Convective Heat Transfer Enhancement by Ultrasound

Deniz Filiz
Mechanical Engineering Department
Bogazici University, Bebek, 34342, Istanbul, Turkey
deniz1filiz@gmail.com

ABSTRACT

In recent period, researchers have focused on ultrasound waves which frequencies are higher than the upper limit of the human hearing range,usually around 16 or 20 kHz, in heat transfer applications because it has been found that ultrasonic waves improve heat transfer rate in heat transfer application such ass cooling applications, heat exchangers, temperature control, and so forth. Firstly, this paper presents some applications of ultrasound which related to enhancement of convective heat transfer. And also, this paper summarizes different factor which effect the heat transfer rate by ultrasound. From the literature review, it has been found that enhancement of convective heat transfer is proportional to the ultrasonic power.

Nomenclature

Symbols

μ viscosity $[m\ Pa\ .\ s]$ or $[cP]$
ρ density $[kg/m^3]$
V velocity $\left[\frac{m}{s}\right]$
E energy
P pressure $[Pa]$
c sound velocity
w angular velocity

Subscript

l liquid
v vapor

1. Introduction

Heat transfer processes in industry are the most important issue. Because of that, researchers and engineers want to improve heat transfer rate with various methods. Among these methods, using ultrasound is the efficient and controllable way for enhancing heat transfer rate. Also, ultrasound is used in many different areas such as medical imaging, welding, cleaning and etc.

First examples of researches which are about heat transfer enhancement by ultrasound, are seen in 60s. These are very interesting researches but they can not give promising results for deeper investigation. As shown in Figure 1, since the 90s researchers have given their attention to this topic. Because scientist developed different techniques for investigation.

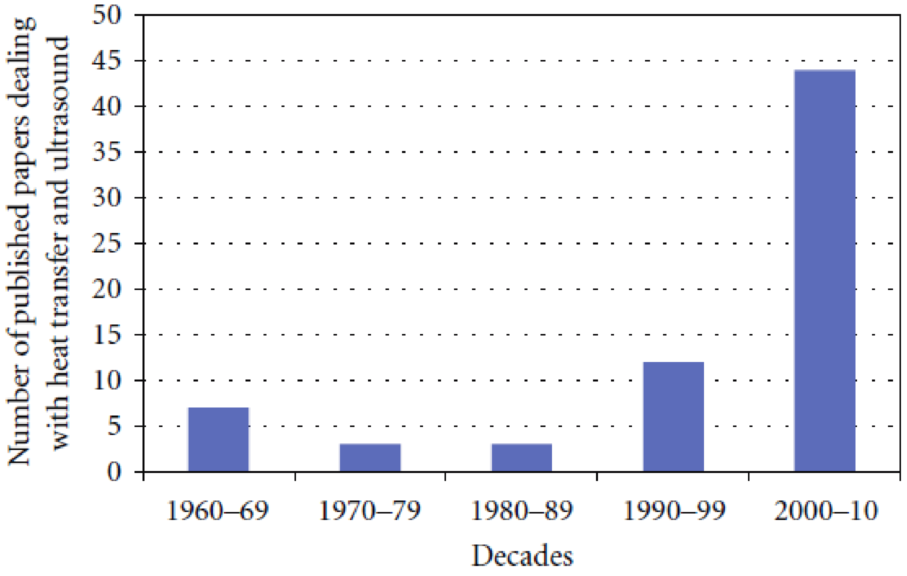

Figure 1: *Number of Publications [1].*

The objectives of this paper are to give information about literature backgrounds concerning heat transfer improvement with ultrasonic vibrations. Firstly, this article gives brief information about ultrasound including how ultrasound enhance heat transfer rate. Then, presents examples in literature. Finally, mentions numerical researches about convection heat transfer by ultrasound.

2. Definition and Mechanism of Ultrasound

Ultrasound have higher frequency than upper limit of human hearing range which is usually around 16 or 20 kHz [1]. According to Figure 2, acoustic waves which have frequency between 20 and 100 kHz, are called power ultrasound. Power ultrasound can cause cavitation or acoustic streaming which are main phenomenas of heat transfer enhancement, in a fluid bulk. It has been found that higher frequency and low power ultrasound is not useful for heat transfer enhancement. It is usually used for medical application.

