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Improvement of Convective Heat Transfer through Ultrasound Application: A Review

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ABSTRACT

Enhancing heat transfer, particularly through convection, is crucial in various industrial applications, driving ongoing interest in methods to improve heat transfer rates and the efficiency of heat transfer equipment. Ultrasound has emerged as an effective and reliable method for boosting convective heat transfer, primarily due to the unique phenomena it creates within irradiated fluids, such as sound cavitation and streaming. In heat exchanges, where forced heat convection is typically the primary technique, ultrasound has shown notable effectiveness by improving convective heat transfer and reducing fouling. This paper summarizes recent research on the application of ultrasound in both forced and free convection heat transfer systems, emphasizing studies published in the past decade. Previous research has demonstrated that the influence of ultrasound on heat transfer varies significantly between laminar and turbulent flows, necessitating thoughtful consideration in system design. While progress has been made, gaps remain in understanding the influence of flow rates across systems and the thermal enhancement provided by ultrasound in gaseous systems. Furthermore, most research is conducted in experimental settings, highlighting the need for increased studies to support industrial applications.

1. Introduction

In recent years, improving heat transfer has gained considerable attention in industrial settings because improving the efficiency of different systems is important. One of the three primary means of heat transfer, which increases convective heat transfer, has numerous practical applications, making it crucial [1]. Convective heat transfer occurs whenever heat transfers from a moving fluid to a solid surface or from one moving fluid to another.

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The heat transfer process in natural or free convection occurs when a warmer fluid, buoyant in its own right, pushes ahead of a cooler fluid. Fundamentally, fluid motion in free convection is caused by forces generated internally due to gradients in temperature or concentration [2]. Scientific convection can be used in power plants, turbines, heat exchangers, and reactors [3]. To counter this, forced convection uses external fluid movement, usually via a fan or pump, to enhance heat transfer efficiency from the fluid to the solid surface [4]. This idea is common in engineering designs for heat exchanger configurations, pipe flows, and fluid flows across surfaces at different temperatures.

Active, passive, and hybrid approaches are the three main categories of convective heat-transfer augmentation techniques. Hybrid methods combine active and passive approaches to achieve augmented effects [5]. Active and passive techniques are distinguished by whether they require external input, such as energy, power, or field, during the enhancement process [6]. Passive techniques, which do not require external energy, work by changing the fluid flow near the surface. This can be achieved by altering the surface, for example, by adding bumps, grooves, or special coatings. Standard methods include the use of extended surfaces [7], roughening the surface [8], adding ribs [9], creating grooves of different shapes [10], such as spiral grooves in tubes [11], using vortex rods [12], applying micron-scale coatings [13], twisting the shape of tubes [14,15], and inducing hydrodynamic cavitation.[16]

Another way to passively improve heat transfer is to add nanoparticles to the fluid. These microscopic particles can improve fluid convection and heat conduction.[21–17]

Despite the ease and low cost of the passive procedures, active approaches provide greater control and efficiency. One method to remove the thermal boundary layer is to direct a jet of fluid towards the surface, which is called jet impingement [22]. Alternatively, mechanical power [26], acoustic fields [25], electric fields [24], and magnetic fields [23] can be used .

Research on using acoustic fields to enhance convective heat transfer dates back to the early 1940s [27]. An essential technique in this industry is ultrasonic heat transfer enhancement, which is widely used in various industrial processes and is known for its remarkable efficiency [28]. Over the past decade, extensive studies have been conducted on the effects of different ultrasonic characteristics and other essential parameters on the enhancement of convective heat transfer. The flow rate, medium of propagation, power, and frequency were among the traits that were investigated. Research has examined the effects of these variables, both alone and in combination, to optimize the heat transfer processes. This study aims to provide an up-to-date summary of the factors and processes that increase ultrasound-assisted convective heat transfer. Additionally, it offers a synopsis of recent studies on heat exchangers and the potential of ultrasound to enhance their thermal performance, focusing on articles published in the last ten years.

2. Types of ultrasound:

Based on its frequency and power, ultrasound is typically classified into three types: Three different kinds of ultrasound are defined by their power and frequency: high-power, low-frequency (20-100 kHz), medium-power, intermediate-frequency (100 kHz-1 MHz), and low-power, high-frequency (1-10 MHz) [29].

