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**Research Article**



# The effect of Mechanical Vibration on the Heat Transfer and Flow Characteristics

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**Abstract:**

This review investigates the variations in flow characteristics and heat transfer performance of an annular chamber when subjected to longitudinal mechanical vibration. Considering previous research, the study demonstrates the thermal radiation induced by vibrations in engineering components, especially in heat exchangers. The research evaluates the effects of changes in vibration frequency, acceleration magnitude, and signal type on heat transfer rates and pressure drop in the annular opening. In addition, the vibration mechanism and flexible fins are investigated as alternative methods to enhance heat transfer by comparing the heat transfer coefficient between the baseline and optimal scenarios. Several studies have examined different flow configurations, spacing ratios, and flow regimes related to heat transfer and fluid dynamics around cylinders experimentally and numerically. Their results shed light on the diverse effects of spacing ratios and flow regimes on heat transfer and fluid dynamics. It is important to note that higher Reynolds numbers are associated with more uniform flow around cylinders without vortex shedding, possibly indicating the complexity within these networks. The present research is an extension of the convection of all types by vibrations, as it reveals the effect of vibration on the heat transfer performance of convection. This section presents a literature review to monitor the potential gaps in the literature related to the topic under discussion, which is helpful for further research.

## 1. Introduction

Various heat exchangers are used throughout several sectors, including power generation, chemical processing, and HVAC systems. The primary objective of current and future research is to enhance the efficiency of existing heat exchangers by operating under mechanical and ultrasonic vibrations, which are anticipated to improve heat transfer performance.
Vibration techniques provide resistance and subsequently discharge conventional layers or even enhance heat transmission, which is advantageous for reducing fouling. This study examines single-phase convection across many configurations, including helical tubes with wavy turbulators, concentric tubes, ultrasonic pulsations, and forced convection in finned cylinders. Among several thermal approaches, mass and heat are the most often used aids and factors, which are affected by frequency, vibration amplitude, and waveforms at each stage.
Prior research has shown how vibrations may enhance heat transfer efficiency and reduce pressure-related losses. Experimentally, it was demonstrated that increasing the diameter of the heat exchanger and using zigzags in the design may result in a doubling of the heat transfer rate and pressure loss [1-34]. Examining the ultrasonic vibration method in water cooling systems reveals that increased ultrasonic power is more effective when combined with reduced airflow velocity, enhancing thermal performance [22]. Examined the expansion of liquid films in micro-grooves and the

heat transfer induced by vertical mechanical vibrations [11]. The study by Manal H. and Hewage Dona addresses the impact of oscillatory flows and various configurations in which waveforms promote heat transmission. These investigations may illustrate new vibration methods' capability to surpass conventional heat exchangers' thermal efficiency, enhancing performance [24,30]. Amin conducted an experimental study on the impact of ultrasonic vibrations on the efficiency of water-cooling systems, seeing enhanced performance with varying power levels of ultrasonic application [22]. The study conclusively reveals that the cyclic compression approach may improve energy transfer in engineering operations. Nonetheless, a knowledge gap persists about the flow and heat transfer alterations inside vertically oriented chambers subjected to mechanical vibration. The investigation of boundary layers in fluid flow inside horizontal annular spaces is nascent since significant gaps exist in the present comprehension of interface interaction processes in these environments. This research addresses this gap by investigating the interplay between mechanical vibration and heat convection in horizontal annular spaces through systematically altering vibration parameters using modern experimental and computational techniques. This research examines the effects of tangential shear oscillation on flow regimes and pressure gradient costs in the central pipe, building upon prior studies. The study of vibration characteristics will include the inverse of frequency, the magnitude of acceleration, and the classifications of signals.

This element will be considered to enhance the heat transfer rate in forthcoming studies conducted in horizontal annular air spaces. This study seeks to rigorously and analytically deduce engineering conclusions pertinent to the integrated use of mechanical vibration to enhance heat transfer. This work addresses the knowledge gap by elucidating the fundamentals of heat transfer processes, enabling practical inferences for strengthening the design and operation of engineering systems to achieve superior thermal performance. This project aims to provide a valuable pathway for using mechanical vibration to enhance heat transfer in engineering applications via rigorous empirical validation and extensive analysis.

## 2. Previous Studies:

### 2.1 Experimental Studies:

Lin et al. (1996) [1] conducted an experimental study using non-Newtonian fluids (Carbopol 934 aqueous solution) with a concentration of 1000 to 2000 parts per million. Using a test platform containing a small square cross-section channel (hydraulic diameter = 0.4), the researcher found that when the concentration of the Carbopol solution increases, the value of the Reynolds number increases. Not only that, but the efficiency of local heat transfer also depended on the Reynolds number determined by the researcher. The researchers concluded that heat transfer can be improved if the Reynolds number is constant. Cmax must be higher than the solution concentration, and the capacity of the solutions is not limited.

Tian et al. (2004) [2] presented a new method for improving heat transfer, specifically transverse vibration methods. The researcher designed a test platform based on directing a beam of vibrations in a fixed range to increase the process of thermal energy transfer. The material used was pure water. The researcher found that the heat transfer process had increased at relatively high rates of up to 150%. As a result, he obtained regularity in the heat transfer coefficients and developed equations related to the Nusselt number. However, he did not try anything other than water as a working material.

The researcher Dae Hun Kim et al. (2007)[3] studied the effect of mechanical vibration on the critical heat flux (CHF) in a vertical annular tube heated at atmospheric pressure. As the flow regime changed from the cooling zone to the bubble zone, the vibration of the heating rod increased. Mechanical vibration improved the critical heat flux by up to 16.4%. Vibration amplitude was one of the factors influencing the increase in critical heat flux, while frequency and mass flow had no significant effect.

Improving heat transfer without increasing surface area is very important. Therefore, E. I. Eid et al.)2009)[4] conducted an experimental study on the possibility of increasing the heat transfer rate of a thin-finned flat-top heat sink in a personal computer as an experimental device using natural vibration. The sink consisted of four identical quadrants, each containing a specified number of fins. The sample was heated by an electric heater placed at the base. The researcher used a circular disc camera with a center of displacement to generate the vibration applied to the sample with an amplitude of 9 mm (BSB = 27 mm) and a displacement frequency of 12.5 Hz (BfB = 50 Hz). The experiment concluded a correlation between the Nusselt number, Strouhal number, and Reynolds number. It was shown that vertical vibration improved heat transfer by 85% in the current study compared to previous studies under constant heat flux and at the same average velocity. Comparing the current study with previously published studies, the heat transfer improvement is slightly greater in the case of vibration than in the case of pulsating flow.

Zena K. Kadhim et al. (2010) [5] The researcher studied the effect of the forced convection heat transfer coefficient on vertical forced vibrations, through an experiment conducted on a cylinder with an inner diameter of 16 mm and an outer diameter of 48 mm, surrounded by annular aluminum fins. The cylinder was heated under a constant heat flux (500, 1000, and 1500 W/m²) generated by an alternating voltage across a fixed resistance installed inside the cylinder, which was positioned at three different angles (0, 30, and 45 degrees). The researcher used frequencies between (2-16 Hz) and vibration amplitude ranges (0-2.2 mm). The study found a direct relationship between the vibration amplitude and the heat transfer coefficient at angles (0°, 30°, and 45°), gradually increasing with the frequency, until it reached a maximum percentage of (13.34%) when the frequency was zero. The greater the inclination angle, the lower the heat transfer coefficient. This is because the fins act as path lines that help increase the movement of convection currents in the horizontal case, while in the inclined case, the fins act as an obstacle to convection currents, reducing the heat transfer coefficient. In general, increasing the Reynolds number increases the heat transfer coefficient. However, they did not try to work vertically. In the same test setup and with the same variables, researcher Wissam Abid (2011)[6] replaced the fin shape from annular to triangular. The test achieved a lower result than the experiment above, with the highest improvement percentage (12.85%). This was due to the geometric shape of the new fin and because the surface area of the triangular annular fins is less than the surface area of the annular fins, therefore the impact of these fins on the heat transfer coefficient was less.