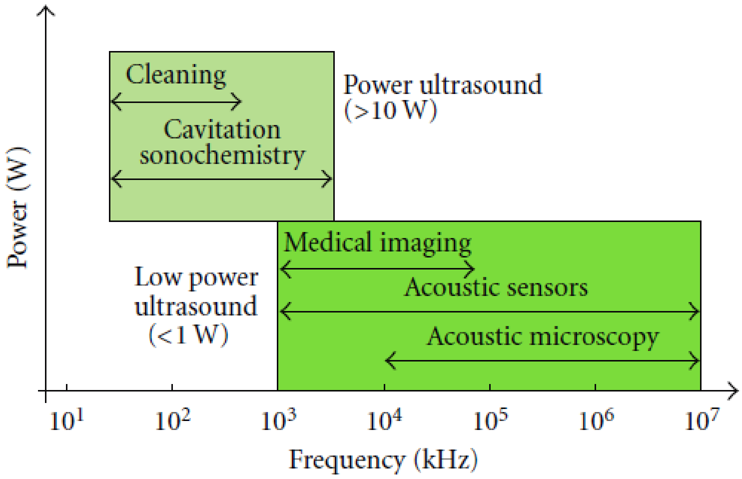

Figure 2: *Usage of ultrasound [1].*

There are 4 major phenomena which are about how can ultrasonic waves effect liquid medium. Two of them which are acoustic cavitation and acoustic streaming, are main reasons of heat transfer improvement. Acoustic streaming which is result of dissipation of acoustic energy, improve speed of fluid currents. As shown in Figure 3, because of the speed improvement, better convection heat transfer coefficient is obtained near the boundaries. And also, this speed enhancement may cause turbulence which improve heat transfer coefficient further. Acoustic cavitation is the formation, growth, oscillations and powerful collapse of gas bubbles into a liquid [1]. During the rarefaction period of the sound wave, the local pressure may decrease below the vapor pressure. Because of that, gas bubbles which are oscillate, grow and then collapse, may occur. Many researchers agree that acoustic cavitation is the major effect of heat transfer improvement. Thermal and velocity boundary layers are deformed by collapsing bubbles. As shown in Figure 3, this can cause decreasing thermal resistance and creating turbulence.

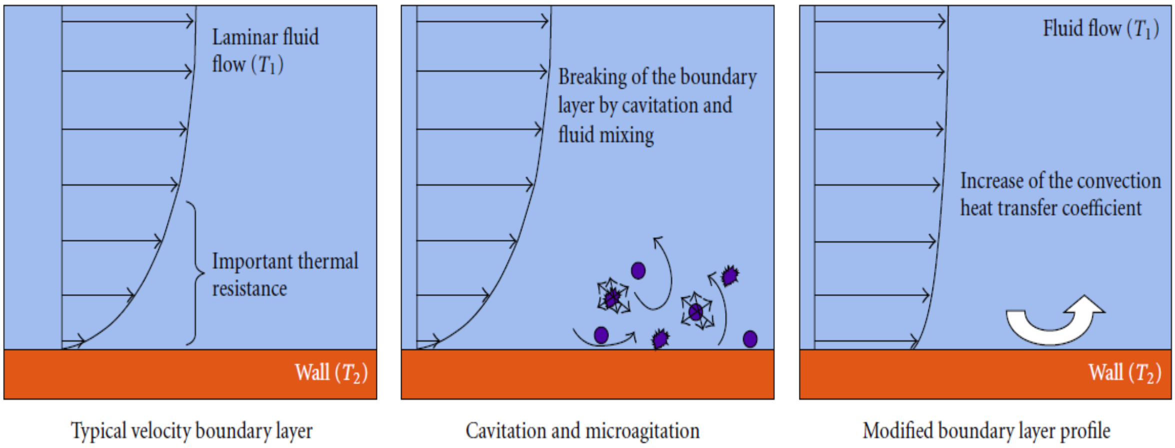

Figure 3: *Effect of ultrasound [].*

3. Literature work about convective heat transfer enhancement by ultrasound

From literature survey, it can be seen that many scientist have interest about convection heat transfer enhancement by ultrasound. Larson [2] states that in his Ph.D. dissertation, acoustic cavitation is the main reason of increasing Nusselt number at the low frequencies, but at high frequencies acoustic streaming is the main reason of enhancement. He investigated natural and forced convection over a sphere.

D. Lee et al.[3] makes an investigation about acoustic streaming which is made by ultrasonic vibrations. They done both numerical and experimental work. They investigated pattern, velocity and heat transfer characteristic of acoustic streaming by using CFD. They observed improvement of velocity near the walls and up to 75% heat transfer rate enhancement.

Dehbani et al. [4] investigated the heat transfer from a thin platinum wire in presence of the 24 kHz and 1.7 MHz ultrasonic waves. They claim that higher frequencies enhance the heat transfer rate better than the lower frequencies. They did some experiment and their findings are shown in Figure 4.

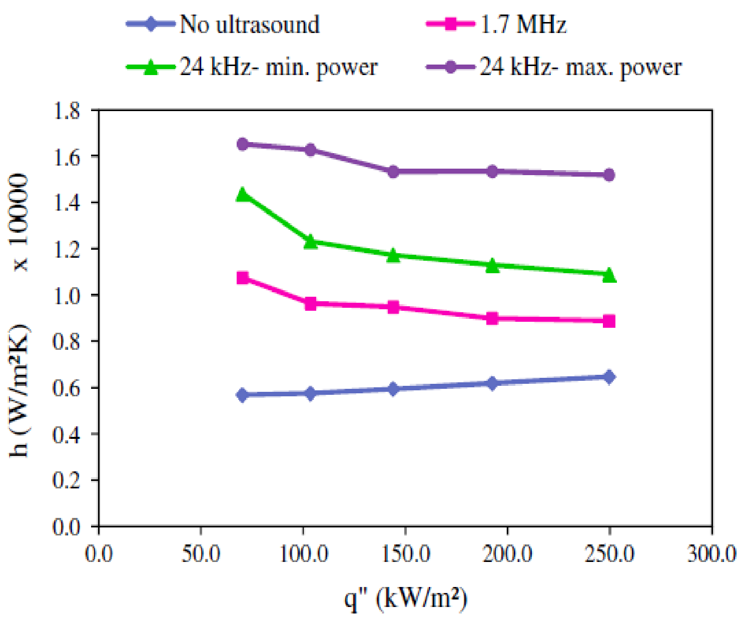

Figure 4: *Heat transfer coefficient with changing ultrasound frequency and power [4].*

Nomura et al. [5] did research about natural convection of water on a downward-facing horizontal surface under the presence of ultrasonic power. They done experiment with 28,45 and 100 kHz ultrasonic waves and claimed that 28 an 45 kHz may cause generation of cavition bubbles which increase heat transfer rate. But for 100 kHz ultrasonic waves, enhancement of heat transfer is small when compared the other frequencies. Figure 5 shows experimental results for the horizontal plate at the bottom of the rectangular object.

