

OVERVIEW OF THE MECHANICAL FORCED VIBRATION USED TO ENHANCE HEAT TRANSFER

Z.Kh. Majeed¹, E.F. Abbas² and I.J. Hasan^{2*}

¹Renewable Energy Research Centre, Northern Technical University, IRAQ

²Mechanical Power Techniques Engineering, Technical Engineering College - Kirkuk,
Northern Technical University, IRAQ

E-mail: ehsanfadhil@ntu.edu.iq

This review systematically examines the role of mechanical vibrations in enhancing heat transfer across various thermal systems. Although vibrations are traditionally considered detrimental to mechanical integrity, controlled application of vibrational forces can significantly improve thermal performance by promoting fluid mixing and surface turbulence. The study synthesizes findings from theoretical, numerical, and experimental research involving different geometries such as flat plates, cylinders, and microchannel structures. Results consistently demonstrate that specific ranges of vibration frequency and amplitude can enhance convective heat transfer, with some studies reporting improvements up to 250%. Conversely, inappropriate vibrational conditions can lead to performance degradation or mechanical failure. Key parameters influencing outcomes include vibration mode, fluid properties, system configuration, and thermal boundary conditions. Applications span aerospace, electronics cooling, and energy systems, where vibrational techniques have reduced fouling, improved heat exchanger efficiency, and enabled lightweight thermal management solutions. The findings highlight the importance of carefully tailoring vibrational characteristics to optimize heat transfer while maintaining structural integrity. This work provides critical insights for the design of advanced thermal systems utilizing vibration-assisted heat transfer mechanisms.

Key words: mechanical vibration, heat transfer enhancement, thermal management, convective heat transfer, vibrational systems, energy systems.

1. Introduction

Vibrations refer to short-term, reciprocating motions that occur within mechanical systems. Although most mechanical systems may be subjected to motion or vibration during operation, the term "vibration" in mechanical engineering is usually used to describe vibrations that occur naturally or under the influence of periodic external forces, whether free or forced. These vibrations can sometimes result in minor issues that may be ignored if they don't negatively impact performance. However, they can also lead to significant performance or safety concerns and can even cause damage to systems. For instance, excessive vibrations in an aircraft wing can lead to discomfort for passengers, particularly when the vibration frequencies align with the natural frequencies of the human body, its organs, or the aircraft structure and components. Conversely, vibrations in thermal systems can be advantageous by enhancing heat transfer due to surface vibrations and increased turbulence in the adjacent layer, which improves the heat transfer rate. Additionally, vibrations promote fluid mixing, further increasing the heat transfer coefficient. However, vibrations can be detrimental when retaining heat within the system, which is crucial, leading to minimizing heat dispersion and reducing heat transfer. In such cases, vibrations have a negative effect. More than sixteen distinct heat enhancement techniques have been identified and systematically classified into two main categories, as illustrated in Fig.1 [1]-[3].

Al-Shorafa'a [4] and Chen *et al.* [5] reported that active heat transfer enhancement methods often require an external power source to modify the system and intensify heat transfer, which makes their

* To whom correspondence should be addressed

implementation and design more complex. Examples of such active techniques include jet impingement, surface vibration, flow oscillation, and mechanical aids. However, oscillation and vibration phenomena in industrial systems such as fluid flow instabilities or vibrations in mechanical and aerospace applications may lead to structural failures due to the additional stresses imposed on material components. Despite these challenges, Shokouhmand *et al.* [6] demonstrated that vibration is an effective technique for improving heat transfer. This enhancement occurs because vibration promotes turbulence in the fluid layer adjacent to the heated surface, disrupting particle trajectories within the fluid and thereby increasing the overall heat transfer rate. According to Bergles *et al.* [1], passive heat transfer enhancement techniques mainly involve geometric modifications to the flow channel surface, usually by adding inserts or other devices that alter the flow structure. Alongside extended surfaces, which increase the effective heat transfer area, these techniques boost heat transfer coefficients by disturbing or redirecting the fluid flow, thereby encouraging turbulence and improving mixing. Common passive methods include twisted tapes, coiled wires, roughened or dimpled surfaces, extended fins, and displaced or vortex-generating inserts. Such modifications effectively enhance convective heat transfer but often come with a penalty in the form of a higher pressure drop across the channel.

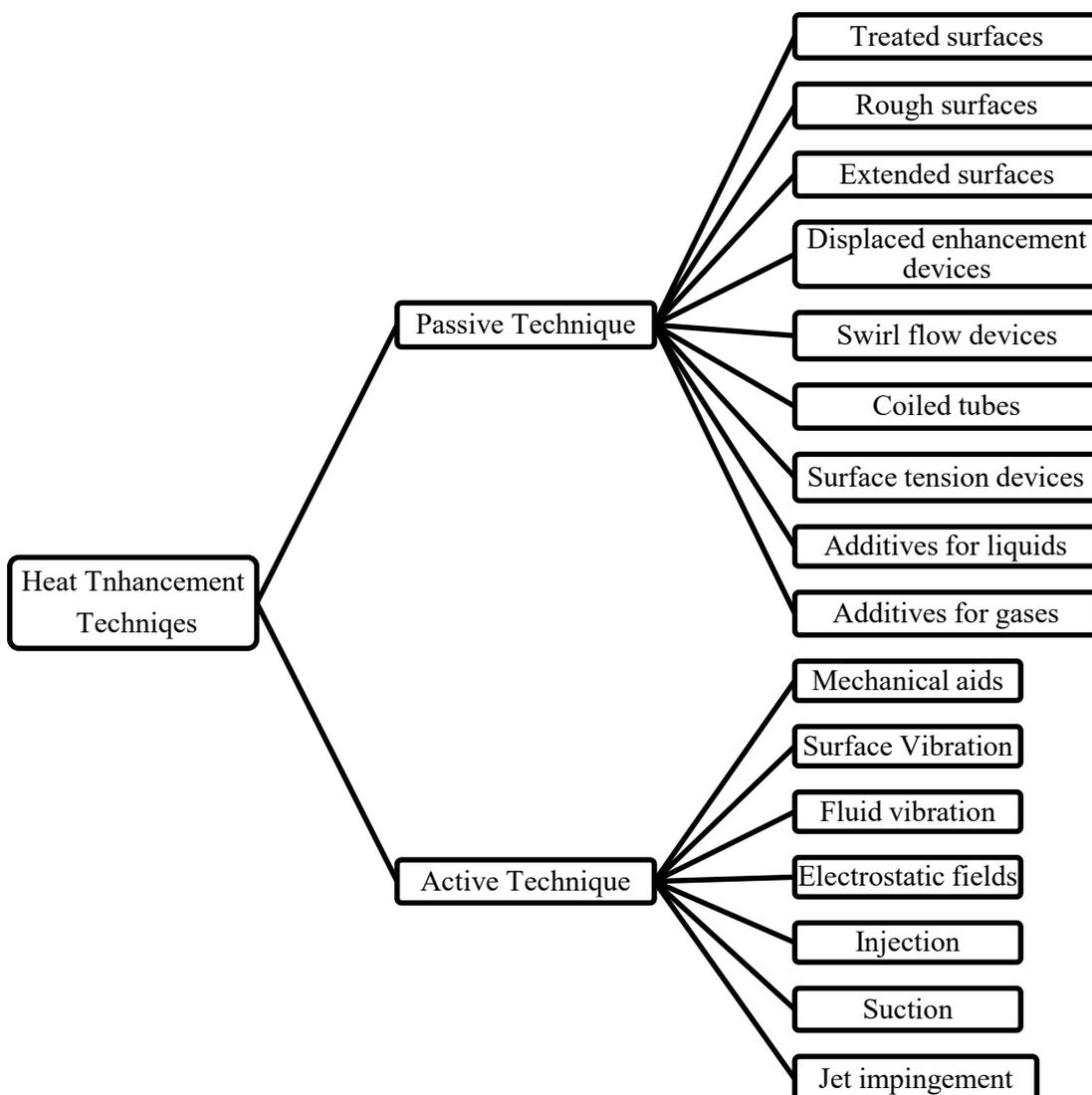


Fig.1. Heat enhancement categories [1]-[3].

Therefore, designing passive enhancement systems requires careful optimization to balance thermal performance improvements against the hydraulic losses involved. De Silva [7] provided a thorough understanding of vibration theory and its practical applications in engineering vibration, incorporating real-world engineering practices through covering modelling, analysis, measurement, and control of vibration in mechanical systems. A review of existing studies examining the impact of vibration on the performance of thermal equipment across various geometrical configurations, frequency and amplitude ranges, and thermal boundary conditions has been conducted. The findings reveal that vibration can either enhance or impair heat transfer performance. To clarify, the reviewed studies are categorized into two groups based on the underlying heat transfer processes, and are summarized as follows:

2. Application of vibration in free convection heat transfer

Li *et al.* [8] investigated numerical methods to the problem of natural convection flow from a flat, vertical plate whose surface temperatures oscillate. There was a wide range of values for the Prandtl number (Pr) from 0.01 to 100 and the Grashof number (Gr) from 0 to 10000. In order to conduct steady-state analysis, used iterative procedure data for Gr ranging from 0 to 625, and used a perturbation technique to confirm lower Gr values. For larger Gr values, an unstable approach was devised; the outcomes shown that the unstable solution reaches a steady-state condition at big Gr numbers, up to 10000.

Kim *et al.* [9] studied natural convection resonance in a side-heated enclosure with a mechanically oscillating bottom wall, as shown in Fig.3. They varied the dimensionless internal air temperature from $(138 \times 10^{-5}$ to $838 \times 10^{-5})$ and explored vibration frequencies from (356 to 8556) and amplitudes (0.03 to 0.06) for Rayleigh (Ra) numbers of 7.3×10^7 and 1.2×10^8 . The results demonstrated resonance by showing that a certain driving frequency was associated with the maximum fluctuation amplitude of the air temperature. Resonant frequency and Ra number were positively correlated; forcing amplitude and frequency both had small effects on time-averaged wall heat transfer rate.

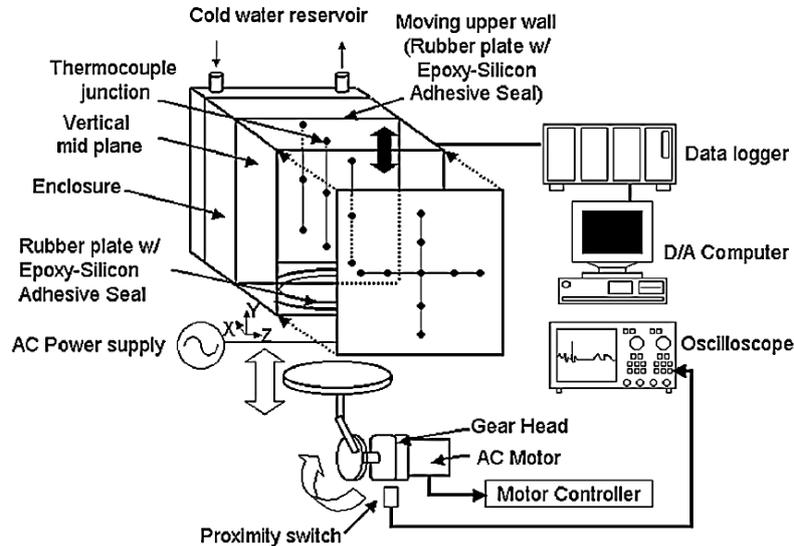


Fig.2. A schematic view of experimental rig [9].

Zhang *et al.* [10] investigated laminar natural convection on a continually heated, vertical flat plate that oscillates at regular intervals. From 0.2 to 20°C, 0.2 to 10 Hz, 2 to 100 mm, and 0.7 to 10 for air and water, respectively, were the temperature differences, oscillation frequencies, amplitudes, and Prandtl values that were varied. Heat transfer improved with dimensionless oscillation velocities, frequencies, and

amplitudes, but decreased with the Gr number, leading to a marked increase in the average Nusselt number. Gomaa and Taweel [11] investigated using both theoretical and experimental approaches, how oscillations impact heat transfer at vertical surfaces. They created a model predicting transient and time-averaged heat transfer rates across three Grashof number ranges $(1, 3, 20) \times 10^6$ and vibrational Reynolds number up to 4750. Oscillatory motion greatly improves heat transmission, especially in the $0 < Gr / Rev^2 < 3$ region, according to their research. There are small overall benefits (less than 2) and much greater improvements could be possible with higher temperature gradients.