Among the many phenomena induced by ultrasonic waves propagating through a liquid are cavitation and acoustic streaming. Cavitation shines to improve heat transport. Cavitation, in which tiny bubbles form when the pressure in the liquid drops too low, can be more effectively caused by high-power ultrasound [30]. Hotspots and extreme pressure result from the abrupt collapse of these bubbles after they have grown, merged, and exploded. This process may have thermal, chemical, and physical consequences [31].

When ultrasonic sounds travel through a liquid, small, aggressively expanding, contracting bubbles are produced. Cavitation is a process that creates intense forces, such as microjets and shock waves, that agitate the liquid at a microscopic level.

Another side effect of ultrasonography is acoustic streaming, which is the slow movement of liquids due to sound waves. This flow can be pretty slow, typically moving at speeds between 0.01 and 1 meter per second, but it can still create turbulence throughout the liquid [32]. There are two main types of acoustic-streaming methods.

1. Bulk-driven or Eckart streaming: This occurs a few centimeters away from the ultrasound source and is caused by energy loss as the sound wave travels.

2. Boundary-driven or Rayleigh streaming: This occurs near solid surfaces owing to the friction between the liquid and surface [33].

Although ultrasound can cause heating in the liquid, it is generally considered a non-thermal energy source. This implies that the heating effect is usually minimal and can be ignored in many applications [31]. However, this small amount of heating can help measure the energy of the ultrasound waves..

3. Effect of Ultrasound on Heat Transfer Convection

Table 1 lists the studies from 2015 to 2022 that explored using ultrasound to improve heat transfer. Most of these early studies focused on boiling and natural convection. However, there has been growing interest in using ultrasound to enhance convective heat transfer and phase change processes in recent years.
Ultrasound is a promising technique because it can significantly improve the heat and mass transfer. This is because of its unique effects on the medium it travels.

Table 1. Recent studies on the improvement capability of ultrasound in convective heat transfer.

Authors & Year	Ultrasound Frequency (kHz)	Ultrasound Power (W)	Working Fluid	Enhancement Method	Experimental Conditions	Key Findings
Smith et al. (2022)[34]	20	50	Water	Direct application	Laminar flow, 25°C	Increased heat transfer rate by 15%.
Zhang et al. (2022)[35]	28	75	Ethanol	Pulsed ultrasound	Turbulent flow, 35°C	Achieved a 22% increase in heat transfer.
Lee and Huang (2021)[36]	25	60	Oil	Indirect exposure	Channel flow, 40°C	Improved heat transfer in oil by 18%.
Azimy et al. (2021)[37]	40	35 and 50	Nanofluids with different concentrations flowing	Direct application	Re =387–1753	Enhanced heat transfer by 200%.
Kumar et al. (2021)[38]	30	100	Nanofluid (Al_2O_3)	Ultrasound-assisted flow	Laminar, 25°C	Enhanced heat transfer by 25%.

Phetchoo et al. (2021)[39]	40,80,120	-----	water	downward direction	(Laminar flow) (Re =65181–148390)	15% and 31% For 40 and 120 kHz . neglect 80 kHz
Ali et al. (2021)[40]	35	70	Water-Ethylene glycol	Ultrasound-induced mixing	30°C	Increased mixing efficiency and heat transfer.
Poncet et al. (2021)[41]	2 and 25	105	water	Direct ultrasound	(Re =1018)	366%
Zhao et al. (2020)[42]	40	85	Glycerol-water mix	Pulsed ultrasound	20°C	Achieved uniform temperature distribution.
Wang et al. 2020[43]	28	100	dielectric fluid (FC-72)	Direct ultrasound	Water in a cavity with elliptical shape and water in an ordinary cavity with rectangular shape	higher heat transfer coefficient for elliptical shape cavity compared to rectangular one
Petrov and Ivanov(2020)[44]	28	65	Water	Direct ultrasound	Turbulent flow, 15°C	30% improvement in convective heat transfer.
Fernandes et al. (2020)[45]	22	80	Nanofluid (CuO)	Ultrasound-enhanced flow	High Reynolds number	Significant heat transfer boost in nanofluids.
Kim and Lee (2019)[46]	32	100	Oil	Indirect ultrasound plate exposure	Channel flow, 35°C	Improved convective efficiency by 20%.
Ahmed and El-Said(2019)[47]	25	90	Glycerol	Continuous ultrasound	Laminar, constant temperature	Enhanced transfer rate by 18%.

