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Review Article

Using Mechanical Vibration to Enhance Heat Transfer on an Extended Surface: A Review Study

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Abstract: Given the significance of improving heat transfer in thermal engineering equipment, researchers in this field have developed numerous methods for heat transfer improvement. These methods are classified as active and passive. Several researchers consider the use of forced vibration in improving heat transfer to be one of the most significant topics in the applied field. This is because some thermal equipment has this feature due to its nature. As a result, the current study emphasizes research dealing with mechanical vibration in enhancing heat transfer in free convection conditions. The results of these studies agreed that heat transfer by free convection and vibration contributed to improving the thermal performance of thermal equipment compared to its at-rest condition. These studies' findings indicate an increased heat transfer coefficient as frequency is raised, particularly in forced convection heat transfer. However, the limited vibration amplitude has an impact on heat transfer. In some studies, the fin slope was studied in addition to vibration. These studies showed that fin tilting reduces heat transfer optimization value with fin tendencies that produce vibrations. Furthermore, while the vibration process does enhance heat transfer capacity, it is accompanied by certain drawbacks. These include the generation of noise, which can disturbance to humans, as well as potential damage to mechanical components of the equipment.

Keywords: Improving Heat Transfer, Vibration, Heat Sinks, Thermal Efficiency, Natural Convection

1. Introduction

Heat transfer improvement techniques are divided into active and passive. Because the former requires an external power source to adjust the necessary flow and enhance heat transfer rate applications, they are designed composite. Yet, passive techniques require no additional energy to enhance the system's thermohydraulic operation. Passive techniques are extensively employed in both experimental and numerical investigations to explore the enhancement of heat transfer and reduction of friction losses, with the aim of achieving energy and cost savings. [1, 2]. It has been shown that natural convection can be used in most heat transfer mechanisms encountered daily, with several applications requiring no additional equipment, such as pumps or fans. It occurs in various settings, including heating and cooling systems, electronic cooling, heat exchangers, stoves, radiators, solar panels, heaters, evaporators, condensers, evaporators, and thermal power plants. Natural convection has the potential to enhance the heat transfer surface as well as the temperature difference between the media during heat transfer [3]. Free convection heat transfer is advantageous in various heat transfer operations where noise emissions or the consumption of electrical energy is a critical factor. Convective systems have a slower heat transfer rate than forced convection. Increasing the mounting area or heat transfer surface can compensate for this drawback. This can be achieved, for instance, by adding fins to the exterior of heat exchanger tubes. Finned tube heat exchangers are utilized in various applications such as air conditioning and refrigeration systems, electronic systems, and thermal power plants [4]. Passive cooling removes heat from numerous electronic and communication devices due to its advantages: silence, dependability, and cost-efficiency. It also demonstrates its safety in hostile environments. Rocket engines, space programs, and other industrial and engineering applications use vibrations. These vibrations are used with free convection heat transfer. Oscillating flows are used in many applications, including high-performance compact heat exchangers. Chemical reactors, pulse burners, high-performance Stirling actuators, cryogenic cooling, and aerospace applications all use circular actuators. Given the importance of vibrations in improving heat transfer in thermal systems, several researchers have addressed it by conducting numerical, experimental, and combined studies to verify how mechanical vibrations contribute to enhancing heat transfer in those systems. Some of these studies are presented below.

2. Numerical Studies

Gururatana and Liin (2013) [5] examined the effect of induced vibration on the heat transfer performance of a pin-fin heat sink. The vibration frequencies used in this study range from 50 to 1000 Hz. The numerical simulation clearly shows a satisfactory increase in heat transfer. However, the pressure decreases increased significantly with frequency. The effect of this phenomenon is to improve the performance of heat transfer. It exhibits a frequency-dependent behavior that increases to a certain threshold and rapidly decreases as the point is reached. Utilizing the concept of vibration, this study's findings can aid in designing heat sinks for electronic cooling.

In order to better understand the dynamics of the flag and the impact of these vortex structures on the thermal boundary layer close to the walls and the temperature field Park et al. (2016) [6] numerically modelled an inverted elastic flag submerged in a hot-walled Poiseuille flow. The submerged boundary method analyzed liquid-inverted flag interaction. Due to its configuration, this inverted flag self-oscillates. Depending on the fluid and the flag's elasticity, an inverted flag can be oblique, floating, or upright. Around six pairs of vortex structures accompany the inverted flag in flutter mode, including anti-vortex structures near the walls and fluid-flag interaction structures. They showed that the kinematic energy of a reversed flag in a flow makes it easy for it to become unstable. In a Poiseuille flow, an inverted flag has three different ways of moving, depending on how tight the bending is: bent, flapping, and straight.

Ghalambaz et al. (2017) [7] conducted a numerical study on the fluid-structure interaction of convective heat transfer in a square cavity filled with air and heated differentially. The study focused on a flexible oscillating fin. Numerical analysis employs an arbitrary Lagrangian-Eulerian-Galerkin finite element method. The flexible fin is excited and buoyant. The range of studied parameters are Ra= 10^4 to 10^7, fin length from 0.1 to 0.4, oscillation capacity from 0.001 to 0.1, τ= 0.01 to 1, k_r= 1 to 1000, and Young's Modulus Dimensions = 10^8 to 10^{13}. The results indicate that raising Ao in the oscillating fin can considerably enhance the Nu number, and periods of 0.1 and higher show better enhancement than lower periods. The optimal fin length for heat transfer and compatibility with various oscillating amplitudes is 0.2.