Fu and Huang [12] studied the effect of a vibrating hot surface on natural convection in vertical channel flow numerically. The principal factors that were examined were the Ra number, amplitude, and frequency; the fluid utilized was air, and the Pr value was 0.71. Based on the results, it seems that a stationary condition may have less natural convection than a vibrating heat plate with a given frequency and amplitude when the Ra number is the same. Kim and Jeong [13] studied the impact of ultrasonic vibration on heat transfer during subcooled pool boiling. Using a 40 kHz vibration frequency, they heated water at two power levels (3 kW and 0.5 kW) with a flat plate covered in copper. The tests included three subcooling levels (5°C, 20°C, 40°C) and six incline angles (0°, 10°, 20°, 45°, 90°, 180°). Results showed that ultrasonic vibration reduced the standard deviation of pool temperature distribution, especially with downward-oriented heated surfaces, enhancing fluid mixing and improving heat transfer by lowering the liquid temperature near the heater.

Al-Shorafa'a [4] investigated experimentally how vertical vibration affected the heat transfer coefficient from electrical cylinders that were heated horizontally. There were three different cylinders used in the experiment, each having its own unique diameter (2.15 cm, 3 cm and 3.8 cm), vibration frequency (10, 15 and 20 Hz), and amplitude (0.5 mm to 7.6 mm). According to the findings, the vibration Re number is positively affected by an increase in the heat transfer ratio with decreasing diameter and frequency. The Gr and Pr numbers perform poorly under conditions of significant temperature differential. Shokouhmand *et al.* [6] examined how a system of oscillating circular cylinders maintained an isothermal heat transfer rate when subjected to horizontal oscillations. Air with a Prandtl number of 0.71, a Rayleigh number varying from 10^3 to 10^5 , oscillation amplitudes ranging from 0.5 to 2 m/s and dimensionless frequencies ranging from 0.1 to 0.4 were utilized in the experiment. The results showed that the average Nu number, together with the amplitude and frequency of oscillations, were improved with increasing the Rayleigh number and cylinder spacing. Further, the lower cylinders lost heat because the vortices formed by the horizontal vibrations were too close to the cylinders.

Kadhim and Sarhan [14] conducted experiments to study the effects of applied vibrations on the free convection heat transfer coefficient of a vertically oriented aluminum flat plate, as shown in Fig.3. The experimental conditions included a heat flux of 250–1500 W/m², vibration amplitudes of 1.63–7.16 mm, a Ra number of 138.991 – 487.275, and a range of tilt angles of 0, 30, 45, 60 and 90 degrees. Based on the results, the heat transfer coefficient drops with increasing vibration response, reaching a maximum reduction ratio of 7.6%, with the exception of the vertical position ($\theta = 90^\circ$). The correlation between vibration amplitude and heat transfer coefficient grows for inclination angles between 0 and 60 degrees when the object is horizontal, reaching a maximum ratio of 13% at the end. Sarhan [15] tested the effects of vertical vibrations on natural convection heat transfer with an aluminum panel that had longitudinal fins. While the panel was subjected to thermal fluxes ranging from 250 to 1500 W/m², it was vibrated at 0, 2, 6, 10, and 16 Hz, with amplitudes ranging from 1.63 to 7.1 mm, and tilt angles of 30, 60, and 90°. Figure 4 presents a schematic of the test rig used. There was a clear relationship between the amplitude of vibrations and the natural convection rate of heat transfer for all of the tilt angles that were investigated. Specifically, compared to 60° and 90°, the heat transfer coefficients were 19.27% and 31.4% greater, respectively, at 30° of tilt.

Kassim *et al.* [16] studied an experimental investigation into the impact of vibrations on the free convection heat transfer of a horizontal cylinder made from composite material. The test was performed with

a heat flux ranging from 500 to 1000 W/m^2 and a vibration frequency range of 0 to 20 Hz . The findings indicated that the heat transfer coefficient enhanced with higher vibration frequencies and more composite layers. However, the vibration heat transfer coefficient decreases as the heat flow increases (see Fig.5).

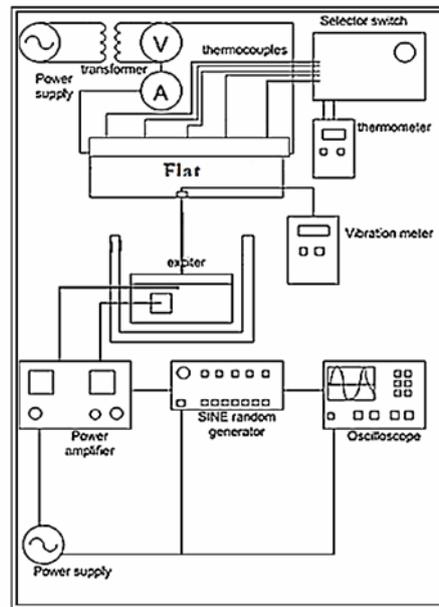


Fig.3. Integrated experimental equipment [14].

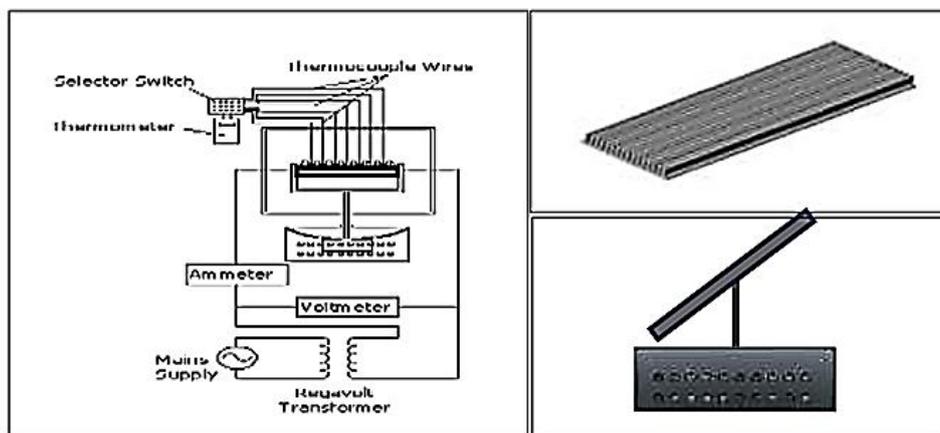


Fig.4. Experimental setup of study [19].

Sultan *et al.* [17] conducted an experimental investigation on a vertically oriented flat plate subjected to constant heat flux and external vibrations to evaluate natural convection heat transfer, as illustrated in Fig.6. The study considered a Ra number range of $(10^7 - 10^{10})$, vibration amplitudes between 0 and 7.6 mm, frequencies from 0 to 25 Hz , and oscillatory Reynolds numbers spanning ranging from 102 to 8×10^4 , they examined the impacts. The results showed that the heat transfer coefficient of the vibrating plate, expressed using a modified Ra number, was higher than that of the stationary plate. Additionally, vibration amplitude had only a minor impact on heat transfer, whereas vibration frequency played a more significant

role. A correlation was identified between the dimensionless Nusselt number (Nu), the modified Ra number, and the oscillatory Re number.

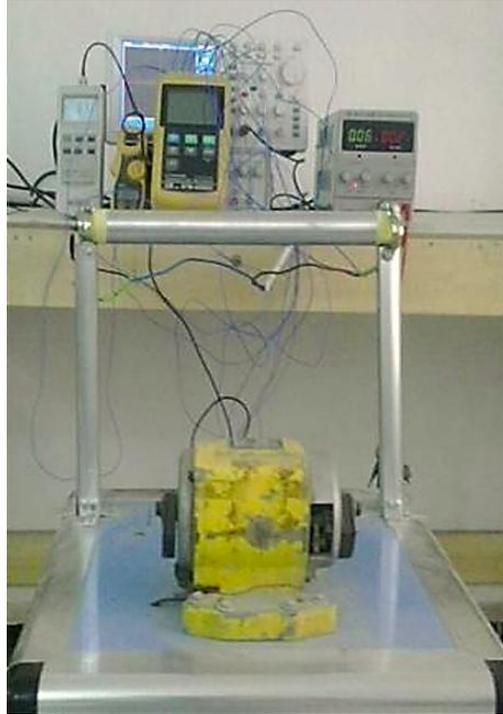


Fig.5. Photo of the test rig used [16].

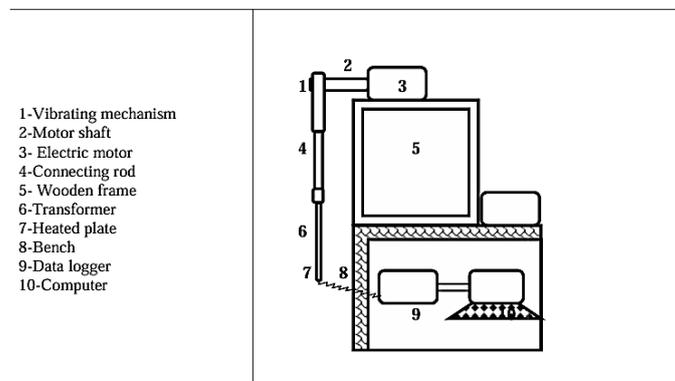
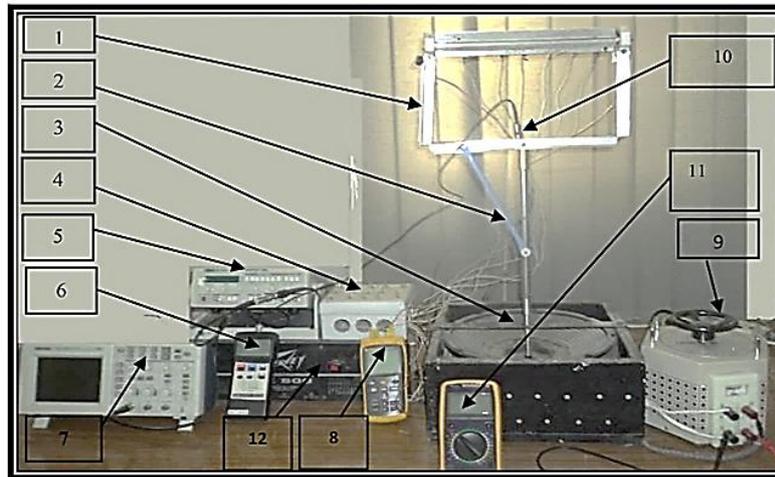


Fig.6. Experimental test rig [17].

Kadhim and Nasif [18] conducted an experiment to determine how longitudinal fins on a hot aluminum cylinder affected the free convection heat transfer coefficient when subjected to forceful vibrations. At angles ranging from 0° to 45° , they used a frequency range of 2 to 16 Hz and a heat flux of 500 to 1500 W/m^2 . Increasing from 0° to 45° , the heat transfer coefficient was shown to be positively correlated with vibration amplitude in this investigation. When compared to angles of 30° and 45° , the heat transfer coefficient ratio (h_v / h_o) at 0° was 8% greater, while at 45° it was 30% higher (see Fig.6).

Kadhim and Mery [19] investigated the impact of forced vibration on the sinusoidal surface's free convection heat transfer experimentally. The experiments included a range of parameters such as heat flux ($250, 500, 750, 1000, 1250, 1500 \text{ W/m}^2$), vibration amplitude (3, 4, 5 mm), vibration frequency

(5, 10, 15, 20, 25 Hz), Ra numbers ($1.5 \times 10^8 - 4 \times 10^8$), Re numbers ($2, 4, 6, 8, 10$) $\times 10^3$, and Pr numbers (0.707 – 0.710). Figure 7 shows a detail photo of test rig. The results of this research show that vibrations generally raise the average vibrational Nusselt number Nu and the rate of heat transfer; however, the extent to which this improvement depends on vibrational Re number, Ra number, and the spot where the heated surface is locate.