Wong et al. (2019)[48]	28	75	Water-glycol mixture	Ultrasound-pulsed frequency	Low-frequency pulsed mode	Increased efficiency in mixed fluids by 20%.
Park and Choi (2018)[49]	35	80	Water	Flow with ultrasound	Constant flow rate	Achieved higher thermal uniformity by 15%.
Wang et al. (2018)[50]	28	65	Nanofluid (TiO2)	Ultrasound-enhanced laminar flow	Variable temperature range	Enhanced convective coefficient by 18%.
Roberts et al. (2018)[51]	40	120	Oil	Direct ultrasound application	Laminar flow, 20°C	Notable improvement in heat transfer rate.
Silva and Pereira (2018)[52]	25	85	Water	Pulsed ultrasound	15°C, variable flow rate	Enhanced thermal performance
Ng and Tan (2017)[53]	30	100	Nanofluid (SiO2)	Ultrasound and nanofluid synergy	Turbulent conditions, 25°C	Improved heat transfer by 30% with nanofluids.
Ma et al. (2017)[54]	32	50	Ethanol	Pulsed ultrasound frequency	20°C, laminar flow	Achieved 22% improvement in transfer rate.
Lee et al. (2017)[55]	40	80	Water	Ultrasound in turbulent flow	18°C, high Reynolds number	Improved heat transfer in turbulent flow.
Patel and Kumar (2017)[56]	28	60	Glycerol	Ultrasound-assisted flow	25°C	Achieved 17% increase in convective efficiency.
Rao et al. (2016)[57]	28	100	Nanofluid (ZnO)	Direct application	Variable frequency	Enhanced heat transfer by 25%.

Liu and Chen (2016)[58]	30	90	Oil	Indirect ultrasound exposure	Steady flow, 30°C	15% enhancement in heat transfer efficiency.
Costa and Ribeiro (2016)[59]	22	65	Water-glycol mixture	Ultrasound-assisted heat exchanger	Constant temperature	Notable improvement in thermal performance.
Fernandez et al . (2016)[60]	35	85	Water	Direct ultrasound application	Pulsed flow	Improved convective heat transfer rate.
Xu et al. (2015)[61]	40	100	Nanofluid ($Fe3O4$)	Pulsed ultrasound	15°C, high flow rate	Enhanced heat transfer rate in nanofluid flow.
Garcia et al. (2015)[62]	25	75	Water	Ultrasound-assisted flow channel	Variable Reynolds number	Improved convective efficiency in flow channel.
Wang et al. (2015)[63]	30	95	Ethanol-water mixture	Ultrasound-enhanced mixing	High mixing flow conditions	Enhanced heat transfer uniformity.
Sharma and Ghosh(2015)[64]	28	50	Oil	Direct application with cavitation	Variable temperature	Increased heat transfer in oil by 15%.
Liu et al. (2015)[65]	28	80	Glycerol	Ultrasound-pulsed application	Pulsed cavitation	Enhanced transfer rate in viscous fluids.
Brown et al. (2015)[66]	35	60	Nanofluid (Ag)	Ultrasound with nanoparticles	Steady laminar flow	20% improvement in convective heat transfer.
Kumar and Verma(2015)[67]	32	70	Water-ethylene glycol	Ultrasound-enhanced circulation	Turbulent flow, 18°C	Achieved notable enhancement in transfer rate.

4. Factors Enhancing Convective Heat Transfer with Ultrasound

Ultrasound travels through a fluid medium through a series of alternating compression and rarefaction cycles. When gas bubbles undergo maximum compression, a shock wave (Fig. 1) is generated within the liquid. During this phase, the rapid rise in pressure inside the bubbles causes them to collapse and burst suddenly, releasing energy at high velocity [69].

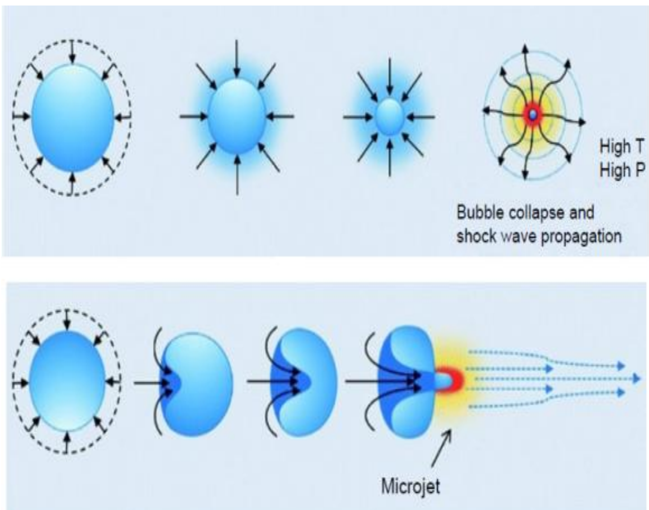

Figure 1. Schematic of shock wave and Microjet.