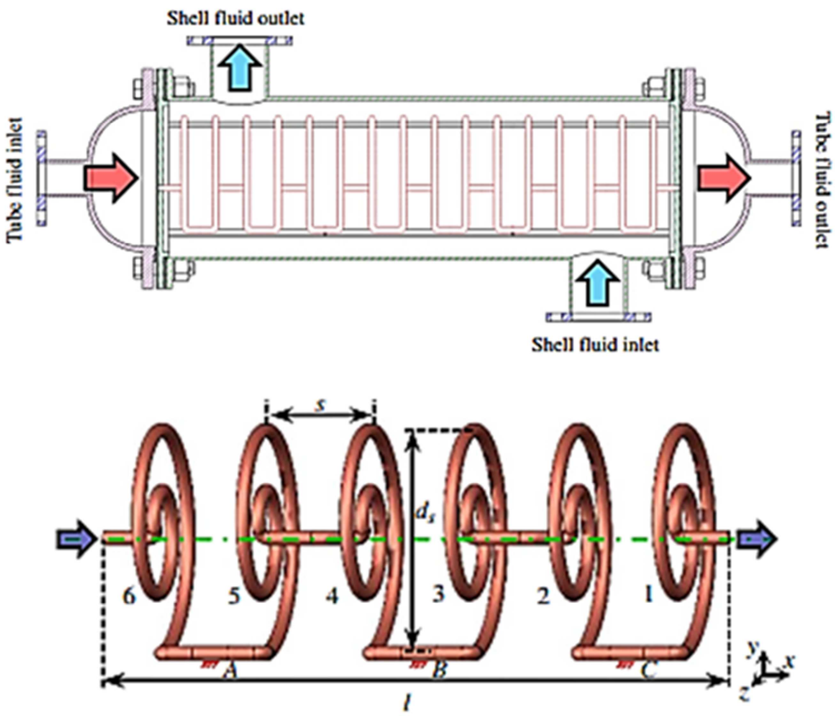

Figure 1. *Elastic scroll tube heat exchanger [9].*

Rahman and Tafti (2020) [8] conducted a numerical study to analyze and enhance the heat transfer rate of an oscillating flat fin in an incompressible and unstable fluid. The simulation's limit was 100 and 0.71 for the infinitesimally thin plate-fin under a forced vibration band with a frequency range of $0.25 \leq f \leq 16$ Hz and an amplitude range of $0.01325 \leq A \leq 8$ mm. The results showed that when the vibration frequency increased, the increase in Nu became more pronounced. The trailing and leading edge vortices act positively to improve heat transfer processing.

Ji et al. (2022) [9] performed a numerical study on the vibration-enhanced heat transfer of a novel flexible passage tube bundle heat exchanger, as illustrated in Figure 1. Using a bidirectional liquid-solid coupling calculation method, the impact of lateral fluid inlet velocity and tube bundle stress condition on heat transfer performance was investigated. The average heat transfer coefficient increases with shell-side fluid inlet velocity in unrestrained single-set spiral copper tubes. The heat transfer coefficient experiences a 140% increase on average during vibration conditions and a 216% increase on average during vibration-free conditions. With increased load during vibration, the heat transfer coefficient drops, reaching a maximum reduction of 42.69%.

Ji et al. (2022) [10] investigated the vibration and heat transfer characteristics of a modified flexible tube bundle heat exchanger. Numerical analysis indicates that the tube bundle exhibits an amplitude that is 7.25 times greater in the z-direction than in the y-direction. There is an increase in frequency and amplitude within the design range when tube rows are spaced apart. Vibration frequency and amplitude increase 21.88% and 10.65% from 50 to 90 mm. Fluid-induced vibration can increase the Nusselt number by 11.67%. The tube bundle's center Nusselt number is lower than both ends. The scientists observed that tube row spacing improves heat transfer from 50 to 90 mm. Account range Nusselt number rises 52.4%.

Rasangika et al. (2022) [11] numerically examined square and sine wave vibration parameters that disrupt the thermal boundary layer for improving convection heat transfer in heat sinks. In Figure 2, square wave vibration improves heat sink thermal performance more than sinusoidal wave vibration. Square wave vibration produces more irregularity of the airflow profile and recirculation zones than a sinusoidal wave, causing the airflow to affect the fin surfaces and increase heat transfer directly. In addition, Square wave vibration increases Nu number values by 25% over non-vibrating fins and 11% over sinusoidal vibration. Thus, Re number values can be dropped by 42.2% to get Nu numbers for non-vibrating fins, which could lower the size of the cooling system or fins. This could reduce the number of electronic systems.

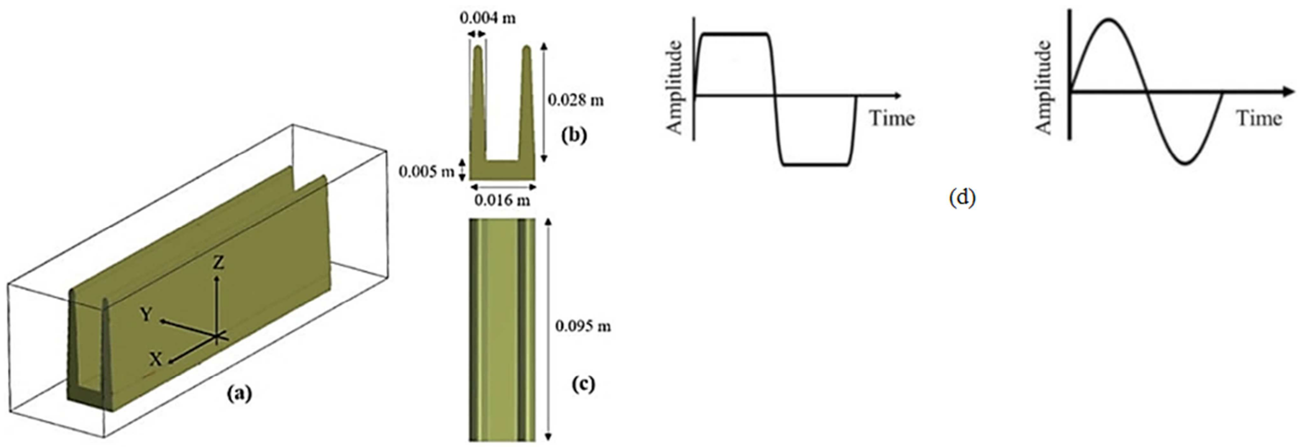

Figure 2. *Heat sink model. (a) Isometric sketch, (b) side perspective, (c) top perspective, and (d) square and sinusoidal wave vibration [11].*

Table 1 provides a summary of the numerical investigations. Vibration on the heat sink typically enhances heat transfer, albeit within a designated range limit of frequency and Re number, for instance, 500 Hz and Re = 800 [5, 6].