(b)

1-U-shaped, 2- lever mechanism, 3- Vibration Exciter, 4- Selector Switch, 5- Sine Function Generator, 6- Accelerometer, 7- Digital Oscilloscope, 8- Digital Thermometer, 9- Auto – transmission, 10- Force Transducer, 11- Digital Voltmeter Ohm Meter Ammeter, 12- Power Amplifier

Fig.7.Photo of experimental rig [18].

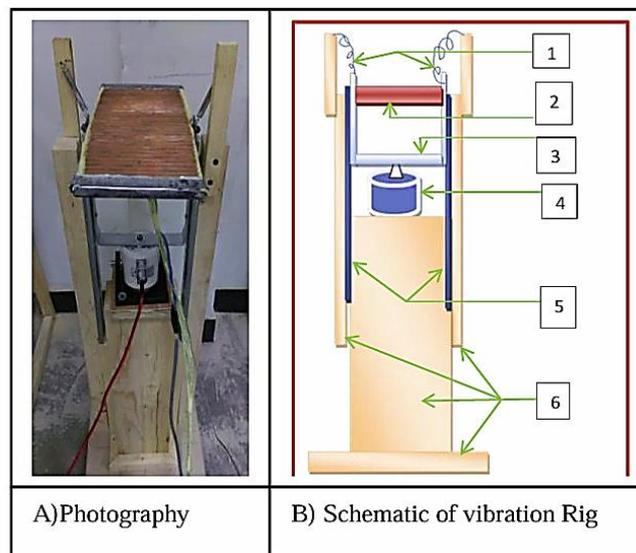
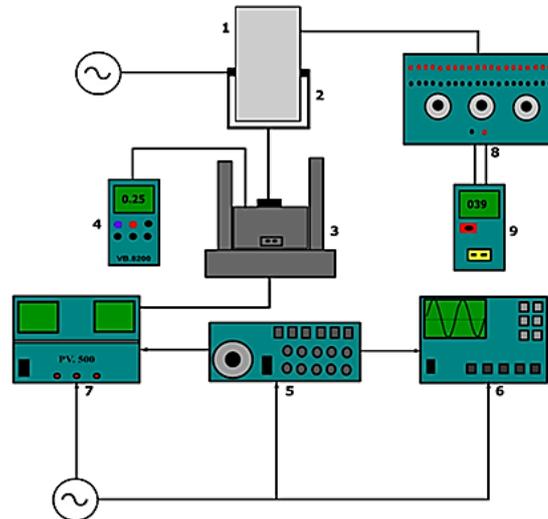


Fig.7. Experimental test rig [19].

Sarhan *et al.* [20] investigated experimentally how vibration affected the thermal performance of a rectangular flat plate subjected to natural convection in a variety of horizontal and slightly inclined orientations

and angles, as shown in Fig.8. They used thermal power readings between 0 and 200 W , vibration amplitudes between 1.5 and 7.5 mm , and tilt angles of 30 , 45 , and 60 degrees, as well as vibration frequencies between 0 and 16 Hz . The research proved that the mean heat transfer coefficient increases linearly with the Rayleigh number across a range of orientation angles. While the average heat transfer coefficient was better for horizontal plates, it was lower and marginally higher for vertical ones. In horizontal orientations and at higher oscillation frequencies, the average heat transfer coefficient was found to be significantly enhanced.



(1) Heat sinks; (2) Sample holder; (3) The exciter; (4) Vibration meter; (5) Sine random generator; (6) Oscilloscope; (7) Power amplifier; (8) Selector switch; (9) Thermometer

Fig.8. Sketchmatic diagram of the experimental test rig [20].

Rao and Babu [21] performed an experiment to determine the effect of mechanical vibrations on the rate of heat transfer in a horizontal cylinder, as shown in Fig.9. A variety of vibration frequencies (100 , 130 , 160 , 190) Hz and amplitudes ($1.63 - 6.16\text{ mm}$) were used in the experiment, along with thermal power variables (30 , 40 , 50 , 60 W). The researchers discovered that both the Nu number and the local heat transfer coefficient caused by vibration grow linearly as one moves from the bottom to the top of the structure.

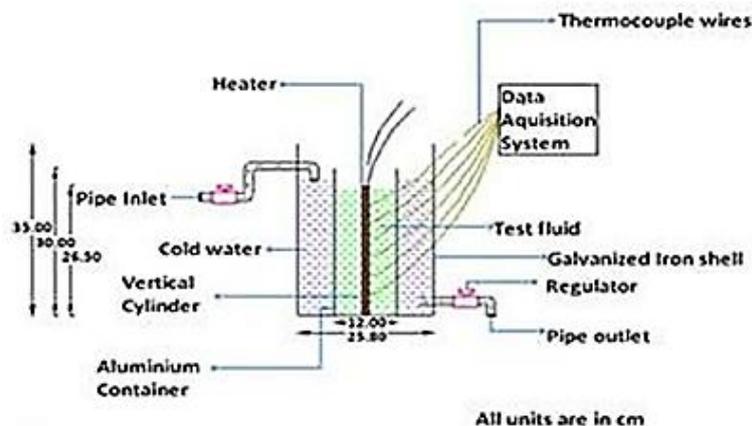


Fig.9. A schematic diagram of the experimental rig [21].

In addition, the study found that when water is heated to 60° , it increases the heat transfer coefficient from $321 \text{ W/m}^2 \cdot ^\circ\text{C}$ to $336 \text{ W/m}^2 \cdot ^\circ\text{C}$, making the vibration effect on natural convective heat transfer larger.

Murad *et al.* [22] investigated the effect of transverse vibrations on the heat transfer via natural convection in a rectangular enclosure filled with air through an experimental research, as shown in Fig.10. The results showed that the forced frequency closest to the system's natural frequency could generate the most heat transfer when four different thermal power values ($20, 30, 40$ and 45) W , a Rayleigh number ranging from $(3.77-10.8) \times 10^7$, an oscillation frequency ranging from $(0.5-2) \text{ Hz}$ and a vibrational Rayleigh number ranging from $(0.12-2.7) \times 10^7$ were applied. Furthermore, for a given heat flux, the values of the heat transfer parameters can be obtained by using two different frequency ratios.

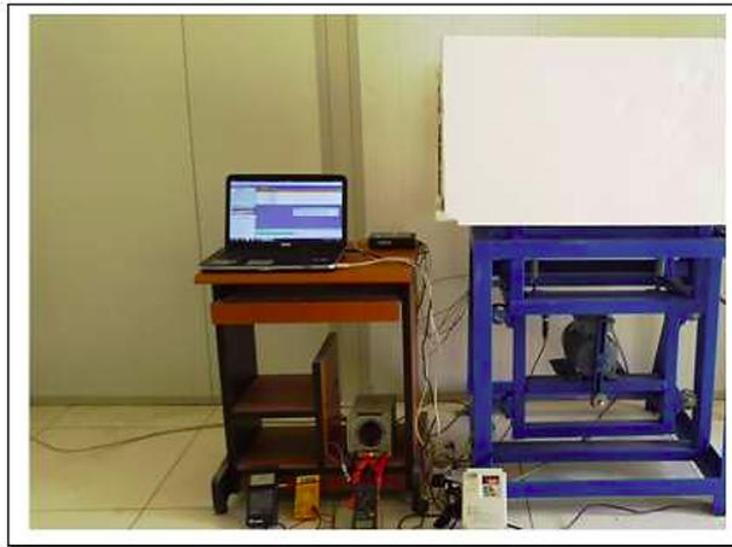


Fig.10. Photo of the experimental test rig [22].

Al-Azzawi *et al.* [23] conducted an experimental study to demonstrate the influence of vertical forced vibration on the coefficient of free convection heat transfer for a long-finned aluminum sheet and to compare the results with those of a flat plate. Figure 11 illustrates the sketchatic diagram of the test rig.

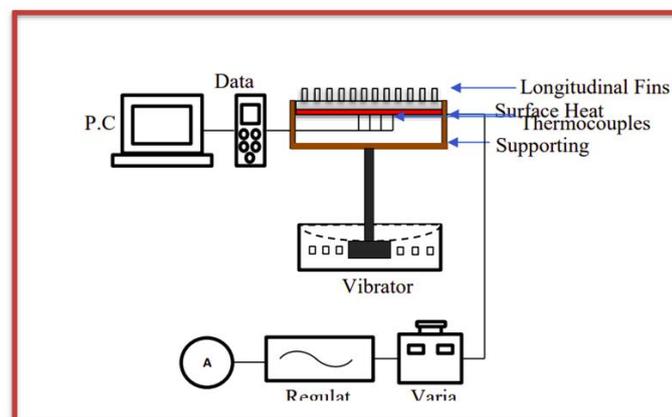


Fig.11. Sketchmatic diagram of the experimental test rig [23].

The experiments included subjecting the plate to a continuous heat flow between 300 and 1750 W/m^2 , varying the tilt angle from 25° to 90° and introducing a range of vibration frequencies from 0 to 16 Hz with amplitudes from 1.51 to 8.4 mm . The results show that the amplitude of vibrations is related to the free heat transfer rate and the tilt angles in a proportional fashion. Moreover, the free convection heat transfer coefficient drops with increasing tilt angle; it was 14.36% higher at 25° than at 45° and 26.71% higher than at 90° .

Abdulrazzaq *et al.* [24] conducted an experiment to determine the effect of mechanical vibration on the efficiency of heat transfer in free convection by reducing the thickness or penetration of the thermal boundary layer. With amplitude frequencies of $3, 5,$ and 7 mm and frequency ranges of $3, 6, 9, 12$ and 15 Hz , the experiments were conducted under a heat flux ranging from 150 to 600 W/m^2 . They found that the heat transfer coefficient is maximum at 597.98 and grows with increasing thermal flux. The Nusselt number improved more rapidly in perforated plates than in non-perforated ones; at 9 Hz , the improvement was 80.26% .

Rahman and Tafti [25] investigated the influence of oscillatory motion on the thermal performance of flat plate fins under laminar flow conditions. Through numerical simulations, the study explored how oscillation affects boundary layer development, vortex dynamics, and flow mixing, resulting in a notable improvement in convective heat transfer. The findings emphasise the potential of oscillation-assisted fins as an effective passive method for enhancing heat dissipation in compact thermal management systems, but incoming heat amount had a positive effect. The Nusselt number increased with increasing cylinder height (see Fig.12).

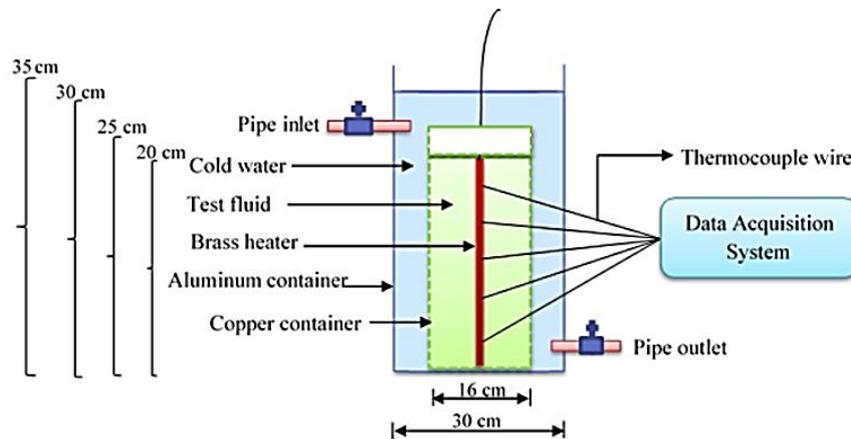


Fig.12. Schematic diagram of the experimental test rig [25].

Al-Azzawi *et al.* [26] studied how vibration affected heat transfer in a concentrated vertical cylinder using low-conductivity materials (water, engine oil, and ethylene glycol). At $90, 110, 140$ and 180 Hz , with a constant heat flow of 35 to 75 W/m^2 , the experiments were conducted with a vibration amplitude of 0.6 mm . They discovered that axial distance had a negative effect on the local heat transfer coefficient. Khudhair *et al.* [27] performed an experimental investigation to learn how a horizontally constrained cylindrical annulus's natural convection heat transport is affected by vertical mechanical vibrations, vertical eccentricity, and the Ra number. A heat flux ranging from 25 to 1500 W/m^2 and a vibration frequency of 0 to 20 Hz were used in the test, along with a Ra number of 5×10^4 to 6.48×10^6 . Based on the eccentricity of the cylinder, the study concludes that the natural convection mechanism is significantly affected by the vibration of the heated inner cylinder. The amount to which the vibrating average Nu number increased was dependent on where the heated inner cylinder was placed.