Alaei et al. (2012) [7] The researchers conducted a practical study of heat transfer through a specially designed platform. They directed a beam of vibrations at the test sample, using water as an intermediate fluid that transfers thermal energy. The researchers found that low frequencies helped in the heat transfer process. The best thermal performance was obtained at a frequency of 25 Hz and a thermal resistance of 0.05 kW.

Zena K. Kadhim et al. (2012) [8]In an experimental study, the researcher used a cylindrical glass bottle (75 mm in diameter and 300 mm in length) subjected to forced vibrations to investigate the effect of vibrations on the heat transfer coefficient at the boiling point of the pool. Heating is performed by an electric heater placed inside the cylindrical bottle to heat distilled water with heat flux values of (27.521 kW/m2 - 53.08 kW/m2). The researcher used frequencies of (2-40 Hz) and the vibration amplitude range was (1.8-3.5 Hz). Tests proved that the heat transfer coefficient at the boiling point of the pool increases with increasing vibration frequency in the frequency range of (2-14 Hz) compared to the transfer coefficient without frequency. The best improvement obtained by the researcher from the experiment was 250% at 5 Hz and 27.521 kW/m², 231% at 6 Hz and q"=36.727 kW/m², 181% at 6 Hz and q"=41.83 kW/m², and 93% at 8 Hz and q"=53.08 kW/m².

Chen et al. (2013)[9] The researcher's study focused on the heat transfer performance of a 600mm long, 8mm outer diameter copper cylindrical heat pipe and the effects of horizontal longitudinal vibrations on the condensing section temperature. Tests were conducted at frequencies of 3, 4, 5, 6, and 9 Hz and frequency amplitudes of 2.8, 5, 10, 15, 20, and 25 mm, allowing accelerations between 0.1 and 1.01 g. The researcher stabilized the condensing section temperature at 20, 30, or 40°C. A heating jacket and a cooling jacket were installed at the evaporation and condensation sections of the test cell to ensure a constant temperature and heat flux. When the vibration was applied horizontally in the longitudinal direction, this vibration caused an increase in heat transfer, and this increase was directly proportional to the vibration energy, which was less than 500 mm2 Hz2. When the vibration energy was increased above 500 mm2 Hz2, the heat transfer coefficient enhancement per unit vibration energy decreased rapidly.

Alaei et al. (2013) [10] The researchers conducted a practical study of heat transfer through a specially designed platform. They worked by directing a beam of vibrations on the test sample using water as a medium to transfer thermal energy. The researchers found that these frequencies significantly affected the thermal performance when using low frequencies. The researchers noted that increasing the frequency was not helpful at high filling ratios. This increase led to a 33.83% improvement in thermal performance at a thermal resistance of 0.064 kW and a frequency of 30 Hz. Figure 1 is evaporation section temperature variation and temperature distribution along the heat pipe as a function of the heating power (f = 3 Hz). Figure 2 is the relation between vibration frequency, and the axial length contact.

Chaohong Guo (2013) [11] The researchers studied the effect of low frequencies in a vertical heat pipe where different heat transfer rates, filling ratios, and frequencies were used to investigate the thermal resistance.

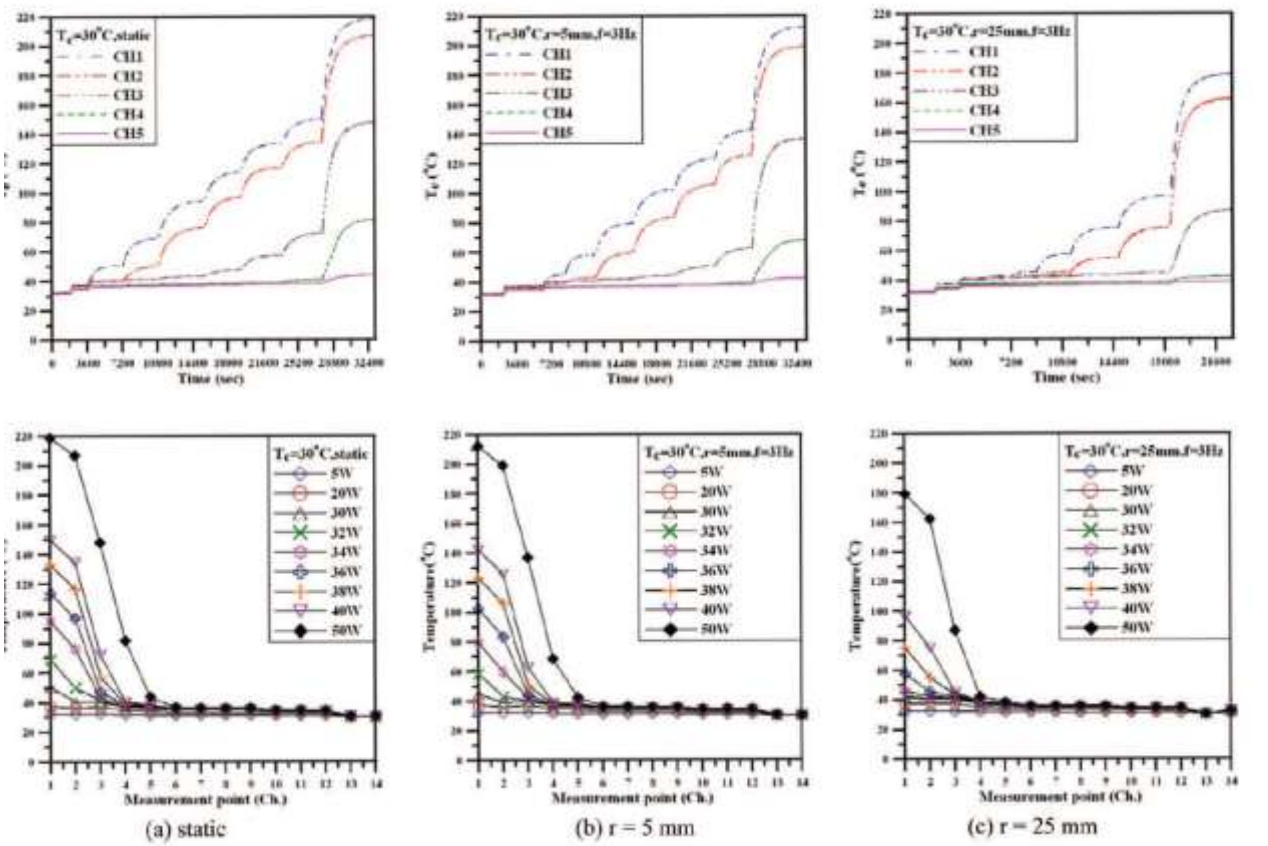


***Figure 1.*** *Evaporation section temperature variation and temperature distribution along the heat pipe as a function of the heating power (f = 3 Hz).*

when applying vertical vibration frequencies of 6, 10, and 30 Hz to a liquid film flowing through rectangular microgrooves with a thickness ranging from 0.2 mm to 0.4 mm and a depth ranging from 0.2 mm to 0.6 mm. The researchers observed that the dry point is pushed forward, and the wettability length is lengthened due to vibration. The researchers' analysis showed that vibration increases the heat transfer intensity in the microgroove due to the increase in its wettability area.