Table 1. *A summary of the numerical studies.*

Ref No.	The aim of the study	Parameters used	Findings
[5]	Vibration at the small-scale heat sink must be considered to improve heat transfer performance.	f= 50 to 1000 Hz.	Lower frequencies enhance the rate of heat transfer, while above 500 Hz, the maximum rate of heat transfer increases.
[6]	Examine the dynamics of inverted flags interacting with walls	Re= 100 to 800 Bending rigidity= 0.2 to 1.5.	Re decreases heat transfer. When Re is 800, heat transfer performance is up to 250% greater than without the flag. Re number reduces mechanical energy loss.
[7]	Identify the oscillation value that provides optimum fin lengths and Nu number improvements.	Ra= 10^4 to 10^7, L= 0.1 to 0.4, A= 0.001 to 0.1, t= 0.01 to 1, k_r= 1 to 1000, E = 10^8 to 10^{13}.	The best fin length for heat transfer enhancement is 0.2, which is compatible with a variety of oscillating amplitudes.
[8]	Examining the impact of vibrations on enhancing heat transfer.	Re=100 $0.25 \leq k \leq 16$ $0.03125 \leq h \leq 8$ Pr=0.7	As vibration frequency increased, Nu increased more.

Ref No.	The aim of the study	Parameters used	Findings
[9]	Enhance the thermal efficiency of the flexible pass beam heat exchanger.	V=0.1, 0.3, 0.5, and 1 m/s Tin= 293.15 K Tout= 353.15 K	The heat transfer coefficient increases by an average of 140% during vibration conditions and 216% during non-vibration.
[10]	Redesigned elastic tube bundle heat exchangers are tested for vibration and heat transfer.	f= 0 to 24 A= 0.08 to 0.1 mm b=50 to 90 mm	From 50 to 90 mm distance, vibration frequency and amplitude increase 21.88% and 10.65%. Fluid-induced vibration raises Nusselt number 11.67%.
[11]	It focuses on improving heat transfer using a vibratory heat sink using the newly introduced square waveform and sine waveform.	q= 6250 W/m^2 Re=1000	Square wave vibration increases Nu number by 25% upon non-vibrated vanes and 11% above sinusoidal vibration.

3. Experimental Studies

Nag and Bhattacharya (1982) [12] studied the vibration impact on free convection heat transfers from vertical rectangular fin arrangement with various fin pitch and fin length. It was seen that giving the fin array vibrations up to a specific threshold value of the products of amplitudes and frequencies 0.015 m/s didn't have a significant effect on how heat moved from the fins. However, as the vibration intensity increased, the heat transfer rate increased substantially. This was achieved with a maximum increase of 2.50 times at 90 W of vibrational energy.

Go J. Sang (2003) [13] used flow-induced vibration to design a microwave array heat sink for laminar flow systems. It investigated how microwave grating flux-induced vibration enhances heat transfer. by comparing microwave grating and smooth wall heat sink thermal resistance. Heat transfer rates increased by 5.5 and 11.5% at 440 and 550 cm/s, respectively. The microphone flow sensor also vibrates. Both microphones vibrate at the natural fundamental frequency, regardless of airspeed. The two microphones' vibratory displacement increases with airspeed and saturates at a given airspeed. They proposed a simple heat pump model that understood heat transfer from a microfine matrix heat sink. This was based on numerical analysis of the temperature profiles created by microfine vibrations and experimental data. The two-micron minimum thickness and bending angle constraint maximized heat transfer enhancement under engineering and structural constraints.

Al-Shorafa M. H. M. (2008) [14] used an aluminum cylinder with an external diameter of 0.0215, 0.03, and 0.038 m and a heating length of 0.38 m to demonstrate the effect of vertical vibrations on heat transfer coefficients. They study various elements impacting the hv/ho from the surface's exterior by vibrating it vertically in static air at frequencies of 10, 15, and 20 Hz with an amplitude between 0.00005 m and 0.0076 m. It was discovered that a decrease in temperature, frequency, and diameter results in an increase in the rate of heat transfer. Furthermore, it was discovered that the Re number has a significant effect on the rates of heat transfer. By contrast, the quantity of Gr. Pr exhibits an insignificant impact on the rate of heat transfer.

Eid and Gomaa (2009) [15] used a heat sink from a personal computer with four identical quadrants and thin planar fins. They studied how fins and vibration frequency affect the coefficient of convection heat transfer. The specimen is heated by an electric heater installed at the bottom. A cam disc can be used as a mechanical vibrator to make the heat sink shake differently, depending on its displacement amplitude and frequency. Temperature readings of the specimen's surface and surrounding air were obtained using a data acquisition system in response to the vibration frequency. This study investigated the impact of vibration frequency and displacement amplitude on enhancing heat transfer rate. It was found that the Nu, the Strouhal, and the Re numbers are all linked. The average speed was the same in both cases, but normal vibration increased the heat transfer rate by about 85% compared to steady flow cases. Comparing this study with others conducted in the past, vibration may have a slightly more significant impact on improving heat transfer than pulsating flows.

