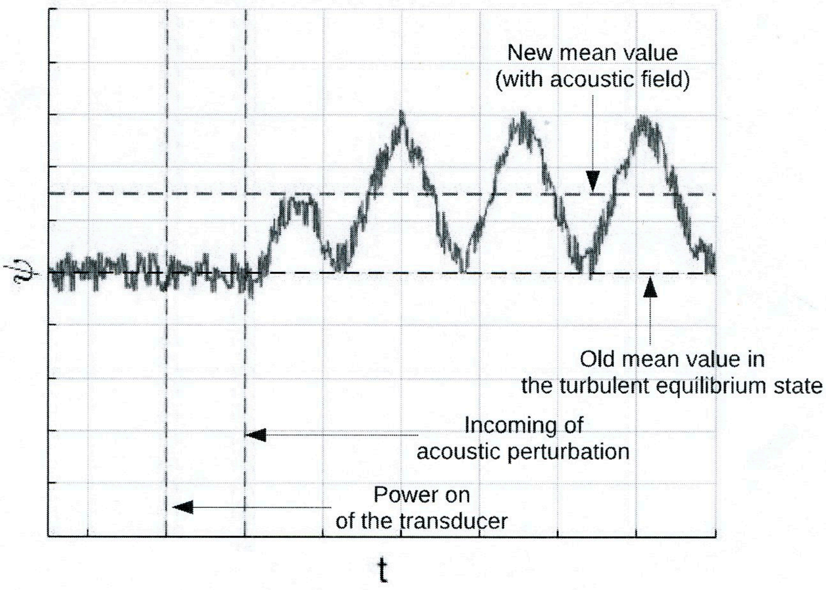

Figure 2. Two different aspects of alteration of the trend of y (turbulent flow).

In this condition, the system has reached a turbulent equilibrium state.

Let's suppose again that the transducer has been activated for a relatively long time and let's imagine and plot the new trend of ψ(t). In this case, there are three different fundamental modifications in the trend of ψ(t):

1. a new mean value of ψ(t) that is in general different from the old one in the previous turbulent equilibrium state;
2. a periodic oscillation of ψ(t), in general (but not always) very close to the sinusoidal shape;
3. a change in the characteristics of random fluctuations, which is a change in the statistical distribution of the frequencies and sizes of vortexes.

Again, it is possible to state that each physical phenomenon involved in the alteration of convective heat transfer in a turbulent flow may be associated to one of the first two fundamental modifications, while the third modification mechanism is not completely understood and, in any case, does not seem to play a key role.

4. Main Involved Phenomena of Convective Heat Transfer Alteration in Presence of an Acoustic Field: The Case of Gaseous Medium

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. The illustration of the different phenomena can be exemplified for an acoustically excited system, but it can be extended without conceptual modifications to the mechanically excited systems.

4.1. Thermo-Viscous Dissipation of Acoustic Field

The phenomena of thermo-viscous dissipation of acoustic field is connected with the second fundamental modification mechanism, in particular with the oscillation of T(t) and of $\vec{v}(t)$. In the first case, in fact, there is a cyclical propagation of heat from compressed zones (at higher T) to rarefied zones (at lower T), so that there is a monotonic production of entropy (and then a monotonic destruction of exergy). Instead, in the second case, the oscillation of $\vec{v}(t)$ causes a cyclical action of frictions, so that there is a monotonic transformation of mechanical energy in internal energy of the gas (and then, again, a monotonic destruction of exergy). In conclusion, this phenomenon may be thought as a perpetual diffusion and transformation of organized mechanical energy provided by the transducer into disorganized internal energy of the continuum mediums: so, a general heating of the gas in the system is expected.

4.2. Acoustic Streaming

The phenomena of acoustic streaming are connected with the first fundamental modification mechanism, in particular with the change of the mean value of $\vec{v}(t)$. Indeed when a gas medium is subjected to an acoustic field, it is possible to observe an alteration of the trajectories of the fluid flow. As such, a macroscopic change of the internal mixing in the fluid domain may be important in determining an increase (or, in principle, a decrease) of convective heat transfer rate.