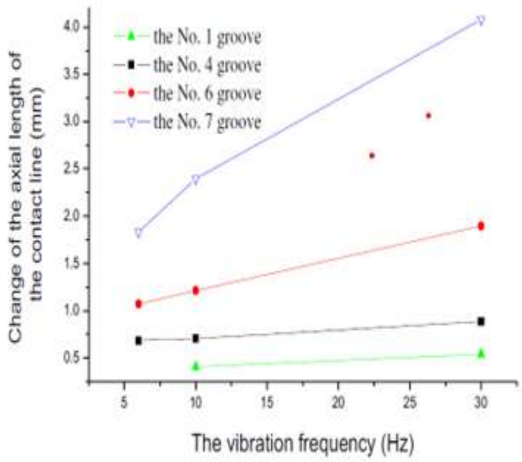


***Figure 2.*** *The relation between vibration frequency, and the axial length contact.*

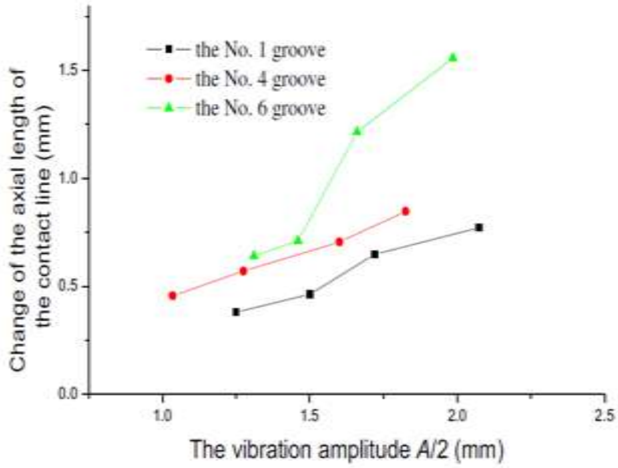


***Figure 3.*** *The effect of vibration amplitude on the axial length contact.*

The researcher Kuen Tae Park et al. (2014) [12]worked to find a relationship between the Nusselt number for convection assisted by vibration of vertical laminar fins. He conducted extensive experiments at different amplitudes and frequencies of forced vibration. The results indicate that the Nusselt number for vibrating fins, evaluated to its fixed fin value, is strongly influenced by the ratio of the vibration speed to the buoyant engine flow speed. Based on this result, the researcher proposed a relationship that can be applied at speed ratios from 0 to 20 and vibration frequencies from 29 to 59 Hz. Figure 3 is the effect of vibration amplitude on the axial length contact and figure 4 (a) Effect of frequency on boiling curves at 1 mm amplitude. (b) Effect of frequency on heat transfer coefficient at 1 mm amplitude.

Haider Zuhair et al. (2015) [13] The researchers conducted an experimental study on the effect of induced vibration on a concentric vertical ring with a radius of 0.365 and a heated outer cylinder of 1.2 m length for constant heat flow and a solid rotating inner cylinder. Study the effect of induced vibration on the hydrodynamic and thermal boundary layer. The study was conducted in the range of 514 to 1991 Reynolds number, 10.44 x 104 and 82.23 x 104 Taylor number, while the heat flux was between 468 W/m2 and 920 W/m2, and the frequency was 32 and 77 Hz. The results showed that forced vibration increases the heat transfer rate, and Nu increases with increasing the rotational speed of the inner cylinder despite the constant frequency and heat flux.

Kadhim (2016) et al. [14] The researcher tried to apply forced vibrations to a heated aluminum cylinder containing longitudinal fins in free convection. The researcher used different vibration frequencies between 2 and 16 Hz and heat fluxes from 500 to 1500 W/m2. The researcher found that the heat transfer coefficient and vibration amplitude increase at angles from 0 to 45 degrees. In contrast, the heat transfer coefficient in free convection decreases with increasing inclination angle. The results were an 8% and 30% increase in the heat transfer coefficient ratio (hv/ho) at angle zero over angles 30 and 45 degrees.

A. Hosseinian et al. (2017) [15]The researcher studied the results of applying vibration to the surface of a double-tube heat exchanger made of PVDF and its effect on the heat transfer coefficient. Using electrodynamic vibrators, and at forced vibration values applied to the outer surface of the exchanger (3-9 m/s², 100 Hz), experiments were conducted at internal Reynolds numbers between 2533 and 9960. The researcher found that the vibration level and mass flow rate increase the heat transfer coefficient. The maximum increase in the heat transfer coefficient reached 97% at a vibration value of (9 m/s²).

The researcher A. Sathyabhama et al. (2017)[16] applied mechanical vibration to a flat circular copper surface to demonstrate the effect of vibration on the heat transfer coefficient of boiling water in a swimming pool at 1 bar. A vibration exciter was used to vibrate the copper surface vertically. The researcher studied the effect of vibration frequency and amplitude on the heat transfer coefficient. The results showed an increase

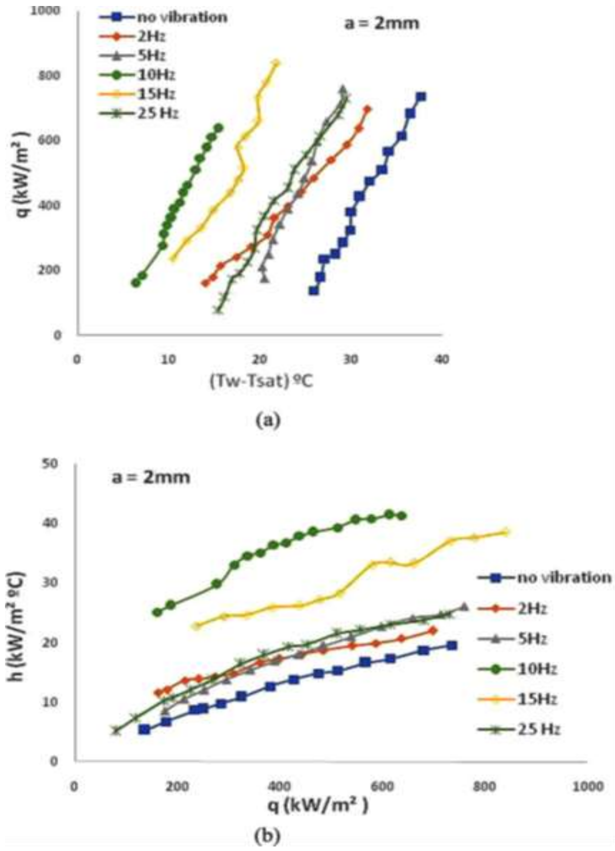


***Figure 4.*** *(a) Effect of frequency on boiling curves at 1 mm amplitude. (b) Effect of frequency on heat transfer coefficient at 1 mm amplitude.*