Idan and Ramadhan [28] studied the influence of free convection on the heat transfer coefficient of a flat aluminum plate that was oscillated vertically through an experimental procedure. Their experiments demonstrated that the heat transfer coefficient is positively correlated with increasing vibration amplitude,

especially between angles of 0° and 60° , when a constant heat flux of 250 to 1500 W/m^2 and different plate tilt angles ($0^\circ, 30^\circ, 45^\circ, 60^\circ, 90^\circ$) were used. Figure 13 shows a sketchmatic diagram of the test rig. In the fatty vibration mode, the maximum correlation was 13.2894% and as the vertical vibration increased, the heat transfer coefficient dropped by as much as 7.6475% . Also, the total vibrational heat transfer coefficient went down as the vibrational Re number went up, whereas the Nu number went up as the Ra numbers went up.

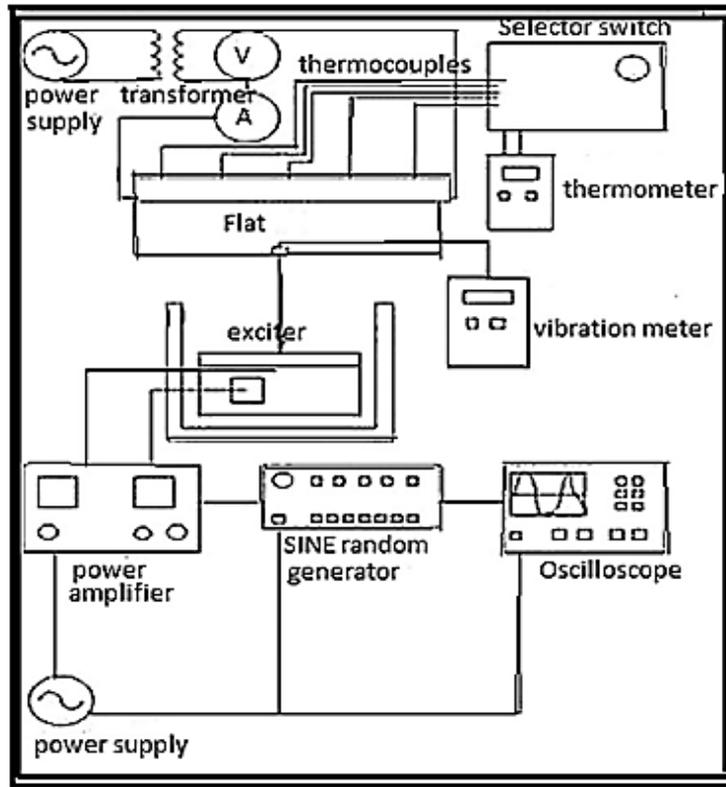


Fig.13. Sketchmatic diagram of the experimental test diagram [28].

Taha *et al.* [29] investigated the impact of circular perforations on vertically oriented sinusoidal waveform plate fin heat sinks under laminar natural convection. The study explored how perforation geometry affects airflow, temperature distribution, and heat transfer efficiency. Results revealed that perforations improve heat dissipation by enhancing fluid mixing and lowering thermal resistance, offering valuable insights for designing effective passive cooling systems.

Table 1. Summary of the application of mechanical vibration in enhancing heat transfer with free convection.

Reference	Study objective	Study of parameters	Working fluid	Finding
[1] Bergles <i>et al.</i> (1983)	Compile bibliography of augmentation in convective heat/mass transfer.	Not parameter-based, literature survey.	Various (general).	Provides comprehensive reference base for enhancement methods.
[2] Bergles <i>et al.</i> (1991)	Review heat transfer enhancement tech for gas-fired applications.	Survey of passive/active techniques.	Air, combustion gases.	Summarizes viable techniques for heat exchangers.

Table 1 cont. Summary of the application of mechanical vibration in enhancing heat transfer with free convection.

Reference	Study objective	Study of parameters	Working fluid	Finding
[3] Bergles <i>et al.</i> (1995)	Update bibliography on enhancement methods.	Survey of studies.	Various fluids.	Extended bibliography supporting researchers.
[4] Al-Shorafa'a (2008)	Study influence of vertical vibration on HTC from horizontal cylinders.	Frequency, amplitude, cylinder diameter.	Air (free convection).	Vibration increases HTC compared to stationary case.
[5] Chen <i>et al.</i> (2015)	Effect of longitudinal vibration on inclined heat pipes.	Frequency, amplitude, orientation angle.	Working fluid inside heat pipe.	Longitudinal vibration enhances performance by promoting fluid return.
[6] Shokouhmand <i>et al.</i> (2011)	Horizontal vibration effect on natural convection from isothermal cylinder array.	Frequency, amplitude, spacing.	Air.	Heat transfer increased at optimal vibration frequency.
[7] De Silva (2006)	Fundamentals of vibration.	General vibration theory.	N/A.	Background resource for vibration applications.
[8] Li <i>et al.</i> (2001)	Natural convection from vertical plate with surface T oscillation.	Oscillation frequency, amplitude.	Air.	Surface oscillation alters boundary layer structure; enhances HTC.
[9] Kim <i>et al.</i> (2002)	Resonance of natural convection in enclosure with oscillating wall.	Wall oscillation frequency.	Air in cavity.	Resonance significantly increases convection intensity.
[10] Zhang <i>et al.</i> (2004)	Numerical study of vertical plate with periodic oscillation.	Frequency, amplitude, Ra number.	Air.	Periodic oscillations improve convection heat transfer.
[11] Gomaa and Al Taweel (2005)	Effect of oscillatory motion on heat transfer at vertical flat surfaces.	Frequency, amplitude.	Air.	Oscillatory motion enhances heat transfer rate.
[12] Fu and Huang (2006)	Vibrating heated surface effect in vertical channel flow.	Amplitude, frequency.	Air.	Induces stronger convection currents, raising HTC.
[13] Kim and Jeong (2006)	Numerical analysis of ultrasonic vibration for heat transfer.	Ultrasonic frequency, amplitude.	Liquid/air (depending).	Ultrasound improves HTC through boundary layer disturbance.
[14] Kadhim and Sarhan (2012)	Experimental study on vertical forced vibration on Al flat plate.	Amplitude, frequency.	Air.	Vibration augments free convection HTC.
[15] Sarhan (2013)	Vertical vibration effect on finned heat sinks.	Amplitude, frequency, fin geometry.	Air.	Vibration enhances cooling performance of fin arrays.

Table 1 cont. Summary of the application of mechanical vibration in enhancing heat transfer with free convection.

Reference	Study objective	Study of parameters	Working fluid	Finding
[16] Kassim <i>et al.</i> (2015)	Composite horizontal cylinder under vibration.	Material, vibration parameters.	Air.	Composite material cylinders show improved heat transfer when vibrated.
[17] Sultan and El-Tahan (2015)	Natural convection from vibrated vertical flat plate.	Amplitude, frequency.	Air.	Heat transfer enhanced compared to stationary plate.
[18] Kadhim and Nasif (2016)	Effect of vertical oscillation on finned tube HTC.	Frequency, amplitude, fin geometry.	Air.	Vibration improves HTC in finned tubes.
[19] Kadhim and Mery (2016)	Vibration influence on sinusoidal surface convection.	Surface shape, vibration parameters.	Air.	Vibration significantly augments natural convection on sinusoidal plates.
[20] Sarhan <i>et al.</i> (2019)	Effect of vertical vibration on flat plate performance.	Frequency, amplitude.	Air.	Experimental proof of vibration-enhanced free convection.
[21] Rao and Babu (2019)	Natural convection augmentation with vibration.	Amplitude, frequency.	Air.	Confirmed vibration improves convection heat transfer.
[22] Murad <i>et al.</i> (2019)	Transverse vibration in rectangular enclosure.	Frequency, amplitude, enclosure geometry.	Air.	Transverse vibration modifies flow patterns, increasing HTC.
[23] Al-Azzawi <i>et al.</i> (2020)	Forced vibration on longitudinal fin heat sinks.	Fin geometry, vibration parameters.	Air.	Enhancement of free convection with forced vibration.
[24] Abdulrazzaq and Abbas (2020)	Vibration effect on perforated plate convection.	Plate perforation, vibration parameters.	Air.	Perforations + vibration yield higher HTC than solid plate.
[25] Rahman and Tafti (2020)	Characterize heat transfer enhancement for oscillating flat plate-fin.	Plate oscillation frequency, amplitude.	Air.	Oscillation enhances heat transfer in plate-fin configuration.
[26] Al-Azzawi <i>et al.</i> (2021)	Vibration effect on concentric vertical cylinder convection.	Cylinder dimensions, vibration parameters.	Air.	Vibration increases natural convection HTC in cylinders.
[27] Khudhair <i>et al.</i> (2023)	Forced vibration on concentric/eccentric horizontal annuli.	Geometry, vibration frequency, amplitude.	Air.	Eccentric annuli exhibit stronger enhancement with vibration.
[28] Idan and Ramadhan (2023)	Flat plate under forced vertical vibration.	Amplitude, frequency.	Air.	Confirmed vibration increases convection coefficient.
[29] Taha <i>et al.</i> (2025)	Heat dissipation of sinusoidal fin heat sinks with perforations.	Perforation size, sinusoidal wavelength.	Air (laminar natural convection).	Perforations enhance dissipation by disturbing boundary layer.

3. Application of vibration in forced convection heat transfer

Sreenivasan and Ramachandran [30] examined experimentally how vibration effected the heat transfer characteristics of a copper cylinder in a horizontal position traveling through an air stream. A cooling temperature of 32.222°C was obtained following sinusoidal vibration in the experiments, which were conducted at temperatures ranging from 60°C to 104.444°C . Between 7.5 mm and 32 mm in amplitude, the vibration frequencies were 3.33 Hz to 46.67 Hz . There was a wide range of Reynolds numbers ($2500 - 15000$) and flow velocities ($5.791 - 28.042\text{ m/s}$). Heat transfer coefficients showed no significant change across the Reynolds number range, even when the average vibration speed relative to the flow speed rose from 4% to 20% . This suggests that heat transmission from the vibrating cylinder remained constant.

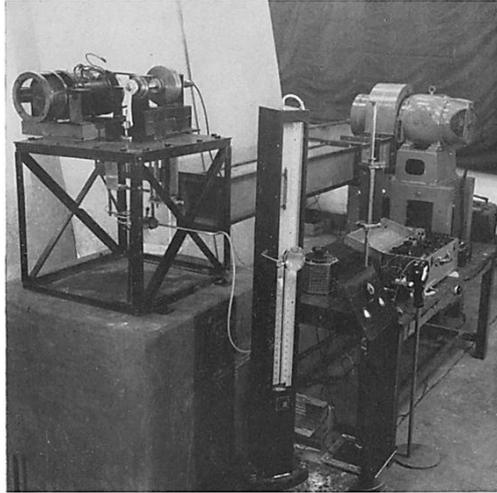


Fig.14. Photo of the experimental test rig [30].

Klaczak [31] conducted a study on heat transfer in a heat exchanger with forced vibrations. Starting with water at 11°C , steam was used to raise the temperature to 99.6°C . With Reynolds numbers ranging from 430 to 2300 , the vibrations occurred in a laminar flow with amplitudes of 0.2 to 0.5 mm and frequencies of 20 to 120 Hz . The results demonstrated that, in comparison to a vibration-free system, vibrations that were horizontally aligned with the flow reduced heat transmission. Murphy and Lambert [32] conducted an experimental investigation on the effect of induced transverse vibrations on the pinned-pinned beam's local heat transfer characteristics. The beam received power at levels as high as 8 V and 300 A .