4.3. Acoustic Modification of the Thermal Boundary Layer

The phenomena of acoustic alteration of thermal boundary layer is connected with the second fundamental modification mechanism, in particular with the oscillation of the component of $\vec{v}(t)$ perpendicular to the portion of wall subjected to convective heat transfer. In fact, it's known from the fundamental courses on heat transfer that the convective heat transfer rate is, strictly speaking, proportional to the inverse of thermal boundary layer thickness:

$$q_{CONV} \approx \frac{1}{\delta_{TBL}} \tag{3}$$

Therefore, it's evident that in the compression phase the convective heat transfer rate increases, while in the expansion phase it decreases. However, supposing that compression and expansion have comparable displacements, it is noteworthy that the mean value in a symmetric interval $[x_M - a, x_M + a]$ of the reciprocal function $y = 1/x$ is greater than the median value $y(x_M)$. By this argument, it is possible to conclude that the acoustic alteration of thermal boundary layer conduces to an increase of the mean convective heat transfer rate.

5. Main involved Phenomena of Convective Heat Transfer Alteration in Presence of an Acoustic Field: The Case of Single Phase Liquid Medium

In the case of monophasic liquid medium, all three phenomena described above for the gas medium are still present, with the only difference that, because of its low compressibility, the acoustic alteration of thermal boundary layer is much less important. Moreover, in this case there are three more involved phenomena which do not manifest in the case of gas. They are: vaporous acoustic cavitation, gaseous acoustic cavitation and the anti-fouling effect of acoustic cavitation.

5.1. Vaporous Acoustic Cavitation

The phenomena of vaporous acoustic cavitation is connected with the second fundamental modification mechanism, in particular with the oscillation of the thermodynamic state P(t) and T(t). To illustrate this phenomena, let's assume first of all that the liquid in the heat exchanger is completely degassed. Let's imagine then and plot in the P-T diagram the local trajectory of the thermodynamic state: when the amplitude is quite big, the fluid locally enters in the vapor state. So, at that point a vapor bubble originates, grows and then, when the compression phase occurs, violently implodes (Figure 3). This violent implosion causes in turns shock waves and jets that, when the implosion happens close to the thermal boundary layer, can sensibly alter the thermal boundary layer, leading to its strong internal mix movements (Figure 4).

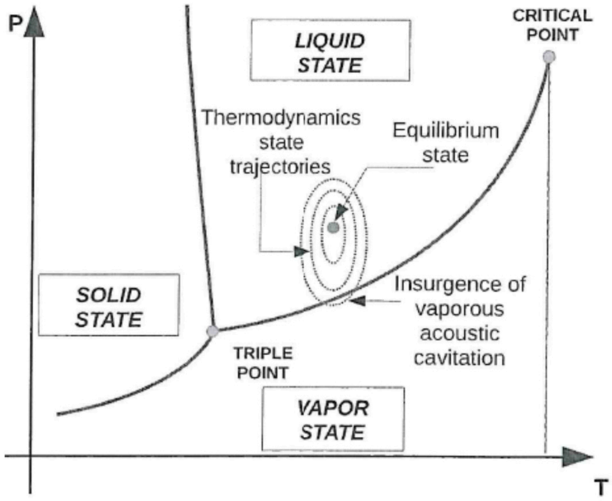

Figure 3. Schematic illustration of the phenomenon of vaporous acoustic cavitation.

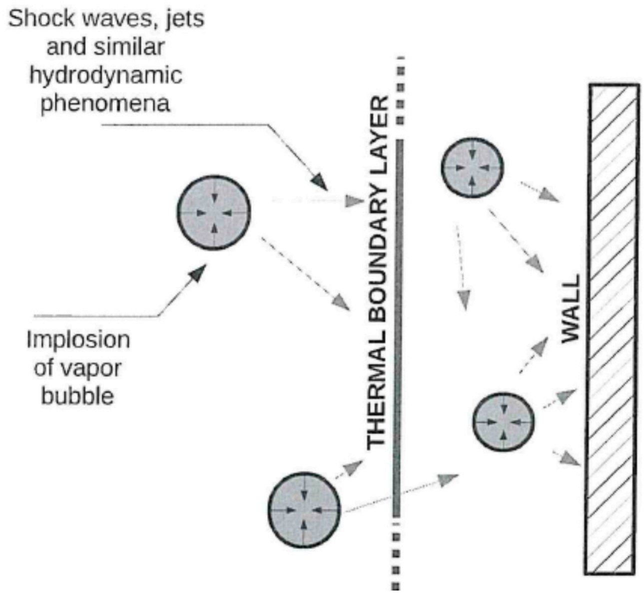

Figure 4. Schematic illustration of the phenomenon of vaporous acoustic cavitation.