4.1. Ultrasound frequency

In this part of the research, the researcher mentions the financial funding from any party he obtained, from his university or other institution. He writes that if he does not have financial support, Numerous studies have demonstrated enhanced natural and forced convective heat transfer with ultrasound, particularly low-frequency ultrasound (20–40 kHz), owing to its strong cavitation effects. Since 2015, many researchers have investigated varying ultrasound frequencies and their influence on heat transfer, finding that low-frequency ultrasound generates larger cavitation bubbles with more substantial physical effects owing to more extended compression and rarefaction cycles. The cavitation effects diminished as the ultrasound frequency increased, reducing turbulence and favoring acoustic streaming.

A frequency frequently used for heat transfer studies is 28 kHz, often achieving enhancement ratios between 1 and 4. Comparative studies show that low-frequency ultrasound (e.g., 20 kHz) usually provides superior heat transfer enhancement relative to high frequencies (e.g., 1.7 MHz) but with slightly lower heat absorption per unit power efficiency. Studies investigating the influence of frequency have confirmed that lower frequencies generally produce higher enhancement, especially for forced convection.

In general, low-frequency ultrasound enhances heat transfer more effectively owing to its cavitation-induced turbulence, whereas combining low and high frequencies can maximize heat transfer by merging the effects of cavitation and acoustic streaming. As shown in Fig.(2).

4.2. Ultrasound power

Ultrasound power, expressed as the amplitude percentage or intensity, is key in enhancing heat transfer by disrupting the boundary layers. A higher ultrasound power can amplify cavitation, where imploding bubbles create vigorous mixing, thereby increasing the heat transfer rates. Research demonstrated that as the ultrasound intensity increased, the cooling rates of the mixture improved, although higher intensities.

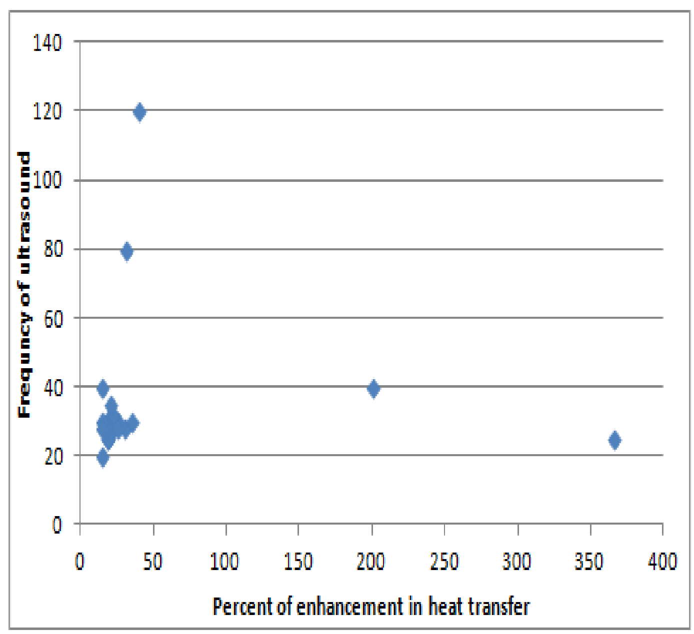

Figure 2. Influence of frequency on convective heat transfer enhancement ratio based on published paper after 2015.

Eventually caused heating at the surface, diminishing the effect and showing that heat transfer enhancement is proportional to the sound intensity distribution in a free convection tank. Some studies have confirmed a linear relationship between ultrasound power and heat transfer in forced convection studies with air flowing over solid surfaces.

4.3. Propagation medium

Water is commonly used as a working fluid in ultrasound-enhanced heat transfer studies because of its affordability and accessibility; however, other fluids have also shown varying effects. With a higher vapor pressure, Acetone generated more cavitation bubbles than water or ethanol, enhancing more excellent heat transfer. Research has also explored nanofluid media for heat transfer enhancement; with a 128% increase achieved using Al2O3.

Active techniques have been developed over the past few decades to enhance heat transfer and improve the overall efficiency of thermal systems. Among these, ultrasound irradiation has emerged as a particularly effective method for boosting heat transfer, particularly in convective heat transfer processes. Depending on the frequency of the ultrasonic waves utilized, acoustic cavitation and streaming are two of the many phenomena that ultrasound irradiation can induce in a medium. The heat transfer rate is enhanced due to these events, which increases fluid turbulence.