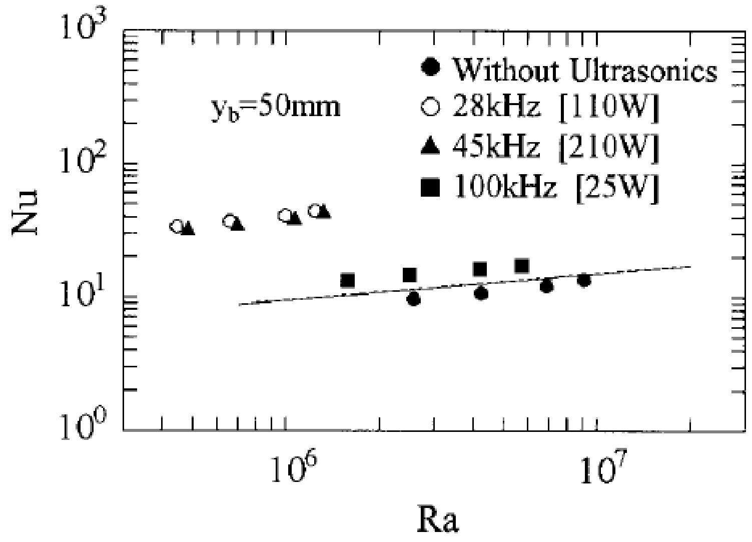

Figure 5: *Effect of ultrasound on Nusselt Number [5].*

O. Bulliard-Sauret et al. [6] did some experiment for studying heat transfer enhancement using ultrasound on a flat plate. They designed an experimental setup to compare effects of low, medium and high ultrasound frequencies with respect to different Reynolds number. Figure 6 shows wall temperature behavior when ultrasound is on at 900 Re number. As it can be understood from figure, ultrasound cause strong decrease of wall temperature. And also, Figure 7a and Figure 7b shows heat transfer coefficient without ultrasound and with ultrasound, respectively. They claim that 1 MHz frequency ultrasound which cause both cavitation and streaming effect has the best improvement on heat transfer coefficient. And also, for 25 kHz ultrasound heat transfer coefficient is high at big Re number because there is strong cavitation effects near the surface.