5.2. Gaseous Acoustic Cavitation

Similarly to the vaporous acoustic cavitation, the phenomena of gaseous acoustic cavitation are connected with the oscillation of the thermodynamic state P(t) and T(t) too. These two phenomena are very similar to one another, but gaseous acoustic cavitation only happens when the concentration of a gas in the liquid exceeds a minimum value.

To explain this phenomena, it is necessary to recall that for every couple of liquid and gas (in particular for water and air) and for every thermodynamic condition a maximum concentration of gas exists (in terms of g/L) that could be dissolved in the liquid. So, once the concentration of the gas in the liquid is assigned, it is possible to represent a border line on the P-T plane: above this line, the gas is completely dissolved in the liquid and only a phase exists; below this line, the gas separates from the liquid and forms a new phase.

Thus, when the amplitude of the trajectory in the P-T plane is large enough, it is possible for the fluid going below the critical line: a gas bubble originates and then, when the compression phase incomes, violently implodes. In these quick movements, the hydrodynamics effects described above and illustrated in Figure 4 arise again, so that, when close to the thermal boundary layer, an increase of convective heat transfer due to internal mixing is possible. (Figure 5).

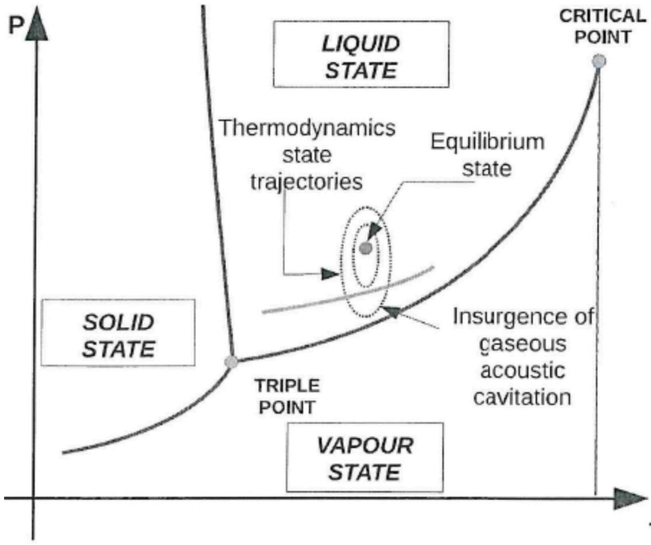

Figure 5. Illustration of the phenomena of gaseous acoustic cavitation (P-T diagram).

5.3. Anti-Fouling Effect of Acoustic Cavitation

The phenomena of anti-fouling effect of acoustic cavitation are quite particular, being indeed an indirect convective heat transfer enhancement mechanism associated with acoustic cavitation (both vaporous or gaseous). It is possible to note that in the working of a heat exchangers, a high thermal resistivity layer (the fouling layer) may originate on the walls of the machine, thus reducing its global efficiency. However, the hydrodynamic actions that originated from the bubble implosion already described below can also induce high mechanical strains in this fouling layer (Figure 6), in some cases making its disintegration and removal possible (and, therefore, a global increase of efficiency).