Kadhim Z. K. (2010) [16] investigated the influence of oscillations on the free coefficient of convection heat transfer. The present study involving three different annular aluminum fin shapes, including rectangular, triangular, and truncated triangle fins, 49 fins were attached to the exterior surface of each 48-mm-diameter cylinder. The test rig was subjected to frequency vibrations with a frequency range of 2-20 Hz and an amplitude of 79×10^{-2} to 179×10^{-2} mm, with tilt angles ranging from 0°-60°. The heat output ranged from 500 to 1500 W/m^2. They discovered that increasing vibration in a horizontal position increased the coefficient of convection transfer and heat flow, reducing the vibrational heat transfer coefficient. They also found that slight angles affected heat transfer. But at angles greater than 30°, its effect diminishes as the angle increases.

Sarhan A. R. (2013) [17] investigated the impact of forced vibration on the enhancement of heat transfer from a longitudinal fin heat sink under conditions of uniform heat flux and free convection. Experiments were performed at various horizontal and inclined heat sink positions (30°, 60°, and 90°), with heat flux from 250 to 1500 W/m^2. The vibration frequency varied between 0 and 16 Hz, and the amplitude varied between 1.63 and 7.16 mm. Results show that the heat transfer coefficients at the 30° angle are approximately 19.27% higher than those at the 60° angle and exceed those at the 90° angle by 31.46%.

Saini and Kumar (2015) [18] experimented with showing how vibration can enhance heat transfer in a rectangular duct heat exchanger. The heat exchanger is equipped with vibration control. The study was conducted using three distinct levels of vibration intensity. Vibration intensity variations were examined, and their impact was compared to different heat transfer properties. These included total heat transfer coefficient, efficiency, and heat transfer rate without vibration. The findings indicated that increased vibration intensity could improve heat transfer properties.

Pandey et al. (2015) [19] investigated the influence of heat transfer improvement in horizontally positioned heat exchangers. The convection heat transfer coefficient, effectiveness, and heat transfer rate were discussed in the presence or absence of vibration. Experiments were conducted using varying cross-sectional areas (100, 150, and 1000 mm^2) and vibration intensities (5, 5.5, and 6.5). Large heat exchangers pose difficulties in utilizing external vibration-generating components, according to findings from studies. Excessive vibrations, such as reflections, leaks, and noise, can damage heat exchangers.

Kadhim and Nasif (2016) [20] investigated the effect of induced vibrations on free convection heat transfer coefficients using an experimentally heated, longitudinally finned cylinder. The influence of vibration frequencies from 2 to 16 Hz and heat fluxes from 500 to 1500 W/m^2 was examined. Heat transfer coefficients and vibration amplitude were found to increase at all inclination degrees from 0° to 45°. Increased inclination angle decreases convection heat transfer coefficient values. A longitudinally finned cylinder at 0° had 8% and 30% higher heat transfer coefficient rates (hv/ho) than at 30° and 45° angles, respectively.

An experimental study was carried out by Hosseinian et al. (2018) [21] to examine the improvement of heat transfer caused by surface vibrations in a flexible PVDF heat exchanger with a double-tube configuration. Electrodynamic vibrators are used to generate vibrations (3-9 m/s^2, 100 Hz) on the heat exchanger's outer surface. Experiments were designed for each internal Re number ranging from 2533 to 9960. The impact of flow rate and temperature on heat transfer efficiency was examined. The results show that the heat transfer coefficient increased as vibration and mass flow rates increased, and the highest vibration level (9 m/s^2) led to the maximum increase in heat transfer coefficient (97%).

Chen et al. (2018) [22] experimented with ultrasonic vibration to improve heat transfer in the heating water tank. The result was validated with empirical correlations. The study involved experiments on a loaded heat flux within a range of 7.6×10^3 to 7.1×10^4. The heat transfer regimes observed during the experiments ranged from free convection to cryogenic boiling. The temperature was maintained within the 50 to 70 K range, while the ultrasonic vibration was set at a power of 150 W and a frequency of 40000 Hz. The findings indicate a highest heat transfer ratio of approximately 3.01 times. Empirical correlations were formulated based on the existing data to enhance heat transfer. These correlations can predict the experimental database with an average error of 14.1%. The current study provides empirical evidence and a prediction approach to improving heat transfer via ultrasonic vibration.

Haghighi et al. (2018) [23] experimentally investigated the thermal characteristic of a new pin fin plate design with natural convection. The present study conducted experiments with fin distances and fin numbers ranging from 5 to 12 and 5 to 9, respectively. The input power range is 10 to 120 W, and the range of Ra is 8106 to 9.5106. Compared to the heat sources of the fin plates, the heat sources of the cubic pin plates exhibited lower thermal resistance and more significant heat dissipation. Furthermore, they discovered that the best heat source consisted of plates with seven fins and a distance of 8.5 mm. Increasing the spacing between heat sources and fins decreased thermal resistance, whereas increasing the number of fins had no effect on heat transfer. The improvement in heat transfer of the novel design is 10 to 41.6% greater than that of the conventional fin-type.

Bassiouny et al. (2019) [24] studied the influence of vibration on the thermal performance of a plate heat exchanger. The testing apparatus comprised six panels and a 30-degree chevron angle. The tested exchanger was subjected to mechanical vibration, and the results were compared to those obtained when the exchanger was at rest. Thermal characteristics, including the heat transfer coefficient, total heat transfer rate, and heat exchanger efficiency, were investigated. An experiment was conducted by subjecting the test rig to vibrations with a frequency range of 13.33 to 46.67 c/s and an amplitude range of 9.14×10^{-3} to 52.66×10^{-3}. Results show that Vibration increases heat transfer coefficient, heat transfer rate, and effectiveness by (43, 31, and 18) %, respectively, compared to the rest state. Moreover, correlations were presented to calculate the Nu number valid for designing plate heat exchangers with an acceptable error of no more than 3.99% and 18%, respectively.