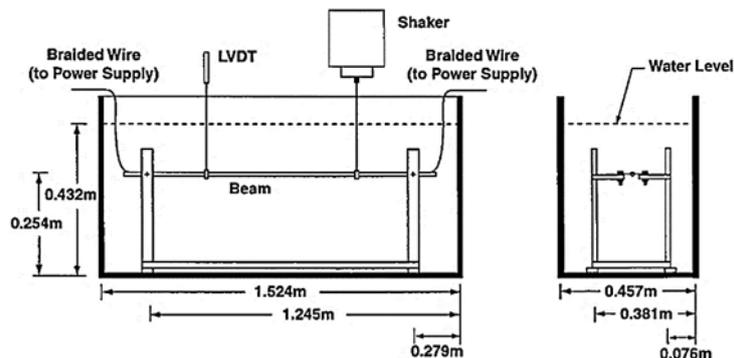


Fig.15. Experimental test diagram [32].

The vibration frequencies that were used for the scans were $(17 - 40) \text{ Hz}$ and $(60 - 80) \text{ Hz}$, as shown in Fig.15. The findings revealed notable fluctuations in the local Nusselt (Nu) numbers, which are intimately related to the modes of the beam. The results show that the recorded Nu numbers are the maximum for enhanced convection due to the vibrations of the beam, ignoring rigid-body modes, because the measurements were done at resonance frequencies. Bronfenbrener *et al.* [33] Studied the impact of vibration on the enhancement coefficient of heat transfer using both experimental and theoretical approaches in the context of a horizontal tube with rotating rings on its external surface, as shown in Fig.16. The experimental parameters included a Re number between 800 and 2000, a vibration frequency between 10 and 120 Hz, and a vibration amplitude between 0.1 and 1 mm. Using dimensionless analysis, a mathematical model of the heat transfer mechanism was built. The mean coefficient of heat transmission increased as the vibration velocity did. The experimental findings matched the theoretical model well.

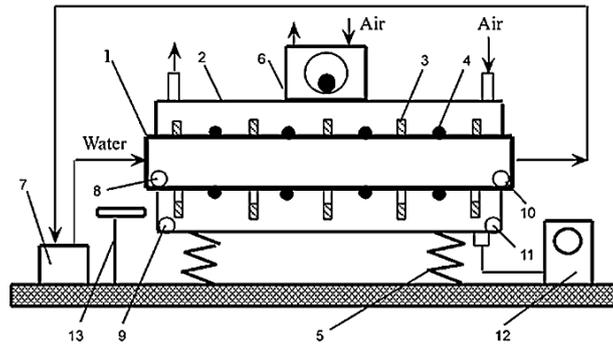


Fig.16. Sketchmatic diagram of the experimental test diagram [33].

Eid and Gomaa [34] examined the effect of vibration on improving heat transfer rates from thin planar fins experimentally, as shown in Fig.17. A 250 W power source was used to heat the heat sink, which was then vibrated with amplitudes of 9, 18, and 27 mm and frequencies of 12, 17, 9, 25, 35, and 50 Hz. The study discovered that for the same average velocity, the rate of heat transfer can be boosted by over 85% in the constant flow case compared to typical vibration.

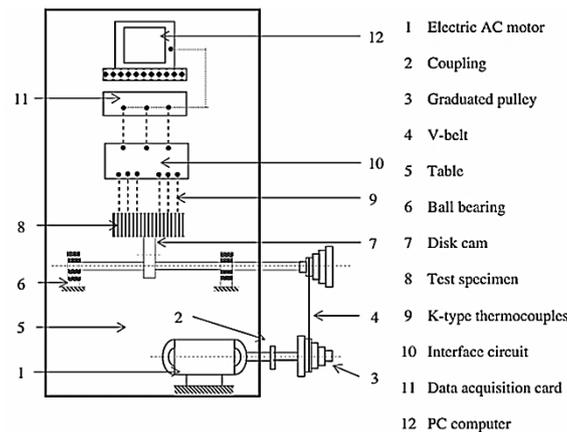


Fig.17. Experimental test rig diagram [34].

Cheng *et al.* [35] investigate the effects of flow-induced vibrations on heat exchanger performance experimentally and numerically. The experiment ran in conditions where the heat flux was constant. The convective heat transfer coefficient can be dramatically increased by vibrations caused by low-velocity

pulsing flow. The average exterior convective heat transfer coefficient of this device was 1.5 times higher than that of the fixed tube bundle. At the same time, there was a 63% drop in fouling resistance (see Fig.18).

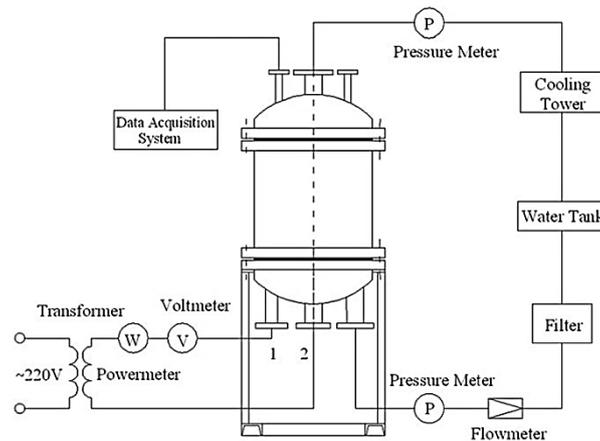


Fig.18. Experimental test diagram [35].

Kadhim and Shamoon [36] studied how forced vertical vibrations affect the heat transfer coefficient in forced convection. They tried out several tilt angles (ranging from 0° to 45°), frequencies (ranging from 2 to 16 Hz), and amplitudes ranging from (0 to 2.2 mm) in addition to a heat flux (500 to 1500 W/m^2). The heat transfer coefficient can be increased by as much as 13.34% across all tilt angles when the vibration amplitude is increased, according to their findings. Nevertheless, the coefficient decreases as the tilt angle increases. Additionally, they discovered that convection flow is enhanced by horizontal fins and decreased by inclined fins in terms of convection heat transfer coefficient values. In contrast to inclined cylinder fins, which decrease the forced convection vibrational heat transfer coefficient, horizontal fins improve convection current flow.

Kadhim *et al.* [37] investigated how a cylindrical glass chamber's pool boiling coefficient of heat transmission was affected by forced vibrations. They applied heat fluxes between 27.521 and 53.08 kW/m^2 , with frequencies ranging from 2 to 40 Hz and vibration amplitudes of 1.8 to 3.5 mm. The findings showed that the coefficient of heat transfer increased significantly within the 2–14 Hz range, especially at angles from 0° to 45° . Notable enhancements included approximately 250% at 5 Hz with 27.521 kW/m^2 , 231% at 6 Hz with 36.727 kW/m^2 , 181% at 6 Hz with 41.83 kW/m^2 and 93% at 8 Hz with 53.08 kW/m^2 . The study also found that increases in the vibration Reynolds number (Re) correlated with heightened heat transfer coefficients.

Gururatana and Li [38] conducted a numerical and experimental study on the effects of forced vibration on small-scale pin-fin heat sinks, aiming to enhance heat transfer performance. The experiment was conducted at a wall temperature of 320 K and an air inlet temperature of 300 K, with vibration frequencies ranging from 50 to 1000 Hz and a Reynolds number of 1000. The study revealed that frequencies below 500 Hz led to an increased maximum heat transfer rate. However, the maximum heat transfer rate slightly improves if the frequency exceeds 500 Hz.

Chen *et al.* [39] investigated how a grooved cylindrical copper heat pipe's heat transfer performance was affected by temperature changes in the condensation section and horizontal vibrations. As they varied the condensation temperature from 20 to 40 °C and applied powers of 31.08 W and 30.43 W to the tube, they measured vibration amplitudes (2.8 to 25 mm) and frequencies (3 to 9 Hz) at accelerations ranging from 0.1 to 1.01 g. Results showed that input vibration energy directly correlated with vibration level, with vibrations improving heat transfer at levels below $500 \text{ mm}^2 \text{ Hz}^2$. The improvement per unit of energy, however, dropped sharply after passing this point. Furthermore, vibrations were not nearly as influential as the condensation section temperature in determining maximal heat transfer.

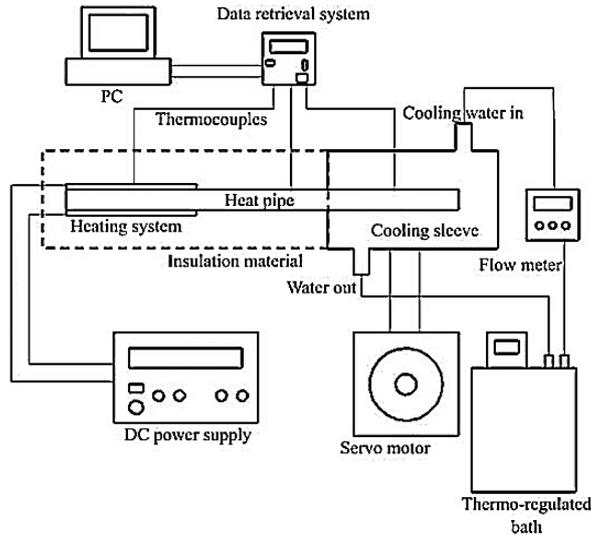


Fig.19. Experimental test diagram [39].

Guo *et al.* [40] investigated the effects of vertical mechanical vibration on flow and thermal transfer in rectangular microgrooves through experimental and theoretical analyses. They studied vibration frequencies of 6, 10, and 30 Hz with an amplitude of 0.5 mm. While the results demonstrated that vibration does improve heat transmission by increasing the wetting area, the contribution of heat transfer through the evaporative thin layer is still only about 0.9 and is little impacted by vibration. In the microgroove, heat transport is mostly driven by evaporation, not by mechanical vibration.

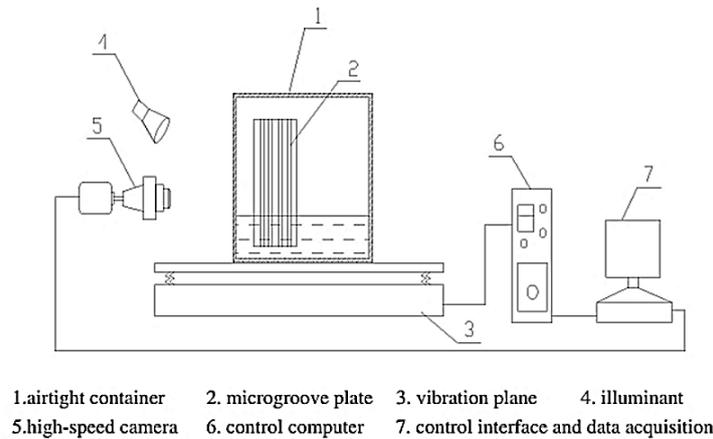


Fig.20. Experimental test diagram [40].

Pilli *et al.* [41] performed a computational analysis to classify the flow regime over a transversely vibrating flat plate, examining both heated (323.16 K) and unheated conditions at an ambient temperature of 298.16 K. Using three different models: Reynolds-Averaged Navier-Stokes (RANS) with $k-\omega$ SST, and Large-Eddy Simulations (LES) with the dynamic Satoransky-Lilly model, they tested vibrations with amplitudes ranging from 0 to 2 mm and frequencies ranging from 0 to 150 Hz. Their results showed that higher vibration amplitudes and frequencies led to increased wall shear stress. Park *et al.* [42] studied an experimental investigation and proposed a correlation for calculating the Nu number for convection-enhanced vibration from vertically oriented plate fins, as shown in Fig.21. A temperature gradient of 30 degrees Celsius, a vibration

frequency range of $29 - 59 \text{ Hz}$, and a Ra number ranging from $8000 - 20000$ were all factors in the experiment. Based on the findings, the Nusselt number of the vibrating fin, which is adjusted to the stationary fin's value is strongly impacted by the ratio of vibration speed to buoyancy-driven flow velocity.