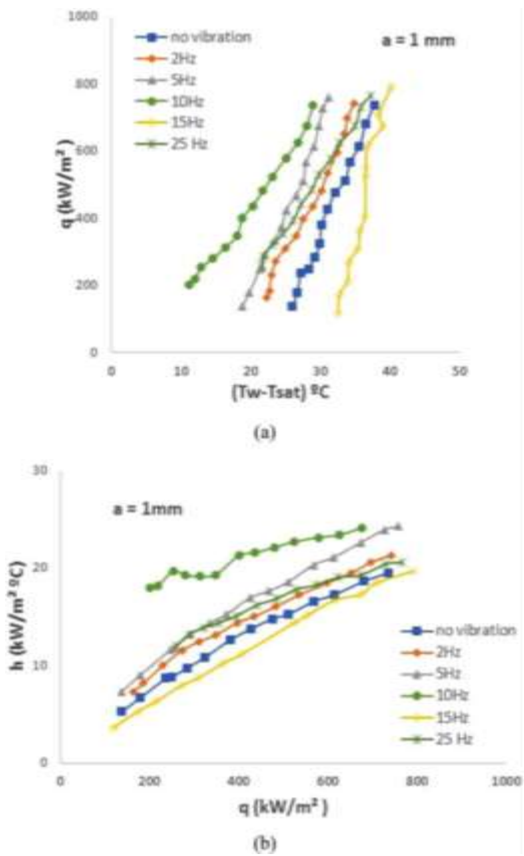


***Figure 5.*** *(a) Effect of frequency on boiling curves at 2 mm amplitude. (b) Effect of frequency on heat transfer coefficient at 2 mm amplitude.*

in the heat transfer coefficient at low frequencies and amplitudes, while high amplitude and frequency lead to a deterioration of the heat transfer coefficient. A 26% increase in the heat transfer coefficient was calculated with vibration intensity, which is represented by the vibration Reynolds number. Figure 5 is (a) effect of frequency on boiling curves at 2 mm amplitude and (b) effect of frequency on heat transfer coefficient at 2 mm amplitude. Figure 6 is intensification of heat transfer. Liu et al. (2017) [17] The researcher conducted practical experiments on a hot circular tube with water as a working fluid to investigate sinusoidal vibrations' effect on the internal flow's heat transfer properties. At the inlet, the Reynolds number was 512 and 2047, while the vibration frequencies ranged from 158 to 3000 Hz, and the vibration acceleration was 1.0 g, 3.0 g, and 5.0 g. The vibrations of mechanical force had a significant effect on heat transfer. In contrast, with the vibration acceleration, the Nusselt number increased, and it was not obvious, but with the increase of the inlet speed, the change in the Nusselt number was weak. At the resonance frequency value of 400 Hz, the Nusselt number increased rapidly, decreasing sharply and stabilizing at 1500 Hz. This study proved that the strength of the effect of vibration frequency is greater than the effect of vibration acceleration on improving heat transfer. They reached the maximum heat transfer improvement at Reynolds number 512 and vibration 400 Hz.

Sathyabhama Alangar (2017) [18]The researcher presents an experiment applying forced vertical surface vibration to the heat transfer of boiling saturated water in a nuclear bath at atmospheric pressure. The vertical vibration was externally induced on the circular copper surface on which boiling occurred, by means of a vibration exciter. The vibration frequency range was 0 to 25 Hz, and the vibration amplitude was 0 to 5 mm. For the same heat flux, boiling occurs at very low superheat temperatures. When the surface is subjected to external stimulation, the slope of the boiling curve decreases significantly. The researcher found that high-frequency and high-amplitude vibrations have a more intense effect on the heat transfer coefficient. He also found combinations of amplitude and frequency that bring the transfer coefficients up to two-fold.

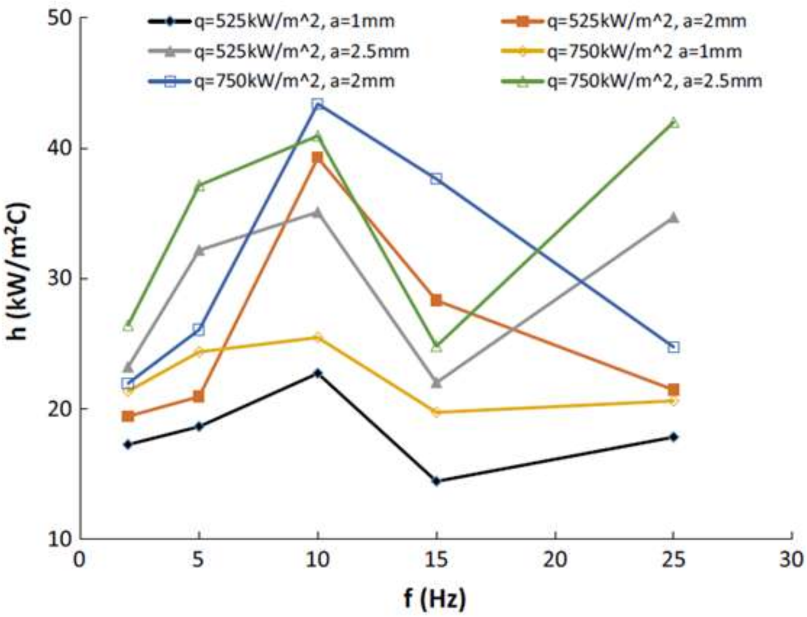


***Figure 6.*** *Intensification of heat transfer*

Ezzat & Ghashim (2019) [19] The researchers conducted a practical experiment on a horizontal circular tube with a length of 0.6 m and an internal diameter of 0.025 m, the outer surface of which was exposed to different heat flow patterns, to show the extent to which the boiling safety coefficient of the cooling channel is affected by the heat flow distribution. Four flow patterns were used, namely (fixed distribution pattern type A, triangular distribution pattern with a maximum at the center of the channel type B, triangular distribution pattern with a maximum at the inlet type C, and triangular distribution pattern with a maximum at the outlet type D). The heat source capacities were 1000 and 2665 W, while the water flow rates were 5, 7, and 9 L/min. At the inlet of the cooling channel, the temperature was fixed at 25 °C. The electric heater was wrapped around the tube so that it covered 0.5

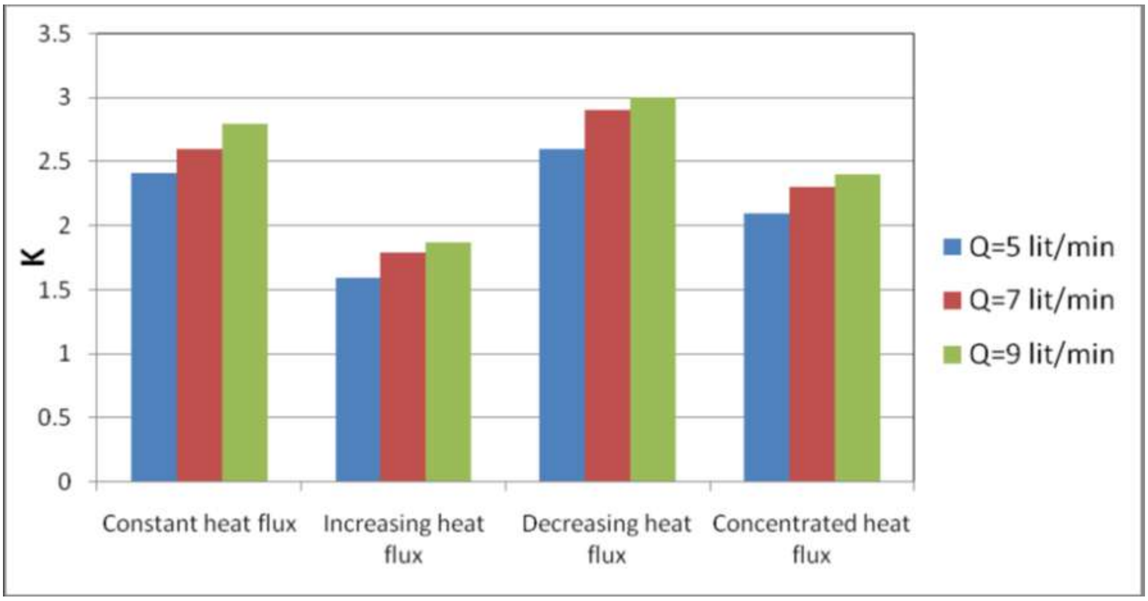


***Figure 7.*** *Variation of the minimum boiling safety factor at maximum wall temperature positions for different heat flux profiles at a heating capacity of 1000 W.*