Rao and Babu (2019) [25] experimented to identify the impact of vibration on enhancing the heat dissipation of conventional consumable fluids, including water, motor oil, kerosene, ethanol, and ethylene glycol. They discovered that the low conductivity of molten liquids prevented their superior use. They predicted that mechanical vibrations imposed on the horizontal cylinder would increase heat transfer. Experiments were conducted using two cylinders of (25 and 12) mm for outer and inner diameters, respectively. The two cylinders were heated within a copper cylinder with varying input powers of 30, 40, 50, and 60 W and vibrations between 100 and 140 Hz. They found that vibration increased the heat transfer coefficient linearly from the base to the tip of the cylinders.

Kumar et al. (2019) [26] used an ammonia-charged miniature LHP to explore the influence of frequency and acceleration of induced vibration on thermal efficiency. Titanium wick was employed horizontally with and without transverse and longitudinal harmonic vibrations of 1–4g, frequencies of 15–45 Hz, and sine-sweep of 15–45 Hz /s. Start-up loads for LHPs range from 5 to 8 W, allowing them can transfer heat loads of up to 0.120 kW at a safe evaporation temperature of 70°C. They found that the mLHP's thermal performance for transverse vibration is unaffected by induced vibration acceleration rate or frequency. Acceleration boosts the device's longitudinal vibration performance. Data trends show that heat loss from the evaporator to the forced vibration compensation chamber is critical to the internal fluid distribution.

Al Sultan et al. (2020) [27] investigated heat transfer by free convection from a vibrating vertical plate heated by uniform heat fluxes. Air is used as the operating fluid. Researchers looked at the effects of a changed Ra number $10^7 < Ra^* < 10^{10}$, vibration frequency (0–25 Hz), amplitude (0–7.6 mm), and vibrational Re number $10^2 < Re_V < 8\times 10^4$. Over the Ra^* numbers tested, the vibrating plate had higher heat transfer coefficients at all amplitude and frequency values. This is compared to a stationary plate. It was also discovered that the frequency of vibrations has a significant impact on heat dissipation, while the size of the vibrations has a small effect. They suggested that the experimental correlation for Nu is a function of the modified Ra* and Rev numbers, as demonstrated below:

$$Nu = 0.76\, Ra^{*2} \tag{1}$$

for stationary plate with maximum error of ±10%
and

$$Nu = 0.64 Ra^{*0.214}\left(1 + 0.00236 Re_v^{\ 0.31}\right) \tag{2}$$

for vibrating plate with error of ±8%

Akcay et al. (2020) [28] investigated the mixed load experimentally on a vertically vibrating flat plate. The experimental models consist of two flat copper plates measuring (210 × 210 × 1.5) mm and two heaters. The study involved testing different heat fluxes of 250, 500, and 625 W/m^2, amplitudes of 0.4, 0.75, 1.1, and 1.4, and frequencies of 65, 92, 113, 131, and 146 Hz. The results showed the vibration amplitude had no effect on the Ra number, whereas the frequency did. The highest heat transfer performance of 145% was achieved with a minimum heat flux of 250 W/m^2, an amplitude of 1.4 mm, and a vibration frequency of 146 Hz.

Al-Azzawi et al. (2020) [29] investigated the influence of forced vibration on the heat characteristics of a longitudinal fin heatsink exposed to heat fluxes between 300 and 1,750 W/m^2. Frequency ranges of 0, 3, 7, 12, and 16 Hz with an amplitude of 1.51 to 8.4 mm. It was compared to an inclined flat plate at 25°, 45°, and 90°. The results showed that the heat dissipation is proportional to amplitude and inclination angle. Additionally, the tilt angle decreases the heat transfer coefficient. It was 14.36% higher at 25° than at 45° and 26.71% higher at 90°.

Al-Azzawi et al. (2021) [30] investigated the forced oscillation impact on the free heat transfer coefficient in a vertical concentric cylinder experimentally. Tests have been conducted with 90, 110, 140, and 180 Hz oscillation frequencies and heat fluxes ranging from 35 to 75 W/m^2. The length amplitude was held constant at 0.6 amps. The amount of heat input and the axial space of the cylinder affect local heat transfer.

Kadhim et al. (2021) [31] experimented to determine how vertical vibrations affect heat transfer by forced convection and the average Nu number in an aluminum tube of 48 mm outer diameter and 300 mm length with eight longitudinal fins arranged at a 45° angle and spread throughout a 0.32 m tube length, and 13 mm fin height. The tube was attached horizontally or diagonally at 0°, 30°, and 45° angles. The excitation effect frequency is less than 16 Hz for heat fluxes ranging from 500 to 1500 W/m^2. They discovered that the present study's findings are in good agreement with other similar works, with only a 5% variance. The results show that the average Nu number at the 45° angle of the longitudinal finned tube is 14% and 16% greater than the 30° and 0° angles, respectively.

Xie et al. (2021) [32] performed a numerical study of heat transfer improvement employing four cylinders equally distributed along the vibrating duct and heated from the bottom with a heat flux of 5000 W/m^2. The other sides of the cylinders were insulated. An air transport duct with a crossflow pattern and a Re number of 746. Compared to the conventional fixed cylinder duct, the experiment's findings showed a 14.7% rise in the coefficient of convection heat transfer and a 16.13% rise in the total heat transfer performance.

Khudhair et al. (2021) [33] experimented to determine the impact of vibration on free convection heat transfer from a closed, hollow space containing air. Other surfaces are thermally insulated. Experiments have been conducted with two Ra numbers: the first at 7×10^7, with a vibration frequency range of (2, 4, and 8) Hz, and the second at 4×10^8, with a frequency range of (3, 6, and 9) Hz. In the case of the first Ra number, vibration significantly improved heat transfer, which increased as the vibration frequency increased. In the second experiment involving the Ra number, vibration did not improve heat transfer. However, the enhancement resulted from gravity.