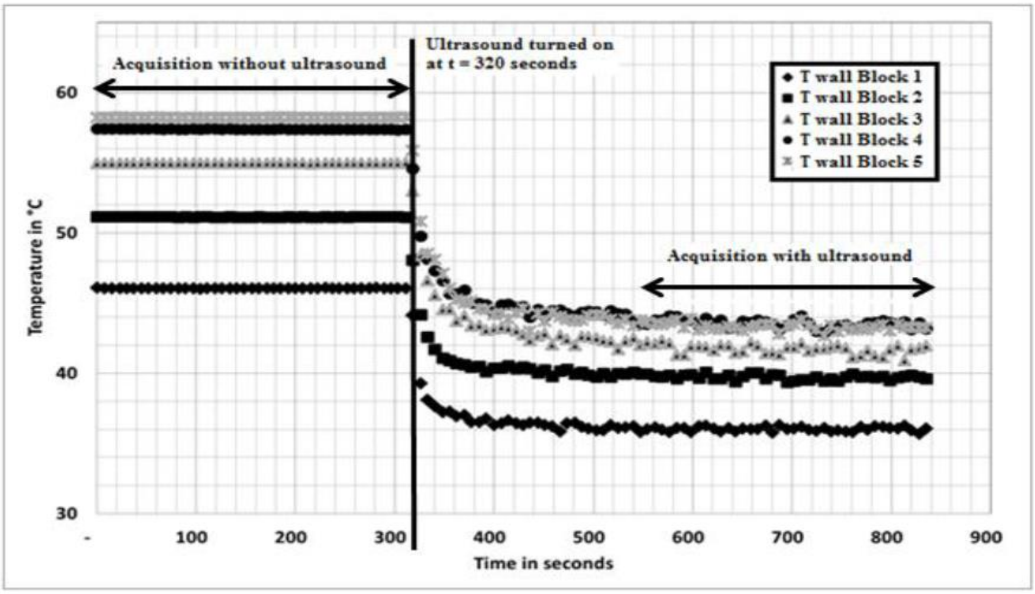

Figure 6: *Wall temperature behaviour with respect to time [6].*

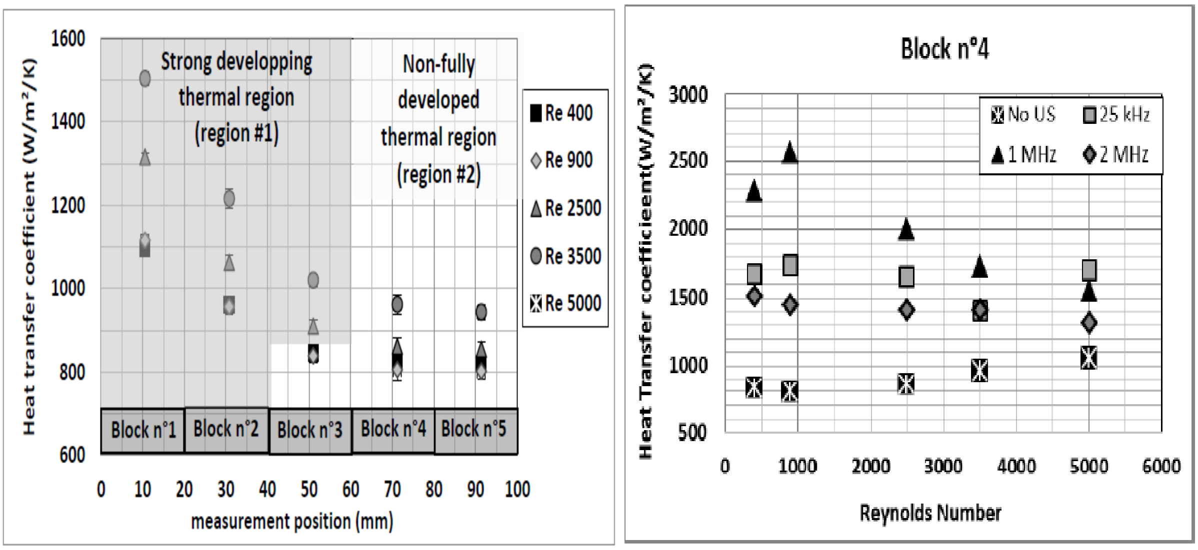

Figure 7a and 7b: *Heat transfer coefficient with and without ultrasound at different location [6].*

Cai et al. [7] did research about effects of acoustic cavitation on natural convective heat transfer from a horizontal circular tube. They claimed that acoustic cavitation causes heat transfer enhancement and best improvement occurs when the head of the ultrasonic transducer is over the midpoint of the circular tube. And also, they obtain the correlation about Nusselt number. Figure 8 shows their result about acoustic cavitation intensity. It is obvious that when the acoustic cavitation intensity increases from 0 to 0.6A enhancement ratio rapidly rises.

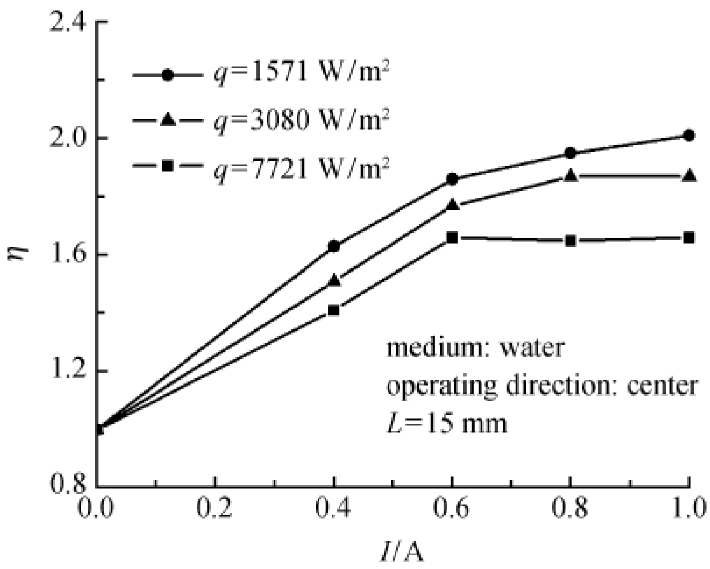

Figure 8: *Enhancement ratio vs acoustic cavitation intensity [7].*

Gould [8] emphasized that when the ultrasound amplitude increases the convective heat transfer rate increases almost linearly for water. However, for more viscous liquids this relationship is non-linear. After the acoustic streaming occurs, heat transfer rate increases 10-fold.

Markov et al. [9] did some experiment with molten metal (1520°C) flow in tube and water to cool the molten metal. They emphasized that when the 20 kHz ultrasound is used the convective heat transfer rate is doubled compared to no ultrasound system.

Monnot et al. [10] performed some experiment with homemade, high-frequency, ultrasonic reactor which has got a cooling helical coil. Experimental setup is shown in Figure 9. They investigated heat transfer between water contained within the reactor and cooling water flowing in coil in presence of ultrasound with different frequencies. They claimed that overall heat transfer coefficient of the coil increased up to 100%. Therefore, cooling rate increased when ultrasound was used. Result of the experiment is shown in Figure 10.