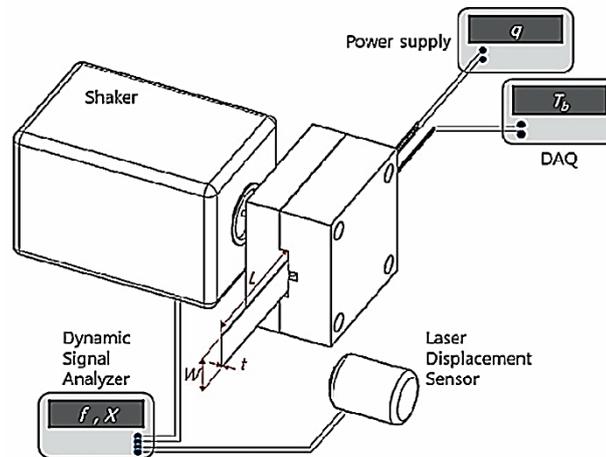
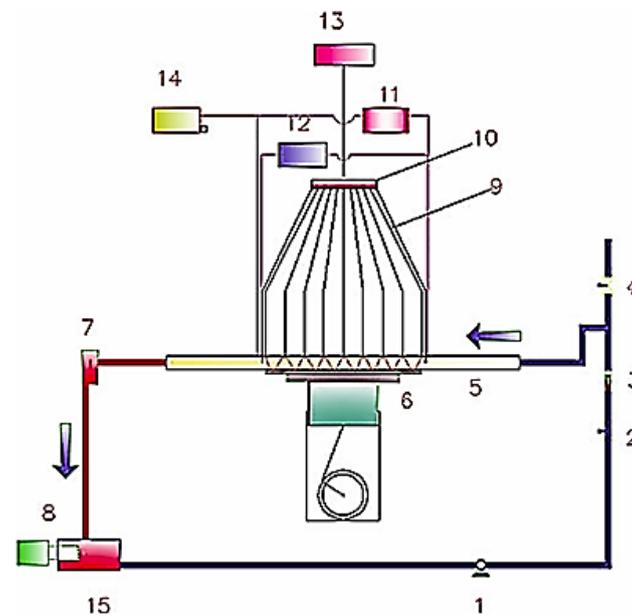


Fig.22. Experimental test setup [42].

Zhang *et al.* [43], examined the effect of vibration on forced convection heat transfer in nanofluids containing SiO_2 and water through an experimental study. Prior to admission, the fluid had a temperature of 25°C , whereas the temperature at exit varied between 25.5 and 40°C . The nanofluid was heated to around 400 W using a thermal power source. The results showed that heat transfer performance is greatly improved by 182% when nanoparticles are added to clean water or when transverse vibrations are applied (see Fig.22).



Measurement system of experimental apparatus: 1, Centrifugal pump; 2, throttle valve; 3, rotameter; 4, air evacuation valve; 5, test section; 6, vibration table; 7, overflow tank; 8, heat exchanger; 9, thermocouples; 10, heat flowmeter; 11, constant flux heating system; 12, U-manometer; 13, computer; 14, power controllers; 15, receiving tank.

Fig.22. Sketchmatic diagram of the experimental test rig [43].

Saini and Kumar [44] conducted experimentally investigated the effect of vibration on the enhancement of heat transfer in a rectangular channel heat exchanger, as shown in Fig.23. Using a volumetric flow rate of (1.5, 1.7, 2) kg / min and an inclination angle of 20°, the experiment was conducted with hot water input temperatures of (53, 58, 63)°C and vibration frequencies of (5, 5.5, 6.5) Hz . Several heat transfer measures, such as the overall heat transfer coefficient, efficacy, and heat transfer rate without vibrations, are used to compare the impact of different vibration intensities on heat transmission. Heat transmission properties can be improved to a certain degree by increasing the vibration intensity.

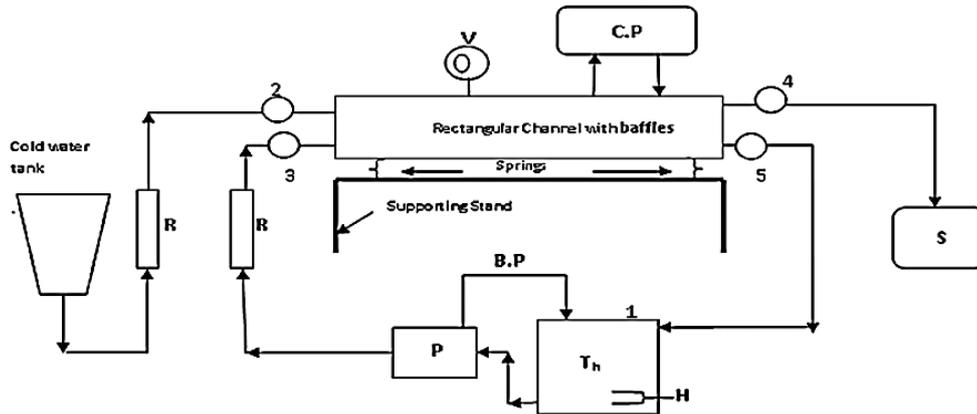
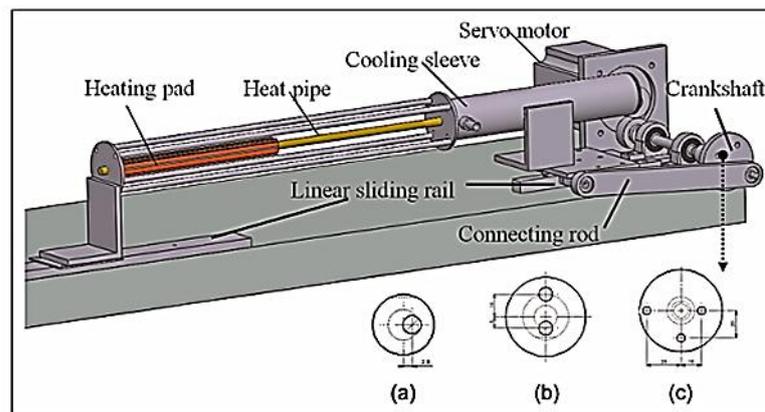


Fig.23. Sketchmatic diagram of the experimental test rig [44].

Wang *et al.* [45] conducted an extensive numerical analysis of a three-dimensional transient-state model that emphasized heat transmission and fluid dynamics in a channel utilizing Longitudinal Vortex Generator (LVG) with pulsed flow to improve heat transfer. The study was carried out with a Reynolds number ranging from 139.7 to 978 and a Prandtl number of 0.7, with the fin surface temperature kept at 330 K, which is more than the inlet temperature of 300 K. The results show that the period and amplitude are critical parameters that significantly affect the efficiency of heat transmission and flow. The total *j*-factor increments for cases 1, 4, and 5 are 19.15%, 1.47%, 24.96% and 1.51%, respectively. The *f*-factor is enhanced by a cumulative 17.61%, 1.06%, 17.58% and 1.06%.

Chen *et al.* [5] investigated how longitudinal vibrations, condensation section temperature, and inclination angles affected the heat transfer efficiency of copper heat pipes with grooves, as shown in Fig.24.



Experimental test cell illustration.¹² Crank endplate design versus desired vibrational amplitude (*r*): (a) *r* = 2.8 mm, (b) *r* = 5, 10 mm, and (c) *r* = 15, 20, 25 mm.

Fig.24. Experimental test rig [5].

They changed the inclination angles to 0° , $\pm 45^\circ$ and $\pm 90^\circ$, the condensation temperatures to 20°C , 30°C , and 40°C , and the vibration frequencies and amplitudes from 3 to 9 Hz and 2.8 to 25 mm, respectively. Regardless of the temperature or vibration, the results showed a stable and low thermal resistance. In particular, with the 600 mm heat pipe's condensation section at the top and the evaporation section at the bottom, the thermal resistance was approximately 0.25 K/W , and with the 150 mm heat pipe, it ranged from 0.75 to 1.2 K/W.

Duan *et al.* [46] studied a numerical investigation into how flow-induced vibration can enhance heat transmission in a planar elastic tube bundle. A constant inlet temperature of 313 K and inlet velocities ranging from 0.2 to 0.5 m/s were used in the experiment, with the wall temperature kept at 333 K. The average heat transfer enhancement for the two middle tubes was 12.97% and 4.58% at 0.2 m/s and 0.5 m/s, respectively, according to the results. This is higher than the 5.37% and is seen in the inner and outer tubes, respectively. A planar elastic tube bundle's heat transfer is enhanced by flow-induced vibration at low input velocities ranging from 0.2 to 0.5 m/s, with corresponding increases of 8.26%, 6.07%, 5.67%, and 3.91%.

Sarafraz *et al.* [47] conducted an experiment to evaluate the thermal performance of a chevron-type flat plate heat exchanger with nanoparticle fouling using a CuO/water nanofluid. To reduce nanoparticle fouling in the heat exchanger, a transient study used low-frequency vibrations. Similarly, a system's total thermal performance is enhanced by regularly vibrating the heat exchanger. Improved heat exchanger efficiency was observed as a function of vibrational wave frequency and amplitude (see Fig.25).

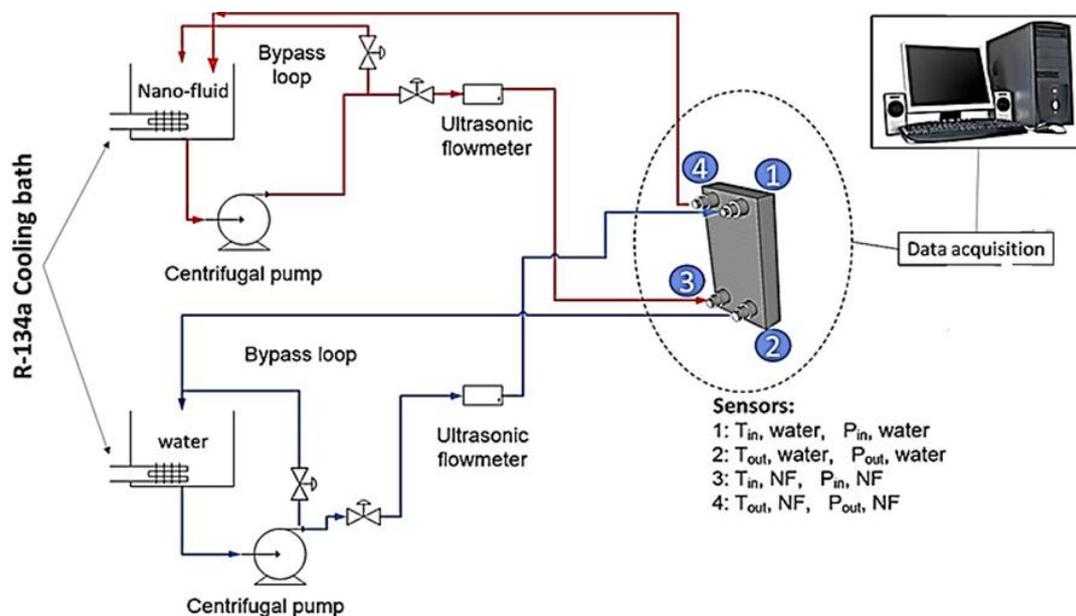


Fig.25. Experimental test diagram [47].

Hosseinian *et al.* [48], Studied how vibrations can improve the heat transfer rate of a liquid mixture made of multi-walled carbon nanotubes (MWCNT) in water, using a special type of heat exchanger, as shown in Fig.26. The temperature of the liquid in the tank was altered to (35, 40, 45, 50) °C and the flow rate through the tube was modified to (100, 200, 300) L/h. The outer tube's cold water flow rate was set at 100 L/h and the vibration frequency was 100 Hz, with vibration levels of 3, 6 and 9 m/s². Their research proved that vibrations significantly boost heat transfer rate and reduce nanoparticle settling. Vibration levels, liquid temperature, flow rate, and mixture concentration all work together to improve heat transmission. A hundred percent improvement in heat transmission was achieved at the lowest concentration (0.04%) and the maximum vibration level (9 m/s²).