Delouei et al. (2022) [34] improved CPU water cooling system thermal performance using ultrasonic vibration. Ultrasonic vibrations at 30, 60, and 120 W for various cooling air flow rates have been tested. Empirical correlations verified the measurement system's correctness. Ultrasonic vibrations increased liquid-cooled heat exchanger heat transfer. Airflow reduction and ultrasonic power increase ultrasonic vibration thermal performance. Ultrasonic is commonly used to clean heat exchangers and improve heat transmission. Ultrasonic vibrations' anti-fouling and anti-accumulation characteristics could make high-performance nanofluid-based computer cooling systems possible.

The presented experimental studies dealt with the influence of various parameters besides vibration, such as fin height, number of fins, fin pitch, fin diameter, surface inclined angle. etc., as summarized in Table. 2. These studies have demonstrated that vibration positively impacts heat transfer performance enhancement. Additionally, the findings indicate that an inclined surface positioned at an angle of 30° from the vertical plane exhibits the most efficient heat transfer compared to surfaces inclined at 30°, 60°, and 90° [17]. On the other hand, M. H. M. Al-Shorafa discovered that the Ra number did not affect the heat transfer rate when vibration was used within a frequency range of up to 20 Hz, whereas H. Al sultan et. al and H. Xie et. al proved the reverse [14, 27, 33]. Furthermore, Refs. [21, 24] demonstrated that when combined with vibration, the Re number significantly enhances the performance of heat exchanger systems.

Table 2. *A summary of the experimental studies.*

Ref No.	The aim of the study	Parameters used	Findings
[12]	The influence of vibration on heat transfer from a vertical longitudinal fin with different lengths and distances.	H =250 mm L=25,38, and 50 mm b =25, 50, and 75 mm t=13 mm	Vibration increased the heat transfer rate by approximately 250% for S/H and L/H values of 0.1 and 0.2, respectively, against an exciter energy input of 90 W.
[13]	The design guidelines for a micro fin array heat sink that enhances heat transfer in laminar flow by using flow-induced vibration.	W=140, 178, and 229mm d=2.15, 3, and 3.8 cm L=38 cm f=10, 15, and 20 Hz A= 0.5 and 7.6 mm	At high frequencies, heat transfer significantly increases, and the Re number positively affects heat transfer from the cylinders..
[14]	Showing how vertical vibrations affect heat transfer in a horizontal cylinder	f= 10, 15, and 20 Hz A= 0.00005 m and 0.0076 m.	Re number considerably affects heat transfer rates. However, Gr. Pr has little impact on heat transfer.
[15]	Heat transfer was increased by vibrating a heat sink with thin scraper fins.	Ts=100°C $12.5 \leq f \geq 50$ Hz $9 \leq S \geq 27$ mm	Compared to dynamic vibration, normal vibration increases heat transfer rates by about 85%.
[16]	Forced vertical vibrations were applied to the forced convection heat transfer coefficient using a circumferential finned cylinder.	Θ= 30° to 45°, q= 500 to 1500 W/m^2 f= 2 to 16 Hz A=0 to 2.2 mm	All inclination angles from 30° to 45° increase the heat transfer coefficient and vibration amplitude to a maximum ratio of (%13.34). Inclination angle reduces forced convection heat transfer coefficient.
[17]	Forced vibrations on free convection heat transfer utilising a longitudinally finned plate vs a vibrating plate.	Θ= 30°, 60°, and 90° q= 250 to 1500 W/m^2 f= 0, 2,6,10, and 16 Hz A=1.63 and 7.16 mm	The heated plate's heat transfer coefficients at (30°) angle are 19.27% higher than those at (60°) and 31.4% higher than at (90°).
[18]	Illustrating how vibration improves heat transfer in a rectangular channel heat exchanger	h= 100mm W=150mm L=1000mm m^*= 1.5, 1.75, and 2 kg/min	higher vibration intensity can enhance heat transfer properties to a certain extent.
[19]	Heat transfer enhancement of in heat exchangers placed in a horizontal duct by vibrations	A_C= 100, 150, and 1000 mm^2. f= 5, 5.5, and 6.5 Hz	According to studies, large heat exchangers make using external vibration-generating components impossible. Vibrations from reflections, leaks, and noise can damage heat exchangers.
[21]	Investigating how surface vibration improves heat transmission in a double-pipe heat exchanger.	f_f= 3 to 9 m/s^2 f= 100 Hz Re= 2533 to 9960	Maximum forced vibration of 9 m/s^2 improves heat transfer coefficient by 97%.
[22]	To investigate and predict ultrasonic vibration-enhanced heat transfer.	q= 7600 to 71000 W/m^2 T_C=50 to70 K f= 40 kHz	Compared to empirical correlation, the heat transfer coefficient increased 301% with a 14.1% margin of error.
[23]	investigated the heat transfer coefficient in a new pin-fin-plate design with natural convection	P= 10 to 120 W Ra = 8106 to 9.5106.	The improvement in heat transfer of the novel design is 10 to 41,6% greater than that of the conventional fin-type
[24]	An investigation of γAl_2O_3-water nano-fluid heat transfer across a gasket plate heat exchanger with low-amplitude mechanical vibration.	f= 13.33 to 46.67 Hz A_o= 9.14×10^{-3} to 52.66×10^{-3} Re= 730 to 3400	The net heat transfer coefficient enhancement ratio increased with increasing Ao and ϕ.
[25]	Analyses the impact of vibration on conventional consumable fluids in order to enhance their free heat transfer coefficients	$NaC_{12}H_{25}SO_4$-Water (ϕ)= 0.05, 0.1, 0.15, and 0.2% P= 30, 40, 50, and 60W f=100 to 190 Hz	With 60W input heat, vibration effects on the free convective temperature are more active as the heat transfer coefficient rises from 321.334 to 341.419 w/m^2. K.
[26]	To understand how acceleration and frequency of induced vibration affect tiny loop heat pipe (LHP) thermal performance.	f_T= 1 to 4 g f=15 to 45 Hz Sin sweep =15 to 45 Hz/ sec P= 5 to 8 W	Acceleration enhances transverse vibration performance but does not affect mLHP thermal performance.
[27]	Oscillations affect convective heat transfer for flat plates, cylinders, and wires with various vibration vector orientations.	$10^7 \leq Ra^* \geq 10^{10}$ $0 \leq f \geq 25$ Hz $0 \leq A \geq 7.3$ mm $10^2 \leq Re_v \geq 8\times10^4$	Ra* increases Nu and Ra decreases Nu. Heat transfer increases somewhat with vibration amplitude at constant Ra*.
[28]	Investigating mixed-convection heat transfer on a vertically oscillating flat plate	q= 250, 500, and 625 W/m^2 A_o= 0.4, 0.75, 1.1, and 1.4 W_o= 65, 92, 113, 131, and 146	The maximum heat transfer efficiency attained was approximately 145% under the condition of 250 W/m^2, Ao is 1.4, and Wo of 146.
[29]	Investigating the impact of vertical forced vibration on a long-finned sheet's free convection heat transfer coefficient.	q= 300 to 1750 W/m^2 θ= 25°, 45°, and 90° f=0, 3, 7, 12, and 16 Hz A= 1.54 and 8.4 mm	Tilt angle reduces free convection heat transfer. However, at the tip of 25°, it was 14.36% higher than at 45° and 26.71% higher than at 90°.
[30]	The influence of forced vibration on heat	d= 16 to 30 cm	At 75W thermal input power, vibration enhances free