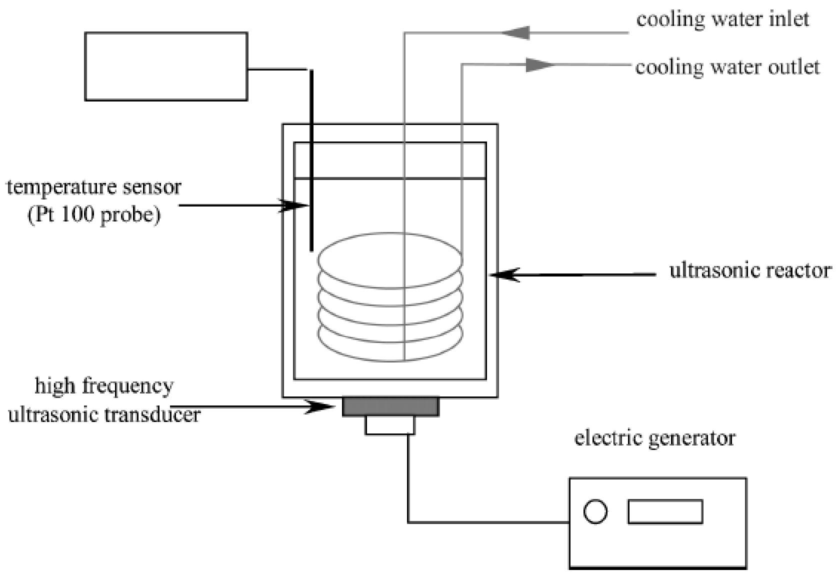

Figure 9: *Experimentall setup [10].*

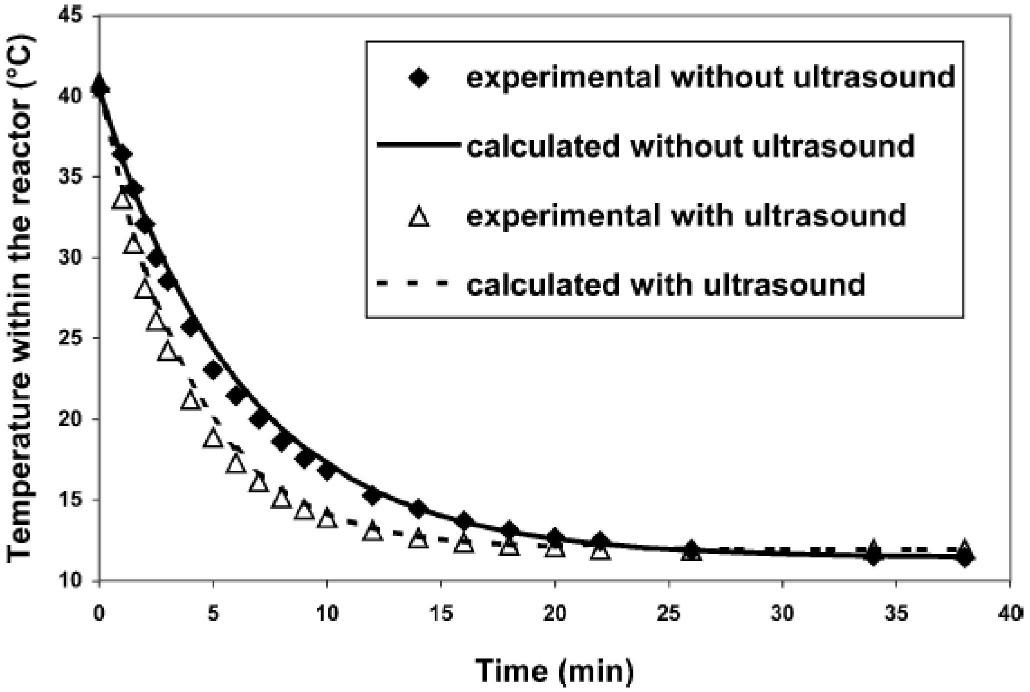

Figure 10: *Temperature in the reactor vs time [10].*

4. Numerical work about convection heat transfer increase with ultrasound

When the ultrasound problem is solved numerically, continuity, momentum, energy and at least one for the streaming forces (Nyborg's Theory) equation must be solved. If the problem involves acoustic cavitation, two phase model (liquid and vapor) must be used for modelling. Also, vibration should be modelled by a moving boundary and dynamic mesh modelling.

From literature work, it has been found that there are a lot of researchers who did research about this topic.

Aktas et al. [11] investigated the convective heat transfer numerically in differentially heated shallow enclosure because of the acoustic streaming which is induced by the vibration of a vertical side wall. They considered the fully compressible form of the Navier-Stokes equations and used an explicit time-marching algorithm to model the acoustic waves. 25 and 20 kHz frequencies are used and best improvement is seen with 20 kHz. This improvement is about h/h_{us}=40/320. Figure 11 shows their numerical solution about average convective heat transfer coefficient.

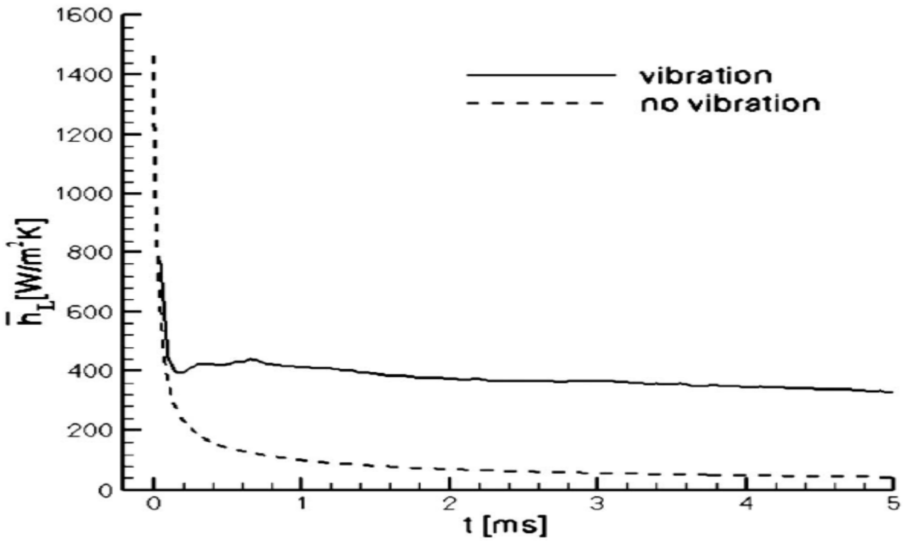

Figure 11: *Average heat transfer coefficient with and without acoustic vibration [11].*