m of the length of the experimental tube. The results showed that pattern C is the most reliable for both capacities regarding thermal and hydraulic safety, while pattern D is the worst in the same respect and for the same variables to which type C is exposed. Figure 7 is variation of the minimum boiling safety factor at maximum wall temperature positions for different heat flux profiles at a heating capacity of 1000 W. Figure 8 is vibrations of Nu and Eh with air pulsation amplitude ($f$=20Hz).Li et al. (2021) [20] The researcher used the reverse flow in hollow fiber membranes widely used in humidification and dehumidification. When vibrating, the hollow fiber membranes are deformed due to the impact force of the flowing air and the gravity of the liquid in the inner tube. In this experiment, the pulsating sinusoidal flow of air was the main deformer of the fibers. Using multiple pulse frequencies and amplitudes, the deformation of single fibers was numerically verified and experimentally by the fluid-structure method and compared with the data of the laser vibration meter, whose data were experimentally tested. The maximum deformation of the fibers was along the airflow direction and even more significant than that perpendicular to the flow direction. Compared with the non-vibrating fibers, the strength of the nickel was enhanced by 14-87% if the pulse amplitude was increased. The heat transfer index was improved by 13.8% to 80% by the vibration caused by the fiber flow. Khalifa Salim et al. (2021) [21] experimentally investigated the extent to which the thermal load force is affected by vertical vibration and its effect on the average Nusselt number if the tube is longitudinally finned. The tube experimental positions were used at 0, 30, and

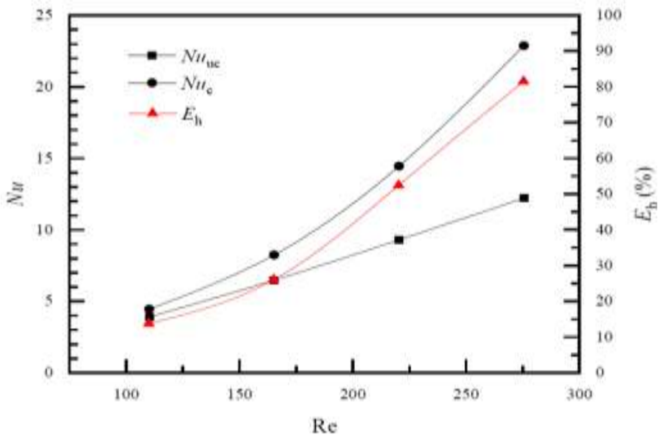


***Figure 8.*** *Vibrations of Nu and Eh with air pulsation amplitude ($f$=20Hz)*

45-degree angles, with a frequency of less than 16 Hz and a heat flux between 500 and 1500 W/m2. It was found that there was good agreement between this study and previous studies, and the deviation of this study was 5%. The results showed that the highest improvement obtained from the experiment is 14% to 16% at an angle of 45 degrees compared to angles of 0 and 30.