Ref No.	The aim of the study	Parameters used	Findings
	transfer enhancement in a concentric vertical cylinder with free convection heat transfer.	q= 35 to 75 W/m^2 f= 90, 110, 140, and 180 Hz A= 0.6 mm	convection heat transfer from 361 to 380 W/m^2.
[31]	Vertical vibration and forced convection affect mean Nu number in a finned longitudinal tube.	q= 500 to 1500 W/m^2 θ= 0°, 30°, and 45° f= 16 Hz	The average Nu number at the 45° of the longitudinal finned tube is 14% and 16% greater than at the 30° and 0°, respectively.
[32]	numerical investigation into the enhancement of heat transfer using four cylinders equally distributed along the vibrating duct	q=5000 W/m^2 Re =746	The experiment showed a 14.7% increase in heat transfer coefficient and 16.13% in performance.
[33]	Vertical mechanical vibration impacts natural convection at normal gravity in the air-filled cubic container.	f= 2, 4, and 8 Hz at Ra= 7×10^7 f= 3, 6, and 9 Hz at Ra=4×10^8	In contrast, in the second experiment involving the Ra number, vibration played no role in enhancing the heat transfer rate. However, the improvement was due to the force of gravity.
[34]	Water-cooling system's thermal performance is improved by studying ultrasonic vibration technology.	Fan speed= 0 to 100% P= 30, 60, and 120 W	Reducing airflow and improving ultrasonic power enhanced ultrasonic vibration thermal performance.

4. Numerical and Experimental Studies

Cheng et al. (2009) [35] conducted a numerical and experimental study of flow-induced vibrations in heat exchangers to improve heat transfer. Flow-induced heat exchanger vibration is hazardous and must be prevented. Its favorable effect on heat transport is underestimated. The present study suggests flow-induced vibrations for a new heat transfer device to improve heat transmission. So, flow-induced shaking is used in the design of the heat exchanger. The heat exchanger is made of new devices that transfer heat. They found a correlation between heat transfer efficiency and convection on the case side. The convective heat transfer coefficient of the newly built heat exchanger increased significantly, and the resistance to fouling went down. Flow-caused effects permanently improve heat transfer.

Hussain et al. (2013) [36] used oscillating fins with a base plate-mounted piezoelectric actuator to increase heat transfer. This geometry represents a flat fin and a triangular fin. Air works. Performance data is provided for one rectangular vane and three vanes for different frequencies (5, 30, and 50) Hz, foreign input powers (5, 10, 20, 30, 40, and 50) W, and input speeds (0.5, 1, 2, 3 and 4, 5 and 6) m/s for single and triple rectangular fins with and without the template. Geometric fin heights of 50 and 35 mm and inter-fin spacings of 3 and 6 mm were also tested. Frequency and Re number boost heat transfer, the researchers say. The triangular fins of 50 mm height and 3 mm spacing improved heat transfer more than the other cases, and the study showed that the piezoelectric actuator on rectangular fins improves heat transfer.

Setareh et al. (2019) [37] performed an experimental and numerical study to optimize heat transfer in a twin-tube heat exchanger with two concentric tubes and a bolt-on Langevin ultrasonic transducer that applied 26.7 kHz ultrasonic vibrations to the inner tube. Open FOAM numerical simulations illustrate why heat transport improves. This study examined heat transfer and pressure decrease with hot and cold fluid flow rates and acoustic capacity. Ultrasonic vibrations affect heat exchanger performance. They noticed that ultrasonic vibrations are more effective at modest fluid flow rates. Consequently, heat transmission is enhanced by 60% for cold and hot fluid flow rates of 0.5 L/min and 20% for flow rates of 1 L/min and 1.5 L/min, respectively, when a 120 W phonon emitter is present. The numerical results indicate that the cross fluxes produced by ultrasound propagation in a cool liquid improve heat transfer.

Li et al. (2020) [38] performed an experimental and numerical study to investigate the effect of vibrations on improving heat transfer from an automobile radiator's finned tube. The test rig was subjected to vibration conditions with an amplitude range of 0–6 mm. It had a fan speed of 1500 rpm and applied wind speeds of 2, 4.6, and 8 m/sec. The experiment revealed that vibration improves heat transfer by 22.9%, and increasing frequency improves heat transfer by 51.5%. The heat transfer coefficient increased by 1.89-11.71% for liquids and 3-16.8% for gases. Furthermore, the pressure drop on both sides increased from 2.6 to 40.5%.