X. Huai et al. [12] investigated natural convection of liquid in a square enclosure with and without acoustic cavitation numerically. A prescribed periodic change pressure is enforced on liquid in the region with ultrasonic beam to model acoustic field. And also they used a cavitation model which involves phase change, bubble dynamics and non-condensable gases effects. 18 kHz frequency is used and it is found that at the centre heat transfer coefficient increases up to 25%. Figure 12 shows the problem and the result. They used equation (1) for prediction of sound field in liquid. The sound pressure in the system is

$$P_S = P_A \cos[w\left(t + \frac{y}{c}\right)] \qquad (1)$$

where P_A is the sound pressure amplitude, w is the angular frequency, y is the location and c is the sound velocity. They said that if the local sound pressure decreases below the vapour pressure, cavitation occurs. When cavitation occurs, this problem must be solved as a two phase problem, gas and liquid. They used a mixture mode without slip velocity which consider the continuity equation, momentum equation and energy equation. Because of the ultrasonic vibration, flow must be treated as a turbulence flow. In the paper k-ε model was used for turbulence modelling. The continuity equation for mixture can be written as

$$\frac{\partial}{\partial t}(\rho_m) + \nabla.\left(\rho_m \overrightarrow{V_m}\right) = 0 \tag{2}$$

where ρ_m is the density of the mixture and $\overrightarrow{V_m}$ is the mass-averaged velocity. And also the momentum equation is written as

$$\frac{\partial}{\partial t}\left(\rho_m \overrightarrow{V_m}\right) + \overrightarrow{V_m}.\nabla\left(\rho_m \overrightarrow{V_m}\right) = -\nabla P + \nabla.\left[(\mu_m + \mu_t)\left(\nabla \overrightarrow{V_m}\right)\right] + \rho_m \vec{g} \tag{3}$$

and the energy equation for mixture can be in the form of

$$\frac{\partial}{\partial t}(\propto_l \rho_l E_l + \propto_v \rho_v E_v) + \nabla.\left[\rho_l \overrightarrow{V_l}(\rho_l E_l + P) + \rho_v \overrightarrow{V_v}(\rho_v E_v + P)\right] = \nabla.\left[\lambda_{eff} \nabla T + \mu_t \overrightarrow{V_m} \nabla \overrightarrow{V_m}\right] \tag{4}$$

where E represents energy and λ_{eff} denotes the effective thermal conductivity. For the cavitation model they used

$$\frac{\partial}{\partial t}(\rho_m H_v) + \nabla\left(\rho_m \overrightarrow{V_v} H_v\right) = \nabla(\gamma \nabla H_v) + R_e - R_c \tag{5}$$

where γ represents the effective exchange coefficient and R_e and R_c denotes vapour generation and condensation rate terms respectively.

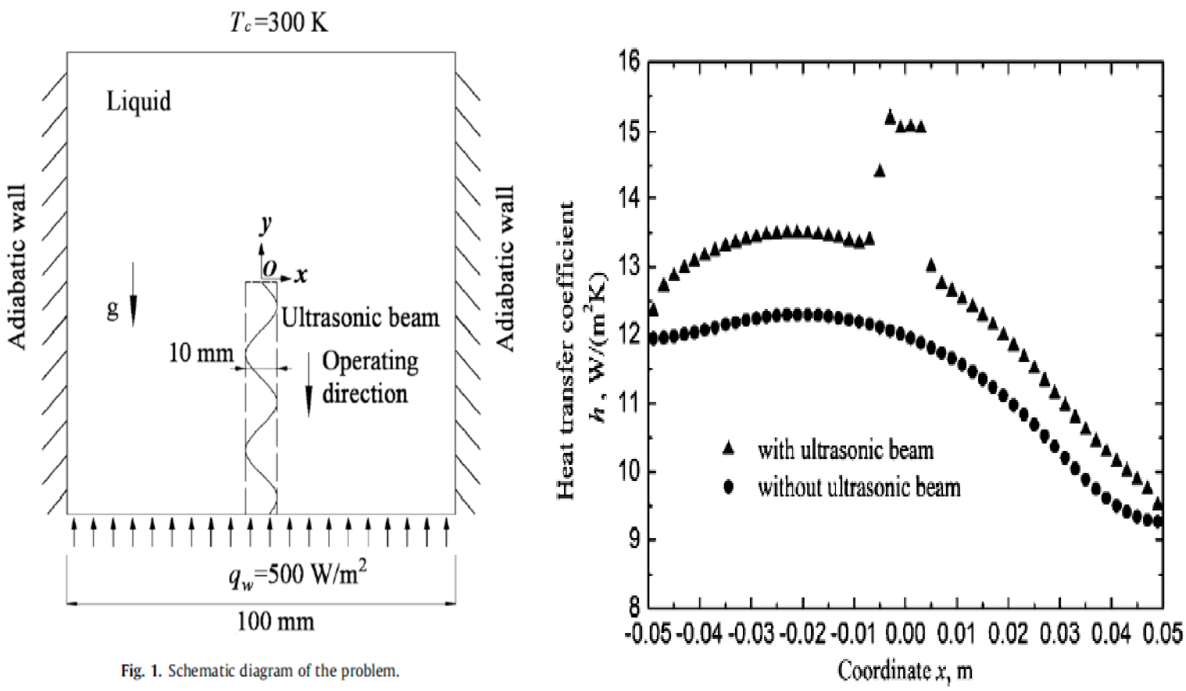

Figure 12: *Problem description (at the left) and numerical result (at the right) [12].*

Lin and Farouk [13] investigated convective heat transfer in a gas filled enclosure with differentially heated horizantol walls numerically. And one of the side walls vibrated with specified frequency and amplitude. The full compressible Navier-Stokes equation is solved by highly accurate flux-corrected transport algorithm. And also, heat conductivity and viscosity is considered time dependant. They found that heat transfer rate increases with streaming flow velocity.