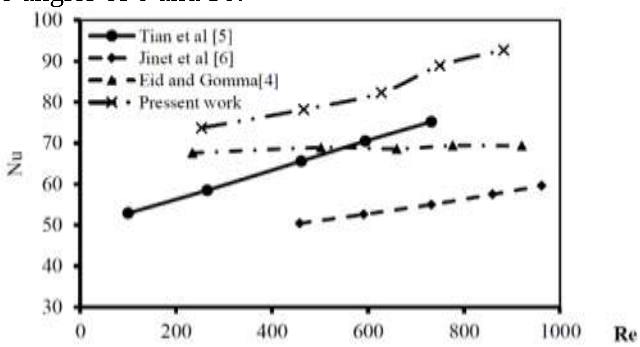


***Figure 9.*** *Comparison between current work and previous studies.*

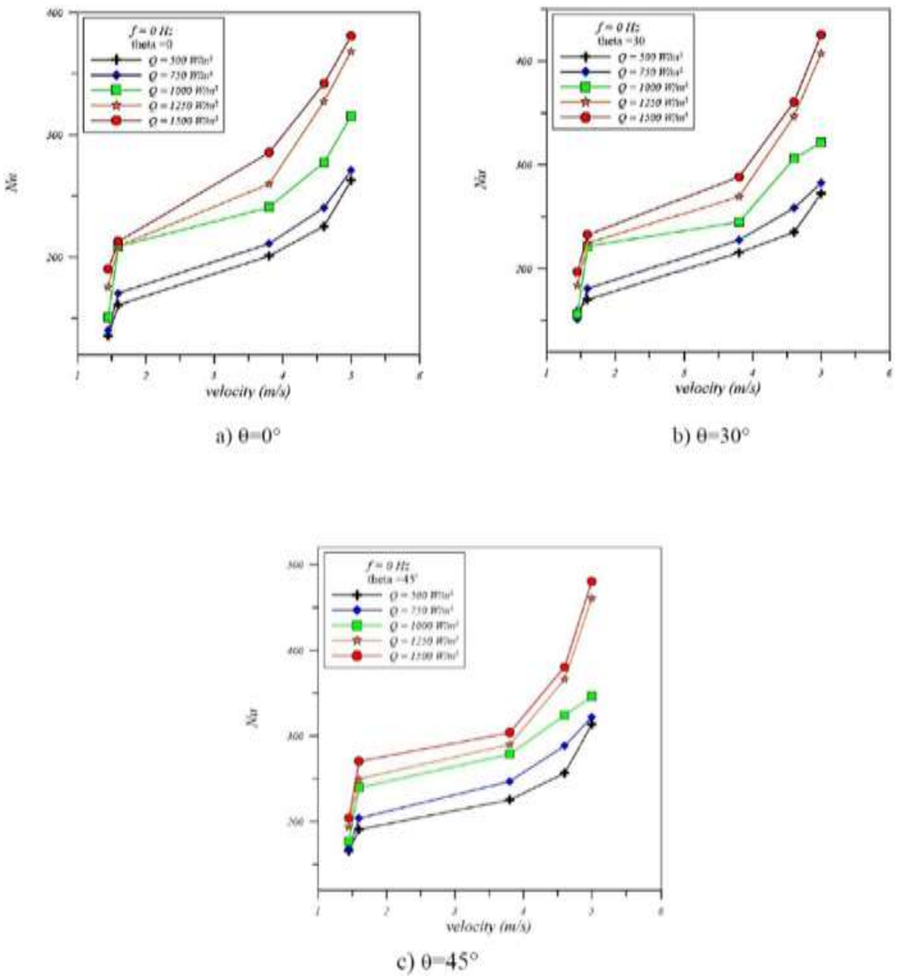


***Figure 10.*** *The velocity effect on the fin tube's Nu with f = 0 Hz at different heat rates and angles.*

Figure 9 is comparison between current work and previous studies. Figure 10 is the velocity effect on the fin tube's Nu with f = 0 Hz at different heat rates and angles. Figure 11 is relation of the airflow rate & Nusselt number. Amin A. et al. (2022) [22] The researcher experimentally studied the effect of ultrasonic vibrations on the power of 30, 60, and 120 watts and different cooling fluid flow rates (air). The researcher verified the validity of the results of his study by experimental correlations to ensure the accuracy of the measurement systems. Ultrasonic vibrations enhanced heat transfer in liquid-cooled heat exchangers. It was also found that reducing airflow and increasing the power of sound waves improved thermal performance. The highest effect ratio was achieved at the highest ultrasonic power and the smallest ventilation volume of the cooling tower fans, as shown in Figure 7). As for improving heat transfer, the highest ratio (qup/q0) and the Nusselt number ratio (Nuup/Nu0) were 1.18 and 1.24, respectively. Researchers Kazem and Sarhan (2023) [23] The researcher conducted an experimental study on a flat metal plate made of aluminum measuring (300L * 100W * 3t mm) and the extent of the effect

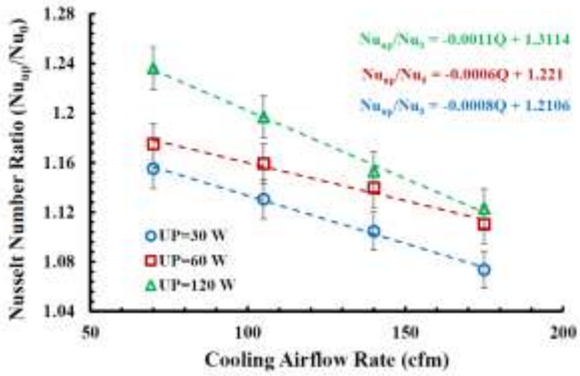


***Figure 11.*** *Relation of the airflow rate & Nusselt number*

of vertical vibrations on the heat transfer coefficient by natural convection. The plate was heated under a constant heat flux of 250-1500 W/m2; the plate was placed at different angles horizontally once and tilted at angles several times (0, 30, 45, 60, 90) degrees. Forced vibration was applied with a frequency ranging between (2-16 Hz) and an amplitude of (1.63-7.16 mm), and the Rayleigh number was (138.991< Ra <487.275). It was found that the heat transfer coefficient and vibration amplitude increase with increasing the tilt angle from 0 to 60 degrees and reach their highest value of 13% when placed horizontally. However, the heat transfer coefficient decreases by 7.6% when placed vertically at an angle of 90 degrees.

**2.2 Numerical studies:**

Manal Al-Hafez et al. (2006) [24] The researcher applied forced vibration to a pipe at a 0° angle with the horizon to find the effect of vibration on forced convection heat transfer with laminar flow and fully developed vibrational incompressible internal flow. The vibration was parallel to the fluid flow; in the inlet region, the boundary layer was studied for Prandtl numbers greater than one, and the hydrodynamic boundary layer grew faster than the thermal boundary layer. The vibrational Reynolds number and vibrational velocity indicated a boundary condition. When the vibrational Reynolds number increases, the local and average Nusselt number increases due to the effect of vibration, and overall, this leads to an increase in the heat transfer coefficient.

Al-Shorafa'a et al. (2008) [25] The researcher selected horizontal cylinders with diameters of (2.15, 3, and 3.8 cm), heated them electrically, and applied vertical vibration to them at frequencies of (10, 15, and 20 Hz) and used amplitude range of (0.0005 to 0.0076). By checking (hv/ho), it was found that high frequency and small diameter improve the heat transfer ratio, while the Reynolds number was not without benefit as it has a good effect on heat transfer. The researcher found that the vibration intensity positively affects heat transfer, while (Gr. Pr) was insignificant at high heat fluxes.

Shoele et al. (2014). [26] The researcher conducted a numerical study on a heated channel using the vortex motion generated by the flow. The researcher developed an immersed boundary method to solve the coupled flow, structure, and temperature problems. The results showed that a vibrating vane significantly improves the heat flow rate. The study concluded that the thermal performance depends more on the inertia of the vane than on its bending stiffness. The maximum thermal performance was achieved by the simulation when large modifications were created in the channel boundary layer by the reeds while avoiding the formation of strong vortices.

Adel Mahmoud et al. (2020) [27] The researcher numerically studied the effect of vertical and horizontal vibration on natural convection in a square container filled with air at Rayleigh numbers 7× 107and 4× 108. The container consisted of two opposite, perpendicular surfaces (the right surface being hot and the left surface being cold), while the other two were stationary. The researcher studied three cases: the first case (after reaching a steady state, the vibration effect starts at each frequency),

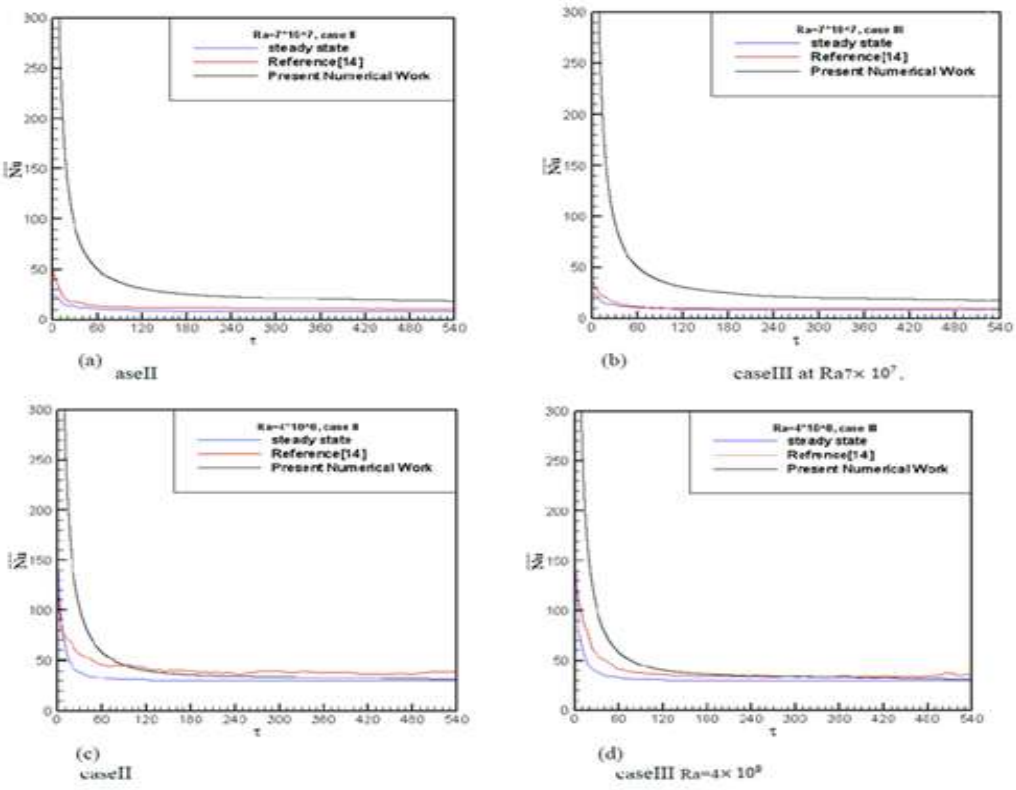


***Figure 12.*** *Comparison of the variation of the average Nusselt number for different time steps*

and the second and third cases (the vibration effect starts at ascending and descending frequencies). The study found that vibration motion does not significantly enhance heat transfer when gravitational convection dominates at Rayleigh number (Ra = 4 × 108), while vibrational convection dominates at Rayleigh number (Ra = 7 × 107), and vibration significantly improves the heat transfer rate. The researcher used frequencies (2, 3, 4, 6, 8, and 9), but did not test the effect of frequencies above 9.