Akcay and Akdage (2021) [39] used Ansys Fluent to investigate mixed convection heat transfer from a flat plate subjected to transient vibrations. It consists of two flat copper plates pressed together and two radiators sandwiched between them, each measuring (210 × 210 × 1.5) mm in size. A range of heat fluxes (250, 500, and 625) W/m^2, vibration amplitudes (0.4, 0.75, 1.1, and 1.4), and vibration frequencies of 65–146 Hz were applied to the experiment. The plate's heat flow, vibration frequency, and amplitude affected temperature performance. Numerical solutions confirm experimental results [17].

Duan et al. (2022) [40] studied the potential of combining flow-induced vibration and pulsating flow to enhance heat transfer using an experimental and numerical methods. The impact of flow-induced vibration on the enhancement of heat transfer in a planar elastic tube bundle subjected to three different flow fields was investigated. A vortex generator was used in this experiment in order to create the pulsating flow. This investigation into flow-induced vibrations and two-way fluid-structure interactions utilized water as the working fluid. Therefore, vibration characteristics and heat transmission in laminar flow could be thoroughly examined. It was found that the planar elastic tube bundle had a primary vibration frequency of 24-25 Hz in all three flow fields. The pulsating flow had the most significant impact on vibration amplitude, resulting in reductions of 18.5% and 51.75% in coupled flow and 62.2% and 59% in steady flow.

Many researchers conducted conjugated numerical and experimental studies to see what range of vibration effects on thermal performance improved; some were mentioned above and listed in Table 3. They included variations in heating power and airflow rate added to the frequency and amplitude of vibration. The experimental and numerical facets of these investigations have achieved a good concurrence, and the outcomes in both cases validate that vibration enhances the thermal efficiency of heat exchangers while augmenting the pressure drop.

Table 3. *A summary of the numerical and experimental studies.*

Ref No.	The aim of the study	Parameters used	Findings
[36]	Heat transfer properties of a fin plate with an integrated piezoelectric actuator mounted to the base plate are investigated.	f=5, 30, and 50 Hz P= 5, 10, 20, 30,40 and 50 W V= 0.5, 1, 2, 3, 4, 5 and 6 m/s H=35 and 50 mm b= 3 and 6 mm	Frequency and Reynolds number increase the transfer of heat. Triple fins having h=50 mm and b=3mm spacing enhance better than others.
[37]	Ultrasonic vibrations improve double-pipe heat exchanger heat transfer.	Ultrasonic power =3 kW f=26.7 kHz Q_h= 0.5, 1, and 1.5 LPM Q_C=0.5, 0.75, and 1 LPM	Ultrasonic vibration increased maximum pressure drop and thermal performance.
[38]	Vibration-enhanced heat transfer to improve fin-tube radiator heat dissipation.	Q= 40 and 60 LPM V= 2, 4, 6, 8 and 9.5 m/s f= 1, 5, 10, and 20 Hz A=1, 2, 4, and 6 mm	Vibration increases heat transfer coefficient by 11.71% and gas side by 16.82%.
[39]	The oscillation properties on a vertical flat plate surface with uniform heat input influence mixed convection heat transfer.	q= 250, 500, and 625 W/m^2 A_o= 0.4, 0.75, 1.1, and 1.4 W_o= 65, 92, 113, 131, and 146	The numerical solution proves experimental results [17]. The oscillating vertical plate improves heat transfer more than the fixed plate.
[40]	Explore how vortex generator-generated pulsing flow improves the transfer of heat.	Pulsating, linked, and constant flows f= 24–25 Hz	Pulsating flow enhanced passive heat transfer by 28%, 25%, and 19.5% in coupled, constant, and pulsating, respectively.

5. Conclusion

By reviewing the studies mentioned above, which experimental and numerical studies on the impact of exposing heat exchangers to mechanical vibration to enhance the thermal performance of these systems, which involve different shapes of heat exchangers, such as heat sinks, vertical plates, and cylinders, the following is concluded:

1. It has been shown in most studies that there is a direct relationship between increases in heat transfer coefficients and vibration frequencies. This is due to decreased boundary layers caused by increased fluid motion.
2. Vibration's influence on heat transfer coefficient depends on its frequency and range.
3. Vibration cannot be used in large heat exchangers to improve performance because it increases pressure drop.
4. Although vibration improves heat transfer in heat exchanger systems, it generates noise as a result of moving objects at frequencies that are uncomfortable for humans. The corrosion may also cause metal bonds to break, resulting in damage to the system. The proposed frequency range must also be studied and specified lower than the natural frequency range since if the projected frequency matches the natural frequency, it would cause resonance, negatively impacting the results' accuracy.

Nomenclature

A	Amplitude, m	Q_c	Cold fluid flow rate, m^3/s
A_C	Cross-sectional area, m^2	Q_h	Hot fluid flow rate, m^3/s
A_O	Non-dimensionless oscillation amplitude	t	Fin thickness, m
b	Fin space, m	Ra	Rayleigh number
d	Fin diameter, m	Ra^*	Modified Rayleigh number
E	Non-dimensional Young's modulus	Re	Reynolds number
f	Frequency, Hz	Re_v	Vibration Reynolds number
f_r	Forced vibration	T_s	Surface temperature, °C
H	Fin height, m	T_{in}	Inlet fluid temperature, °C
k_r	Thermal conductivity ratio	T_{out}	Outlet fluid temperature, °C
L	Fin length, m	W	Width, m
m^*	Mass flow rate, kg/s	W_O	Womersley number

Nu	Nusselt number
P	Power, W
q	Heat flux, W/m^2
Q	Fluid flow rate, m^3/s

Greek symbols

θ	Inclined angle, degree
ϕ	Volume fraction
τ	Time, s

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