5. Ultrasound applications to heat exchanger

Heat exchangers are widely used in industry. Researchers and engineers want to improve heat transfer characteristic of heat exchanger. Because heat exchangers consist of two working fluid, it is more difficult to adapt ultrasonic vibrations to them. So, their development is quite new.

Kurbanov and Melkumov [14] did some research about liquid-liquid heat exchangers. They claim that acoustic waves homogenize velocity vectors in pipes and decrease the surface tension near pipe walls. Lubricants stuck pipe walls and decrease thermal efficiency in refrigeration system. They found that acoustic waves help removal of this lubricant and improve thermal performance.

Gondrexon et al. [15] designed a new kind of ultrasonically assisted heat exchanger. They calculated energy balance of heat exchanger. They claimed that ultrasound can be used for heat transfer enhancement. Figure 13 shows sketch of the vibrating double pipe heat exchanger and Figure 14 shows results.

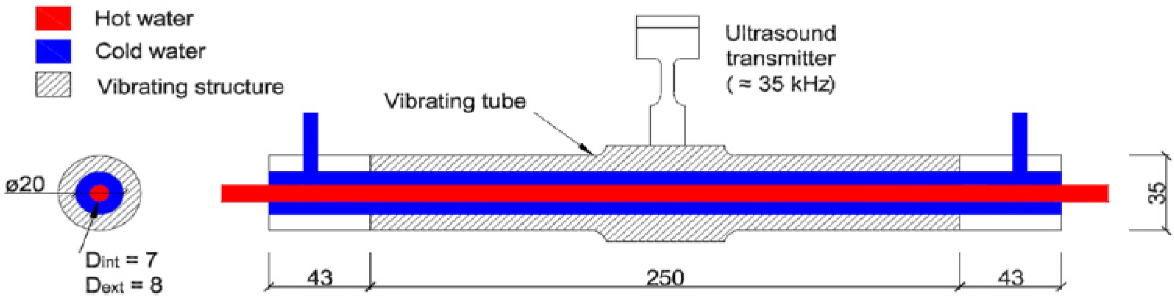

Figure 13: *Heat exchanger design [15].*

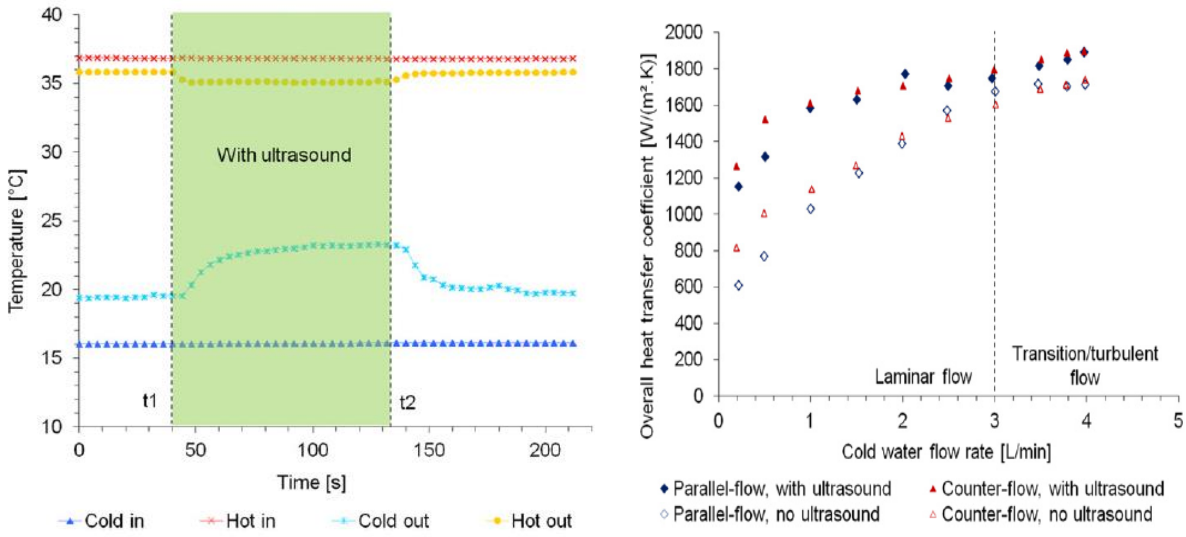

Figure 14: *Results of the problem [15].*

Tisseau et al. [16] did some experiment about shell and tube heat exchanger with 35 kHz ultrasound. They found that overall heat transfer coefficient increase up to 35%.