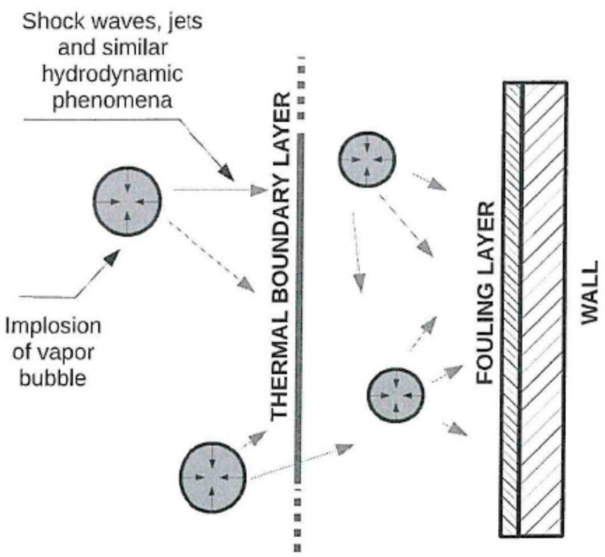

Figure 6. Illustration of the phenomena of anti-fouling effect of acoustic cavitation.

5.4. Considerations about the use of Acoustic Fields as a Way of Convective Heat Transfer Enhancement in the Case of Single-Phase Liquid

The indications given in the previous section for the gas are still valid in the case of liquid medium; moreover, for a good achievement of convective heat transfer enhancement for this kind of fluid, it is possible to

1. originate high pressure oscillations near the portion of wall subjected to convective heat transfer, so that an intense acoustic cavitation may be present there. Furthermore, from this point of view, it is quite evident that the closer the equilibrium state is to the liquid-vapor line, the easier it is to put the liquid in acoustic cavitation;
2. not degas the liquid in the heat exchanger in order to facilitate the occurrence of gaseous acoustic cavitation;
3. originate high pressure oscillation close to the zones more drastically subjected to fouling, so as to guarantee a possible removal of the fouling layer and good prevention of depositing phenomena.

Further considerations can be exposed. First of all, the difficulty of modeling the convective heat transfer process in the presence of an acoustic field is still more drastic in the case of liquid medium: now, three more basic phenomena are involved, phenomena that may in turn strongly alter the precedent thermo-fluid dynamics regime. Furthermore, the presence of two-phase separation surfaces on the bubbles of acoustic cavitation make necessary, for a detailed analysis, the relations of two-phase thermo-fluid dynamics.

Also in this case, it is highly probable that only a systematic experimental analysis could evidence the real characteristics of this enhancement technique. The use of mechanical energy for getting a heat transfer enhancement again seems to make very improbable the possibility of reaching a global higher exergy efficiency. However, in the case of liquid medium, the possibility of removing and preventing the fouling problems is very interesting and could in itself justify the utilization of acoustic fields: the heat exchanger could always work in an almost completely clean manner, with low pressure drops and without the undesirable necessity of frequent cleaning stops. By focusing the attention only on the fouling problem, it is possible to imagine a particular excited heat exchanger that periodically induces acoustic cavitation in all the parts of the walls subjected to convection: in this way, it could be possible to ensure cleaning without the constant spending of mechanical energy.

6. Main Involved Phenomena of Convective Heat Transfer with of an Acoustic Field: The Case of Boiling Liquid

The case of boiling liquid medium is, in all probability, the most complicated one. Indeed, with this kind of fluid medium all the six phenomena described above still manifest, while a new peculiar phenomenon emerges: the acoustic release of vapor bubbles. The phenomena of acoustic release of vapor bubbles is connected with the second fundamental modification mechanism, in particular with the oscillation of the strain tensor T(t) near the part of the wall subjected to convective transfer (Figure 7). In fact, the periodic action of vibrations on the vapor bubble results in an increased instability and therefore in a facilitated release of the bubble itself from the heating surface. In this way, a higher rate of latent heat departs from heating surface, causing so a global increase of convective heat transfer rate. It's important to note that the characteristics of heating surface (in particular its shape and its roughness) are very important both for boiling in presence or in absence of an acoustic field.

The indications given in the previous sections for gas and liquid medium are still valid in the case of boiling liquid; moreover, it is possible to add the further new advice for the purpose of reaching a good convective heat transfer enhancement: originate high pressure oscillations near the portion of wall subjected to convective heat transfer, so that the acoustic release of vapor bubble could be effective there.