Yang Z. (2020) [28] Using FLUENT software, the researcher simulated an isothermal circular cylinder to investigate the effect of vibration on the heat transfer properties of forced convection. The Reynolds number was set to 100, and the flow was assumed to be two-dimensional, incompressible, and laminar. The low-speed range was $3 \leq U* \leq 10$, where $U* = U\infty / (f\ n\ D)$. Changing the low-speed range affects the formation and shedding of vortices, which in turn affects the vibration response and heat transfer of the cylinder. Both the displacement Nusselt number and the surface-averaged Nusselt number change over time. Vibration causes a shift in the position corresponding to the largest local Nusselt number at the front stagnation point. The results show that the cylinder's maximum heat transfer performance is achieved when $U* = 6$ and that the spatial and temporal average Nusselt number increases by 5.73% and 2.46% compared to the steady-state and vibration cylinders, respectively.

Mitsuishi et al. (2020) [29] A series of direct numerical simulations were conducted by the researcher to investigate the effect of transverse vibration in a tube and the extent to which it enhances heat transfer in a convective catalytic converter. Assuming that turbulent flow enters a thin tube from a honeycomb solution, the frictional Reynolds number was set at 60, which is determined by the tube radius and the frictional velocity, with the initial state of fully developed turbulent flow at a higher Reynolds number. The researcher controlled the vibration by amplitude and frequency, applying vibration frequencies of 1.6 and 0.4. The study found that the increase and decrease of the Nusselt number were periodic with time, achieving the highest increase of 70% on average compared to the uncontrolled case. It is observed from the flow field visualization that double vortices play a significant role in improving heat transfer. The study also confirmed that another important parameter in improving heat transfer is the vibration velocity amplitude.

Ambagaha et al. (2022) [30] The sine-wave vibrating heat sink is one of several electronic cooling methods that improve heat transfer by creating vortices in the thermal boundary layer, thereby breaking or vibrating it. Sine-wave vibration has reached its limit in improving heat transfer. Therefore, this study used a new waveform, the square wave, and numerically investigated the performance of a heat sink subjected to vibration in both sine and square waveforms. It was found that the square wave enhanced thermal performance more than the sine wave. The results showed that the square wave enhanced the Nusselt values by 25% compared to the normal state (without vibration), which is 11% greater than the sine wave enhancement. The Reynolds number can be reduced by 42.2% to reach the Nusselt number of the non-vibrating fins. This leads to a smaller cooling system or heat sink size, contributing to the electronic systems' integrity.

Ambagaha et al. (2023) [31] The researcher conducted a numerical study to investigate the effect of vibration direction on the vibration waveform and, in turn, on a conventional heat sink, with a maximum deviation of 2.4%. The researcher used sine and square waves, with frequencies ranging from 0 to 80 Hz and amplitudes ranging from 0 to 0.005. The researcher found that frequencies greater than 40 Hz increase the Nusselt number, with the square wave dominating the Nusselt number. The highest Nusselt number increase occurred at a frequency of 80 Hz and an amplitude of 0.005 m, with increases of 9.3% and 7.2% for the square and sine shapes, respectively. Compared to published work, horizontal vibration outperforms vertical vibration in heat transfer by 7% and 3.2% for square and sine waves, respectively. Figure 12 is comparison of the variation of the average Nusselt number for different time steps and figure 13 is effect of the oscillatory Reynolds number on the heat transfer coefficient. Figure 14 is improvement in heat transfer coefficient concerning vibration values.

### 2.3 Numerical and Experimental Studies

Leonid Bronfenbrener et al. (2001) [32]The research conducted an experimental and theoretical study on a tube with rotating rings on its outer surface due to the applied vibration forces (the hula hoop effect) to demonstrate its effect on heat transfer. The researcher chose water as the medium for forced heat transfer, and the Reynolds number was between 800 and 2000. The researcher chose a vibration amplitude between 0.1 mm and 1 mm, and a frequency between 10 and 120 Hz. The study showed good agreement between the experimental and theoretical models, such that the average heat transfer coefficient increases with increasing vibration.

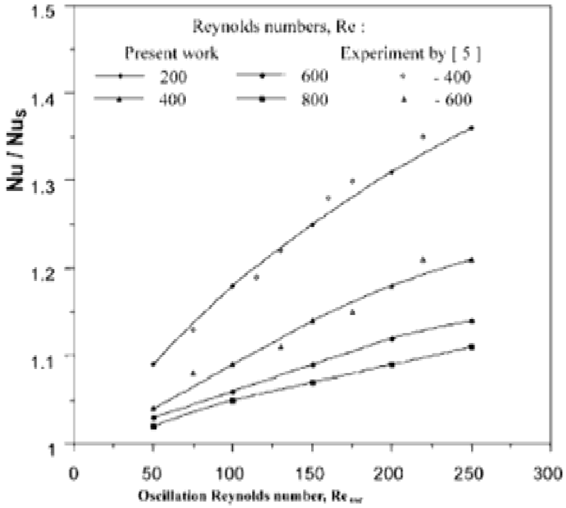


*Figure 13. Effect of the oscillatory Reynolds number on the heat transfer coefficient.*

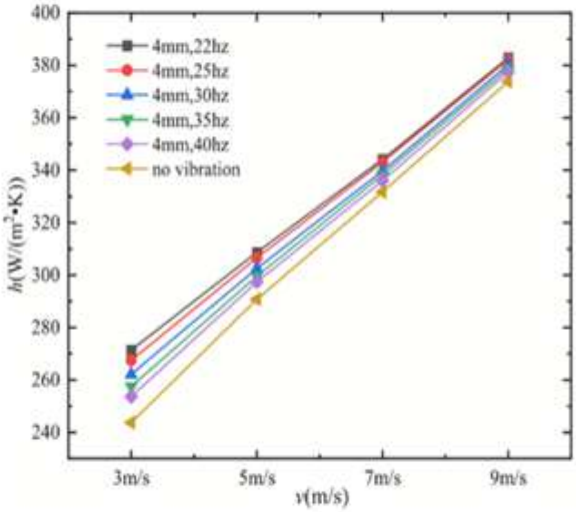


*Figure 14. Improvement in heat transfer coefficient concerning vibration values.*

## 2.4 Vibration Effect in heat exchangers:

Li et al. (2024) [33] Conducted a practical study to demonstrate the extent of improvement in the heat transfer process using vibration technology. The researchers designed a test platform containing an air duct containing fins on which vibration waves were directed. The researchers found a 12% noticeable improvement in the heat transfer coefficient, which shows the importance of the improvement provided by vibration technology. The researchers also found that the layer near the wall was significantly affected, indicating that the flow near the wall was disrupted. This improves the heat transfer process compared to the regular flow in which there is no disruption.