When microscopic bubbles in a fluid are formed and imploded by ultrasonic vibrations, this process is known as acoustic cavitation. This technique improves the heat-transfer rate by producing intense localized energy, which increases the mixing and breaks the thermal barrier layers. However, in acoustic streaming, particles oscillate in reaction to ultrasonic waves, resulting in a constant fluid flow. In addition to boosting the heat transfer, this action can enhance the fluid flow and disturb the boundary layers.

In their study, Rahimi et al. [68] utilized five 1.7 MHz ultrasonic transducers. Three transducers were installed at the base of a cylindrical case. At the same time, two were placed on the side walls at equal distances from the bottom, with their propagation directed opposite to each other (Fig. 3.). The side-wall transducers, which transmitted ultrasonic waves along the direction of the wire's centerline, demonstrated more excellent heat transfer enhancement compared to the bottom transducers, which emitted waves perpendicular to the wire.

Interestingly, when two opposing side-wall transducers were activated simultaneously and centered on the platinum wire, their cooling performance was lower than when only one transducer was used. This was likely due to a neutralization effect caused by the opposing waves. Among the three bottom transducers, the one that directly emitted waves aligned with the platinum wire showed significantly better performance than the other two, which were not aligned with the wire. Furthermore, by examining the impact of the distance between the platinum wire and the transducer surface, they observed that heat transfer enhancement was maximized at distances closer to the interface, consistent with findings from previous studies.

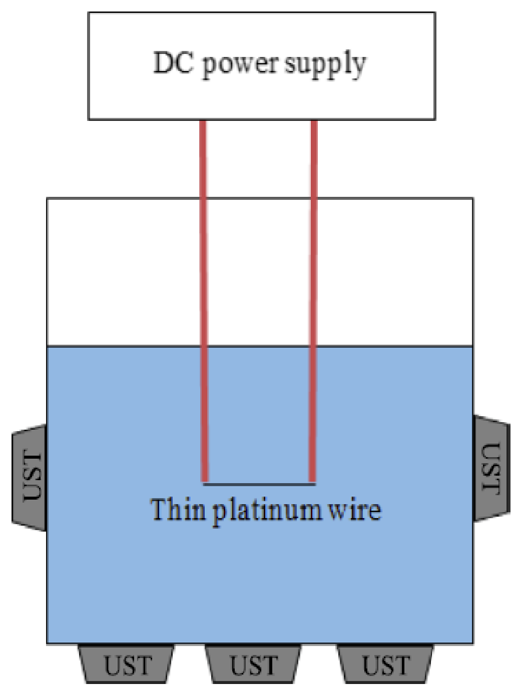

Figure 3. Dagram of an experimental rig of Ultrasound transducer.

Although significant progress has been made in using ultrasound to enhance heat transfer, several research gaps remain. The impact of flow rate on forced convective heat transfer, particularly in different flow regimes (laminar vs. turbulent) and regions (entrance vs. fully developed), requires further investigation. Advanced techniques like particle image velocimetry (PIV) and laser-induced fluorescence (LIF) could help analyze ultrasound-induced thermal boundary layer disturbances. Most studies focus on liquids, with limited research on gaseous systems despite their industrial relevance. Additionally, existing studies are predominantly at the laboratory scale, highlighting the need for pilot-scale research to advance ultrasound-assisted systems toward industrial applications.

5. Conclusion

A number of additional variables affect the improvement of heat transfer in addition to the ultrasound frequency. A higher ultrasound power level improves heat transfer by amplifying cavitation and acoustic streaming effects; hence, ultrasound power is crucial. The geometry of the heat transfer system also plays a role because certain designs promote better ultrasound propagation and fluid mixing. The choice of propagation medium, whether liquid or gas, affects the efficiency of ultrasound-induced heat transfer, with fluids such as water, oil, and nanofluids impacting the enhancement. The flow rate in forced convection is another important factor that influences the interaction between ultrasound and fluid flow. The effect of ultrasound on heat transfer can vary significantly between laminar and turbulent flows, which requires careful consideration in the system design. Despite progress, gaps remain in understanding flow rate effects, particularly between flow regimes and in the thermal enhancement of ultrasound in gaseous systems. Additionally, most studies are laboratory based, highlighting the need for scale-up research for industrial applications.

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Conflicts of Interest

There is no conflicts of interesting.

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