Benzinger et al. [17] did some experiment about microstructured heat exchangers which have small dimensions about a few hundred micrometer. This small size can cause fouling within the channels. They tried reduction of possible fouling with ultrasonic power. They used a solution of calcium nitrate/sodium hydrogen carbonate. The precipitation of solid calcium carbonate on the surface due to temperature can cause decreasing heat transfer coefficient. They claimed that an ultrasonic pulse of 1 min duration cleans the fouling layer and return the heat transfer coefficient its first value.

6. Conclusion and Recommendation for Future Work

Heat transfer enhancement by ultrasound was investigated in this article. Both experimental and numerical works were considered in this paper. And also heat exchanger application of ultrasound was presented. Literature survey showed that using ultrasound showed great promise for heat transfer enhancement. Heat transfer enhancement strongly depends on frequency of ultrasound. It is observed that acoustic cavitation, acoustic streaming and oscillation of fluid particles are the main reason of heat transfer enhancement. More recent researches are mostly about design of vibrating heat exchangers. Researchers showed that ultrasound improves heat transfer rate also shows great promise for fouling process.

Although results of using ultrasound is promising, applications were limited with laboratory. Industrial scale heat exchangers has not been investigated yet. If researchers investigates industrial scale of using ultrasound, promising characteristic of ultrasound may be used in many applications.

7. References

1. M. Legay, N. Gondrexon, S. Le Person, P. Boldo, A. Bontemps, Enhancement of Heat Transfer by Ultrasound: Review and Recent Advances, Int Jou of Chem Eng (2011) doi:10.1155/2011/670108
2. M. B. Larson, A study of the effects of ultrasonic vibrations on convective heat transfer in liquids, Ph.D. dissertation, Stanford University, Stanford, Calif, USA, 1961, Mic 61-1235.
3. D. R. Lee and B. G. Loh, "Smart cooling technology utilizing acoustic streaming," IEEE Transactions on Components and Packaging Technologies, vol. 30, no. 4, pp. 691–699, 2007.
4. M. Dehbani and M. Abolhasani, "CFD modeling of convection heat transfer using 1.7 MHz and 24 kHz ultrasonic waves: A comparative study", Heat and Mass Transfer, April 2014
5. S. Nomura, K. Murakami,Y. Aoyama, J. Ochi, "Effects of Changes in Frequency of Ultrasonic Vibrations on Heat Transfer", Heat Transfer-Asian Research, 29 (5), 2000.
6. O. Bulliard-Sauret, S. Ferrouillat, L. Vignal, E. Pashmi, A. Memponteil,N. Gondrexon, "Experimental study of heat transfer enhancement using ultrasound on a flat plate in forced convection", Turbulence, Heat and Mass Transfer 8, 2015.
7. J. Cai, X. Huai, S. Liang, and X. Li, "Augmentation of natural convective heat transfer by acoustic cavitation," Frontiers of Energy and Power Engineering in China, vol. 4, no. 3, pp. 313–318, 2010.
8. R. K. Gould, "Heat transfer across a solid-liquid interface in the presence of acoustic streaming," The Journal of the Acoustical Society of America, vol. 40, no. 1, pp. 219–225, 1966.
9. A. V. Markov, Y. S. Astashkin, and I. I. Sulimtsev, "Influence of ultrasound on heat transfer under the conditions of forced flow of a high-temperature melt," Journal of Engineering Physics and Thermophysics, vol. 48, no. 2, pp. 242–244, 1985.
10. A. Monnot, P. Boldo, N. Gondrexon, and A. Bontemps, "Enhancement of cooling rate by means of high frequency ultrasound," Heat Transfer Engineering, vol. 28, no. 1, pp. 3–8, 2007.

11. M. K. Aktas, B. Farouk, and Y. Lin, "Heat transfer enhancement by acoustic streaming in an enclosure," Journal of Heat Transfer, vol. 127, no. 12, pp. 1313–1321, 2005.
12. J. Cai, X. Huai, R. Yan, and Y. Cheng, "Numerical simulation on enhancement of natural convection heat transfer by acoustic cavitation in a square enclosure," Applied Thermal Engineering, vol. 29, no. 10, pp. 1973–1982, 2009.
13. Y. Lin and B. Farouk, "Heat transfer in a rectangular chamber with differentially heated horizontal walls: effects of a vibrating sidewall," International Journal of Heat and Mass Transfer, vol. 51, no. 11-12, pp. 3179–3189, 2008.
14. U. Kurbanov and K. Melkumov, "Use of ultrasound for intensification of heat transfer process in heat exchangers," in Proceedings of the International Congress of Refrigeration, vol. 4, pp. 1–5,Washington, DC, USA, 2003.
15. N. Gondrexon, B. Simony, M. Legay, P. Boldo, S. Le Person, and A. Bontemps, "Improvement of heat transfer by means of ultrasound: Application to a double-tube heat exchanger", Ultrasonics Sonochemistry, 19 (2012) 1194-1200.
16. Y. Tisseau, P. Boldo, N. Gondrexon, and A. Bontemps, "Conception et ´etude pr´eliminaire d'un ´echangeur de chaleur tubes et calandre assist´e par ultrasons," in Proceedings of the 18`eme Congr`es Franc¸ais de M´ecanique, Grenoble, France, Aout 2007. (Original Name)
17. W. Benzinger, U. Schygulla, M. Jäger and K. Schubert, "ANTI FOULING INVESTIGATIONS WITH ULTRASOUND IN A MICROSTRUCTURED HEAT EXCHANGER", ECI Symposium Series, 2005 JUNE 5-10.