The researcher Mohammed et al. (2021) [34] Conducted a practical study to demonstrate the effect of vibration on the heat transfer process. The researchers designed and implemented a test platform consisting of a concentric tubular exchanger with air as a heat transfer fluid, with a Reynolds number ranging from 10,000 to 55,000. To increase the turbulence, the researchers placed oscillators inside it that work to improve the turbulence of the flow. Different types of vibration devices were used to demonstrate their practical effectiveness. The variable parameters of the vibration phenomenon are acceleration (amplitude) (a = 100, 300, and 600 m/s2), frequency (F = 100, 300, and 600 Hz), and signal type (cosine, chirp,

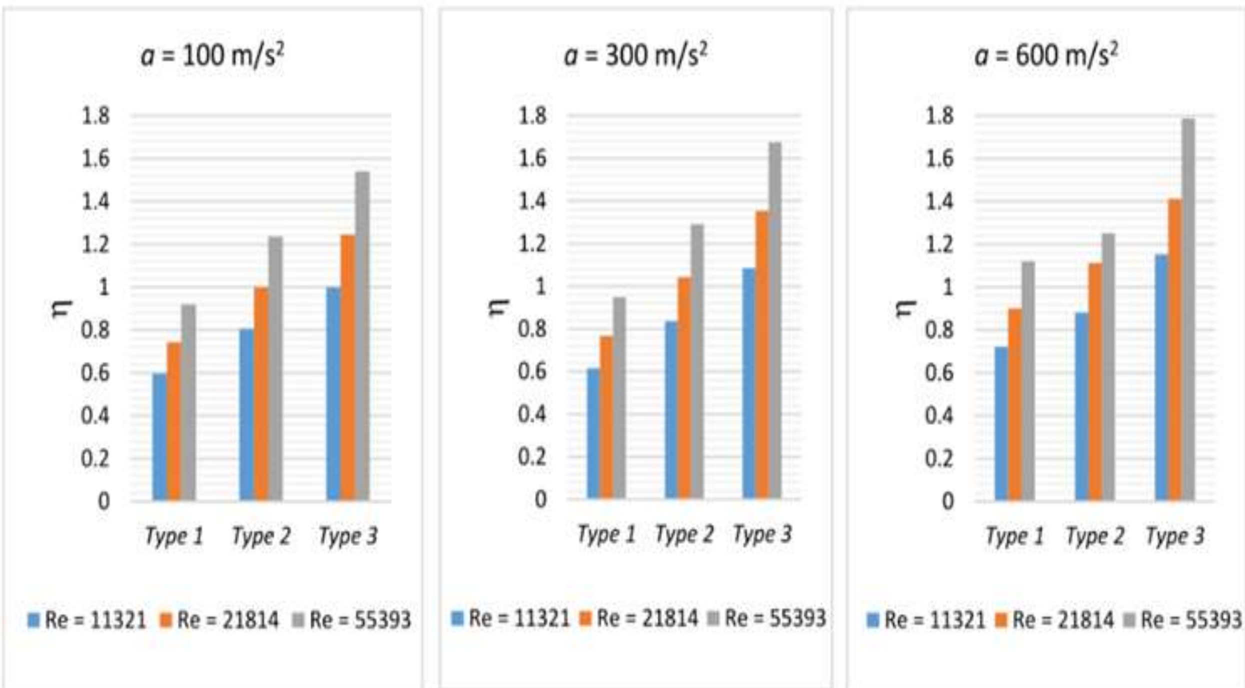


*Figure 15. Effect of acceleration on thermal performance factor.*

and random noise). The researchers found that vibrations helped improve the heat transfer process, as indicated by the increase in the thermal performance coefficient, which reached the highest percentage of 16%. However, they also found an increased friction coefficient of up to 95%.

### 2.5 Newtonian and Non-Newtonian Fluid Under Vibration:

Newtonian fluids are fluids whose viscosity remains unchanged with any change in applied stress or shear rate, such as water, air, and most common liquids. Non-Newtonian fluids, on the other hand, change their viscosity with any change in applied stress or shear rate. Their behavior is different from that of Newtonian fluids, such as when pressure is applied to them, they become thicker or thinner. Common examples of these fluids are ketchup, toothpaste, and cornstarch in water. These two types are very important in various fields, such as medicine, engineering, and construction. [[35],[36]

Mechanical vibration can significantly improve heat transfer by breaking up the thermal boundary layer and promoting more efficient mixing within the fluids [37]. In heat exchangers, the use of mechanical vibrations of various frequencies and amplitudes helps increase turbulence, accelerating the rate of heat transfer between fluids. Vibration is often used in applications involving phase change materials, such as cooling systems, to improve heat dissipation efficiency. Additionally, vibration excitation is used in microgravity environments (such as space stations) where natural convection is weak, helping to maintain a uniform heat distribution. Vibrating surfaces, such as those found in some industrial heat exchangers,[38] can help prevent the buildup of dirt and deposits by reducing contaminant accumulation. Furthermore, vibrating fluidized beds enhance heat transfer by improving particle movement and contact with heat transfer surfaces.[39] In electronics cooling, vibration-assisted systems are increasingly being explored to improve the thermal management of precision machinery. The application of vibration in heat transfer systems can lead to smaller and more efficient designs, reducing energy consumption. It is also used in applications such as drying, where vibration accelerates the removal of moisture from materials. However, the effectiveness of vibrations depends on the frequency, amplitude, and properties of the fluid or material being processed [[40,41,42]. Figure 15 is effect of acceleration on thermal performance factor. Figure 16 is effect of vibration (20 Hz) on heat transfer [40].

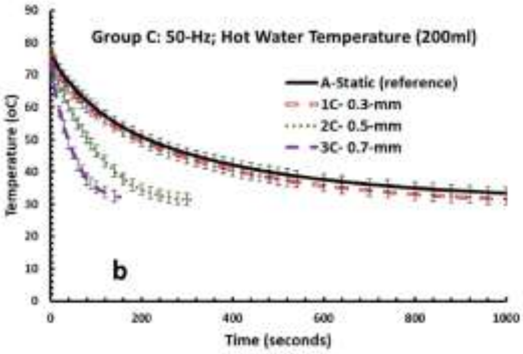


***Figure 16.*** *Effect of vibration (20 Hz) on heat transfer [40]*

## 3. Conclusion

In conclusion, the research indicates that vibration significantly enhances heat transfer efficiency across the engineering domain. This study examines heat exchange between the annular chambers due to mechanical vibrations, utilizing frequency, acceleration, and signal as parameters. It discusses methods such as vibrating and flexible fins to enhance heat retrieval and, consequently, heat transmission efficiency. Previous research has demonstrated that heat pipe cavities using ultrasonic vibrations and flexible fins are highly effective. This study aims to address the current gap in comprehension and employ diverse experimental and computational methods by adjusting vibration parameters. This work seeks to identify the theoretically feasible engineering concepts that optimize heat transfer by altering mechanical vibrations. Additionally, this pertains to the interaction of fluids with structures, primarily focusing on the flow field around tubes and encompassing significant aspects of the problem's features. Experimental and computational methodologies have emerged as pivotal tactics in contemporary science and engineering, facilitating the discovery of complex flow patterns and subsequent bioengineering applications. Even there are some previous works done on Thermal Efficiency [42-45], it is needed to further investigations.

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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