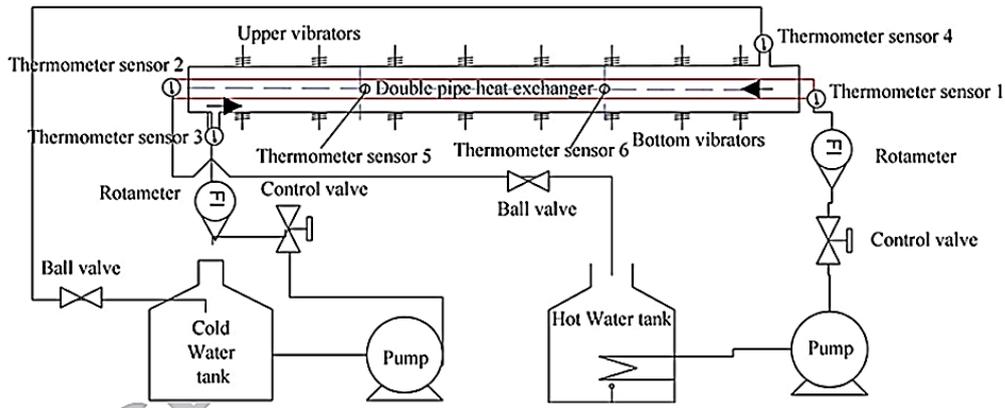


Fig.26. Experimental test diagram [48].

Hosseinian and Isfahani [49] conducted an experimental study to enhance heat transfer due to surface vibration in a Polyvinylidene Fluoride (PVDF) twin-pipe heat exchanger. The experiment was conducted at hot water temperatures within the basin at $(35, 40, 45, 50) ^\circ C$ and three levels of vibration $(3, 6, 9) m/s^2$, with an internal volumetric flow rate of $(100, 200, 300) L/h$, a vibration frequency of $(100 Hz)$, and a Rayleigh number ranging from $(2533 \text{ to } 9960)$. The study found that the heat transfer coefficient also increases as the mass flow rate and vibration level increase. The highest vibration level $(9 m/s^2)$ in the experimental range results in the most significant increase in the heat transfer coefficient at 97%.

Liu *et al.* [50] conducted the impact of sinusoidal vibrations on the heat transfer characteristics of internal flow in a heated circular tube using an experimental investigation shown in Fig.27. A Reynolds number

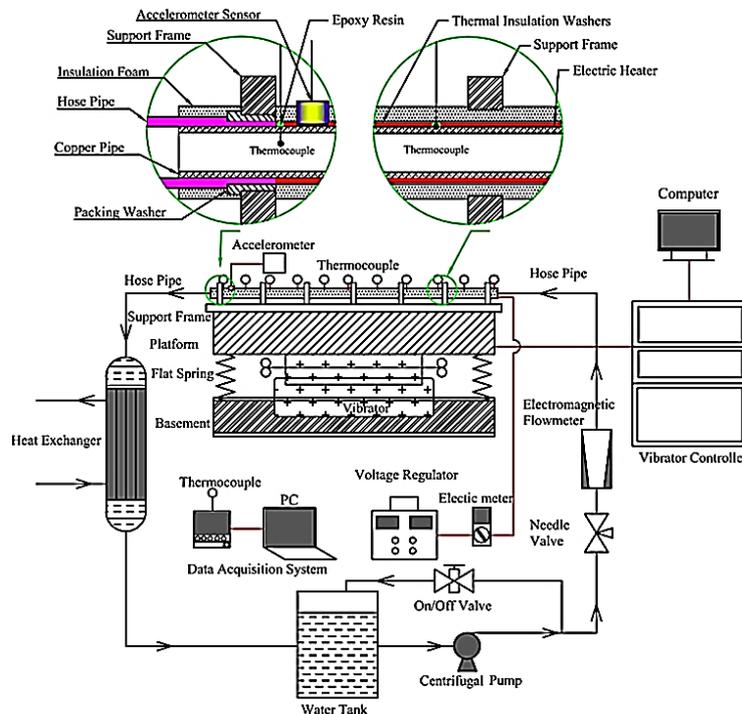


Fig.28. Experimental test rig diagram [50].

between 512 and 2047, vibration frequencies between 158 and 3000 Hz, and accelerations of 1, 3, and 5 g were all part of the experimental setup used in the investigation. The tube temperature was maintained at 323 K. The results showed that vibrations caused by mechanical factors have a major impact on the rate of heat transfer in a heated pipe. A little increase in vibration acceleration causes the Nu number to rise; but, as the inlet velocity increases, the improvement in the Nu number becomes less pronounced. In particular, as the vibration frequency gets close to the resonance frequency of 400 Hz, the Nu number increases significantly, then drops quickly, and finally settles at 1500 Hz.

Mousavi and Heyhat [51] presented a numerical study on the simultaneous application of alumina/water nanofluid and transverse oscillation in the convective thermal transfer of a heated circular cylinder. The experiment was conducted with a dimensionless vibration frequency of 1, a dimensionless amplitude of 0.6, 0.4, and 0.2, and a Re number ranging from 200 to 100. The results indicate that, within the examined parameters, the use of alumina/water nanofluid is more effective in enhancing heat transfer in cross-flow than the oscillation of a cylinder.

Abadi *et al.* [52] conducted a numerical study to assess and measure the improvement in heat transfer from pool boiling caused by mechanical vibrations. The study introduced a heat flux of ($20000 \text{ kW} / \text{m}^2$) and a vibration frequency of (2 Hz). The results indicated that the heat transfer rate increases by up to 90% under the simulated working conditions. The enhancement ratio is not significantly affected when the oscillation frequency exceeds 2 Hz. As the frequency amplitude of mechanical vibration increases, so does the heat transfer rate.

Setareh *et al.* [53] performed both theoretical and practical research to determine the effect of ultrasonic vibrations on the efficiency of a double-pipe heat exchanger's heat transfer. In the experiment, 120 W of thermal power was applied to water with temperatures ranging from 60°C to 20°C, with a frequency of 26.7 kHz and a flow velocity that varied between 0.5 and 1.5 L/min. At reduced fluid flow rates, the results showed that ultrasonic vibration worked better. When the flow rates of cold and hot fluids are 0.5 L/min, the heat transmission improves by around 60%; when the flow rates are 1 and 1.5 L/min, respectively, at an acoustic power of 120 W, the augmentation in heat transfer is 20%.

Akçay *et al.* [54] presented an experimental study on the mixed-convection heat transfer on an oscillating vertical flat plate, as shown in Fig 28. By applying three thermal fluxes (250, 500, 625) W / m², a non-dimensional oscillation amplitude (0.4, 0.75, 1.1, 1.4) and a Reynolds number (65, 92, 113, 131, 146), it was found that at low heat flux ($q'' = 250 \text{ W} / \text{m}^2$), the highest heat-transfer performance was approximately 1.45, with rising amplitude ($A_0 = 1.4$) and frequency ($W_0 = 146$).

Li *et al.* [55] conducted an experiment to find out how fin-tube radiators' heat transfer performance changed when subjected to vibration. Researchers used input water and gas temperatures of 60°C, water flows of 40 and 60 L/min, and speeds of 2, 4, 6 and 8 m/s for the study. Results showed that for every given amplitude and frequency, the average heat flow density climbed by 22.92% and 51.50%, respectively. As a result of the vibration disturbance, the heat exchange field synergistically expanded, which improved heat transfer.

Xie and Zhang [56] studied a computational and experimental study to enhance the efficiency of heat exchangers employing a vibrating cylinder for active flow control. The experiment was carried out using vibration durations of 0.015, 0.020, 0.030, and 0.060 seconds under a heat flux of 5000 W / m². Results show a 16.13% improvement in heat transfer performance and a 14.69% improvement in thermal transfer coefficient when compared to the standard stationary cylinder channel.

Akçay and Akdag [57] presented the effects of oscillation settings on mixed convection thermal transfer from a flat plate surface in a vertical orientation under conditions of constant heat flux by both experimental and numerical means. The non-dimensional vibration amplitude (0.4, 0.75, 1.1, 1.4), the Reynolds number (65, 92, 113, 131, 146) and the heat flux (250, 500, 625 W / m²) were some of the factors considered in the

study. An improvement in heat transfer efficiency was shown by the results. When compared to heat transfer via natural convection from a stationary plate, the greatest boost in performance was observed at 250 W/m^2 thermal flux, with a 45% enhancement. This was at a Womersley number of 146 and a capacity of 1.4.

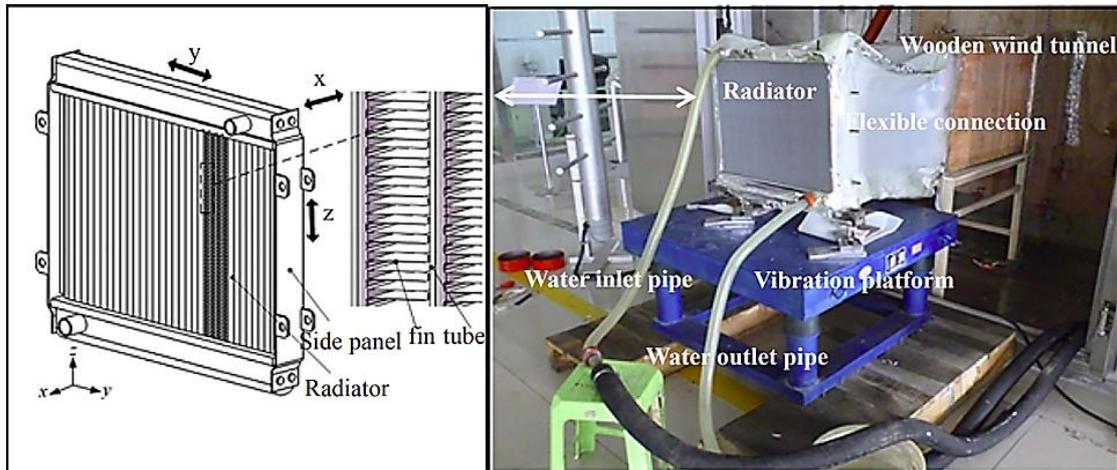


Fig.29. Photo of the experimental test rig [55].

Kadhim *et al.* [58] investigated how forced convection and vertical vibration affected the average Nu number in a finned tube running longitudinally through an experiment. Among the factors taken into account in the study was the following: the heat flow, which ranged from 500 to 1500 W/m^2 , the inclination angle of the tube relative to the horizontal, which can take on values of 0 , 30 , and 45 degrees; and vibration frequencies below 16 Hz . It was demonstrated that the average Nusselt number values at a 45° angle were up to i higher than those at a 30° angle and 16% higher than those at a 0° angle. Vibration intensity at a 45° angle increased heat transmission more than at lower angles (see Fig.30).

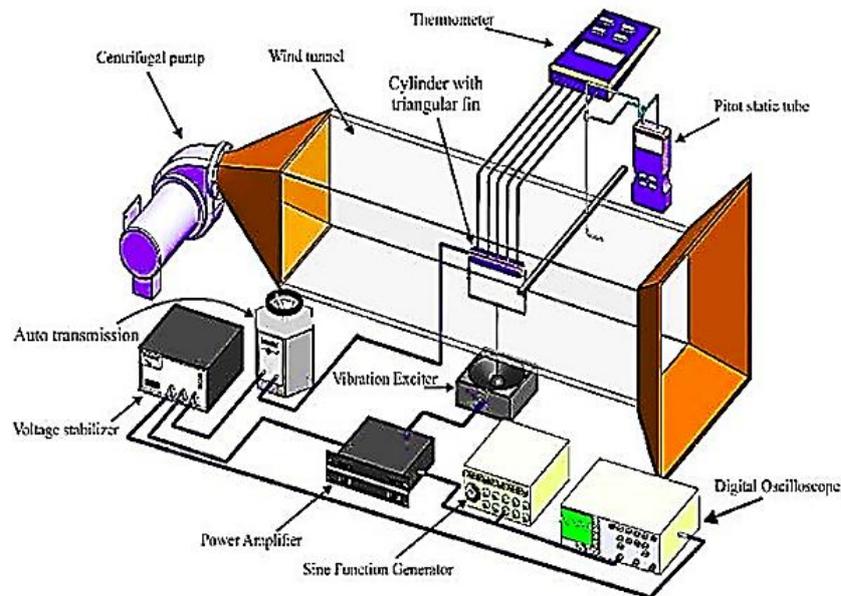


Fig.30. Sketchmatic diagram of the experimental test rig [58].