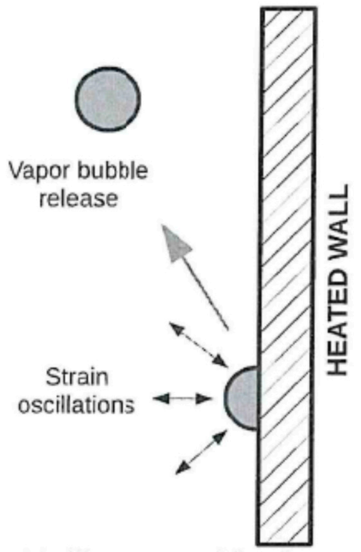

Figure 7. Illustration of the phenomenon of acoustic release of vapor bubbles.

Furthermore, it's quite evident that the complexity of a good modeling and prevision of the influence that vibrations may have in the case of boiling liquid medium reaches perhaps its maximum: not only all the six phenomena described for the other two case still manifest, but the presence of this new particular interaction between bubbles and acoustic fields seems to make farfetched the construction of an accurate forecasting theory. So, again, only an accurate experimental analysis could show the concrete effects that induced vibrations may have on boiling mechanisms.

7. Conclusions

In this article, the possibility of exiting a heat exchanger by using voluntary vibrations has been taken in consideration and analyzed using the fundamental point of view of applied thermodynamics.

The vibrational energy could be provided in the heat exchanger in two ways: directly to the fluid, that is the acoustically excited system; or to the solid structure of the heat exchanger, that is the mechanically excited system. In both cases, the proposed control volume is quite similar to the one usually presented in the standard courses of convective and mass transfer, except for the presence of a new element, which is the acoustical (or the mechanical) transducer. Therefore, with the geometry of the heat exchanger being known, as well as its working conditions and the characteristics of transduction (frequency and amplitude), the next major step is to understand how this new element can influence the convective heat transfer. So, the three fundamental modifications that the different thermo-fluid dynamics fields exhibit are:

(1) the change of the mean value;
(2) the insurgence of an oscillatory trend;
(3) only for turbulent flows, the change of aleatory oscillations characteristics.

Then, the different physical phenomena of convective heat transfer alteration individuated by the authors of bibliography are presented and explained for the three fluid medium of gas, monophasic liquid and boiling liquid. Each of these phenomena has been attributed to one of the first two fundamental modifications above.

In the case of gas, current literature has identified three phenomena of convective transfer alteration: the dissipation in heat 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 rate in the thermal boundary layer (acoustic modification of thermal boundary layer).

In the case of liquid, more than the three phenomena of gas, three other phenomena have been individuated: the violent alteration and mixing of fluid flow, in particular the thermal boundary layer, through the implosion of low pressure vapor bubbles (vaporous acoustic cavitation); a similar violent alteration of vaporous acoustic cavitation, but through the implosion of a low pressure gas bubble (gaseous acoustic cavitation); the removing of eventually present fouling layers by the mechanical stress inducted by acoustic cavitation (anti-fouling effect of acoustic cavitation).

In the case of liquid boiling, all the six phenomena exposed above are still present. Furthermore, a new peculiar phenomenon has been identified: the destabilization of the vapor bubble on the heating surface and its facilitated detachment (acoustic release of the vapor bubble).

Just from this first presentation of the main involved phenomena, some qualitative considerations can be shown.

First of all, it's quite evident that, even in the simplest case of the gas medium, a lot of complicated and interrelated thermo-fluid and thermo-solid dynamics mechanisms are present: an accurate, instantaneous and punctual modeling of these mechanisms is very challenging, while some phenomenological modeling might be possible in specific working conditions for which a particular phenomenon prevails.

In addition, the use of mechanical energy for the purpose of increasing a heat transfer rate seems to determine an increase of energy use. However, in the cases of single phase and boiling liquid, the possibility of working with clean devices could be an interesting industrial application. Moreover, the possibility of a continuum controlling of the global efficiency of the heat exchanger, as well as the preventing and elimination of local hot spots, could be interesting with further features of this technique.

Finally, an extended experimental analysis of the problem is strongly recommended. Particular configurations of voluntary excited heat exchangers should be installed, and the relative increase of efficiency measured as a function of the previous equilibrium state (kind of mediums, Reynolds number, maximum ΔT, average pressure etc.) and of the transducing inputs (frequency and vibrational power).

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Conflicts of Interest: The authors declare no conflict of interest.

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