Mohammed *et al.* [59] focused on an experimental investigation of the effects of mechanical vibration on heat transfer, pressure drop, and a specific heat exchanger configuration, as shown in Fig.31. Using three different accelerations ($100, 300$ and 600 m/s^2), a temperature of $100 \text{ }^\circ\text{C}$, and a Re number between 10000 and 55000 , we may create vibrations with frequencies of $100, 300$, and 600 Hz , respectively. The highest improvement percentage for the friction factor was 95% , while the best increase for heat transmission was 116% , according to the study. There is a stronger relationship between frequency and acceleration than between the two.

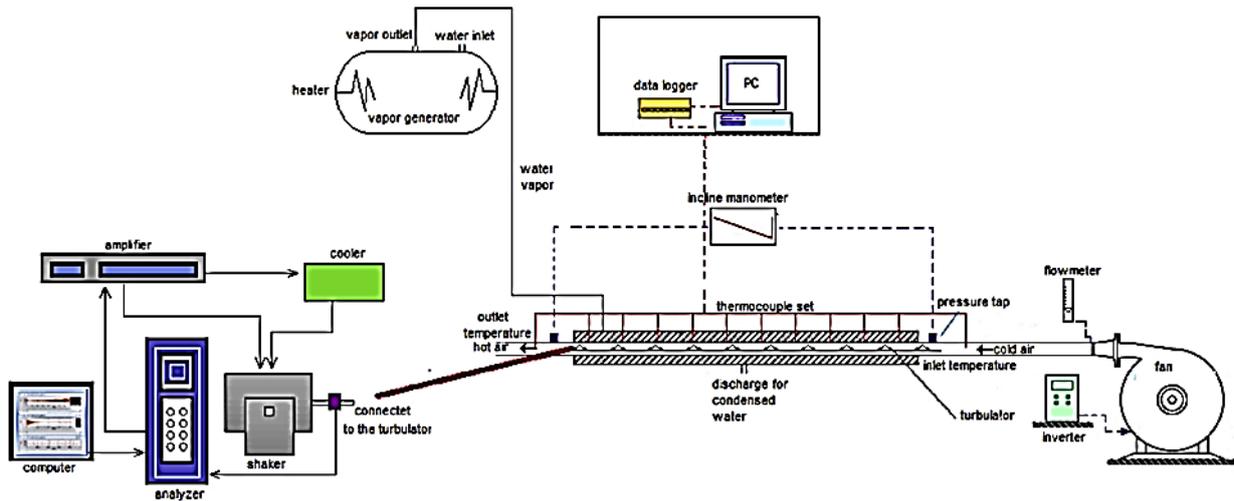


Fig.31. Experimental test rig diagram [59].

Rasangika *et al.* [60] conducted a numerical analysis comparing square and sinusoidal wave forms to determine how different vibration parameters could enhance heat transmission in a vibrating heat sink. With a 17 W thermal power, a frequency range of $0 - 100 \text{ Hz}$, a vibration amplitude of $0 - 5 \text{ mm}$, and a Reynolds number of 1000 . Compared to nonvibrating fins, the Nusselt values are 25% higher with square wave vibration, and compared to sinusoidal vibration, they are 11% higher. Hence, a decrease of 42.2% in Reynolds number values is necessary to get the Nusselt numbers of nonvibrating fins, which may lead to a smaller cooling system or fins altogether.

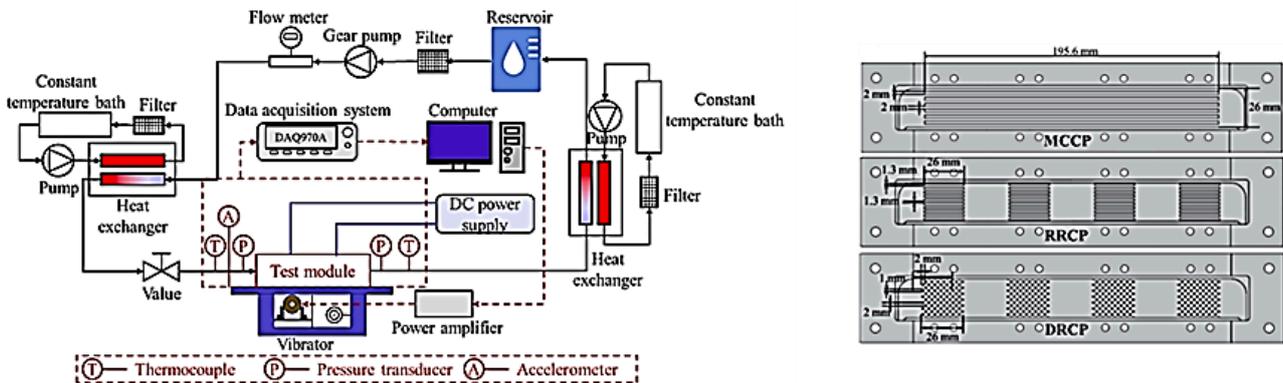


Fig.32. Experimental test rig diagram [62].

Ali *et al.* [61] conducted an experimental and numerical study on the enhancement of heat transfer under natural convection in a rectangular, long-finned heat sink under static and vibrating conditions. In this experiment, three different constant heat fluxes ($150, 230$ and 360 W/m^2) were subjected to vibrations with amplitudes ranging from 0.07 to 6.99 mm and frequencies from 0 to 50 Hz . According to the results, the modified Rayleigh number increases as the heat transfer coefficient does, which is better with low-frequency vibrations and worse with higher-frequency ones. Both the stationary and vibrating states showed an increase in airflow as the thermal flux climbed; however, the stationary state showed that the fins were more efficient.

Zhou *et al.* [62] performed research on the hydrothermal performance of cold plates subjected to vibration, with an emphasis on rectangular ribbed cold plate (RRCP), diamond ribbed cold plate (DRCP), and mini-channel cold plate (MCCP) cold plates, as shown in Fig.32. When tested in both stationary and vibrating modes, the researchers discovered that RRCP's heat transfer coefficients increased by 5.94% and DRCP's by 2.77% at 1.5 mm and 30 Hz vibration, respectively. On the other hand, as the vibration frequency increased, MCCP showed a little drop in heat transmission. The greatest pressure drop oscillation for MCCP was 306.18 Pa , but RRCP and DRCP both had notable increases in pressure drop.

Table 2. Summary of the application of mechanical vibration in enhancing heat transfer with forced convection.

Reference	Study objective	Study of parameters	Working fluid	Finding
[30] Sreenivasan and Ramachandran (1961)	Investigate vibration effect on horizontal cylinder heat transfer	Frequency, amplitude, air velocity	Air (cross flow)	Vibration increases heat transfer rate
[31] Klaczak (1997)	Experiments on heat exchangers under forced vibrations	Amplitude, frequency, exchanger geometry	Air/water	Vibration improves heat transfer capability
[32] Murphy and Lambert (2000)	Study modal effects on local HTC of vibrating body	Mode shape, vibration amplitude	Air	Different vibration modes lead to varying local heat transfer
[33] Bronfenbrener <i>et al.</i> (2001)	Experimental intensification of heat transfer under vibration	Frequency, amplitude, geometry	Air/water	Vibration enhances heat transfer significantly
[34] Eid and Gomaa (2009)	Influence of vibration on planar fins	Fin geometry, vibration frequency	Air	Vibrated fins exhibited higher HTC
[35] Cheng <i>et al.</i> (2009)	Heat transfer enhancement by flow-induced vibration	Flow rate, vibration response	Water/air	Flow-induced vibration intensifies heat transfer
[36] Eng. Technol. J. (2010)	Effect of vertical vibration on forced convection from finned cylinder	Frequency, amplitude, fin geometry	Air	HTC improved with vibration
[37] Kadhim <i>et al.</i> (2012)	Vertical forced vibration effect on pool boiling	Amplitude, frequency, heat flux	Water	Vibration enhanced boiling HTC
[38] Gururatana and Li (2013)	Vibrating pin fins for small-scale heat sinks	Pin geometry, vibration parameters	Air	Vibration improved fin efficiency

Table 2 cont. Summary of the application of mechanical vibration in enhancing heat transfer with forced convection.

Reference	Study objective	Study of parameters	Working fluid	Finding
[39] Chen <i>et al.</i> (2013)	Horizontal vibration and condensation temperature in heat pipes	Vibration parameters, condensation T	Heat pipe fluid	Vibration enhanced condensation heat transfer
[40] Guo <i>et al.</i> (2013)	Vibration in rectangular microgrooves	Frequency, amplitude, groove size	Coolant	Vibration enhanced flow and HTC
[41] Pilli <i>et al.</i> (2014)	CFD analysis of vibrating heated plate	Frequency, amplitude	Air	Simulation shows vibration improves convection currents
[42] Park <i>et al.</i> (2014)	Develop Nusselt correlation for vibration-assisted fins	Fin spacing, vibration frequency	Air	Proposed correlation for Nu with vibration
[43] Zhang <i>et al.</i> (2015)	Vibration effect on SiO ₂ -water nanofluid convection	Nanoparticle conc., vibration params	SiO ₂ -water nanofluid	Vibration + nanofluid greatly improved HTC
[44] Saini and Kumar (2015)	Effect of vibration in rectangular channel HX	Amplitude, frequency	Air	Vibration enhanced HX performance
[45] Wang <i>et al.</i> (2015)	Delta winglets under laminar pulsating flow	Frequency, amplitude, winglet geometry	Air	Pulsating flow improved HTC and reduced resistance
[46] Duan <i>et al.</i> (2016)	Flow-induced vibration in tube bundles	Tube elasticity, flow velocity	Water/air	Flow-induced vibration improved HTC
[47] Sarafraz <i>et al.</i> (2017)	Low-frequency vibration for fouling mitigation	Frequency, nanoparticle conc.	CuO/water nanofluid	Reduced fouling and improved performance
[48] Hosseinian <i>et al.</i> (2018a)	Surface vibration on nanofluid stability	Amplitude, frequency, nanofluid conc.	MWCNT/water nanofluid	Vibration enhanced HTC and fluid stability
[49] Hosseinian and Isfahani (2018b)	Surface vibration in double pipe HX	Amplitude, frequency	Water	Vibrations increased HTC in double-pipe HX
[50] Liu <i>et al.</i> (2017)	Vibration effect on tubular laminar flow	Amplitude, frequency	Water	Vibration improved HTC in laminar flow
[51] Mousavi and Heyhat (2019)	Nanofluid + transverse oscillation for cylinder cooling	Nanofluid conc., vibration params	Nanofluid	Oscillation improved nanofluid heat transfer
[52] Abadi <i>et al.</i> (2019)	Vibration on pool boiling from heated tube array	Frequency, amplitude, array layout	Water	Boiling HTC improved with vibration
[53] Setareh <i>et al.</i> (2019)	Ultrasonic vibration in double-pipe HX	Frequency, amplitude	Water	Ultrasound intensified HX thermal performance

Table 2 cont. Summary of the application of mechanical vibration in enhancing heat transfer with forced convection.

Reference	Study objective	Study of parameters	Working fluid	Finding
[54] Akcay <i>et al.</i> (2020)	Mixed convection on oscillating vertical plate	Frequency, amplitude	Air	Oscillations increased mixed convection HTC
[55] Li <i>et al.</i> (2020)	Vibration-enhanced fin-tube radiator	Frequency, amplitude	Coolant	Radiator performance improved with vibration
[56] Xie and Zhang (2021)	Laminar convection in channel with vibrating cylinder	Frequency, amplitude	Water	Vibration improved mixing and HTC
[57] Akcay and Akdag (2021)	Mixed convection from oscillating vertical plate	Frequency, amplitude	Air	Vibrations enhanced mixed convection HTC
[58] Kadhim <i>et al.</i> (2021)	Vertical vibration on finned tube	Frequency, amplitude, fin geometry	Air	Vibrations improved HTC of finned tubes
[59] Mohammed <i>et al.</i> (2021)	Vibration in HX with turbulator	Frequency, amplitude, turbulator design	Air/water	Vibration improved HTC/ ΔP trade-off
[60] Rasangika <i>et al.</i> (2022)	Square vs sinusoidal vibration on heat sinks	Waveform, frequency, amplitude	Air	Sinusoidal vibration yielded higher HTC
[61] Mohammed Ali and Abbas (2022)	Oscillating vertical plate fins under natural convection	Frequency, amplitude	Air	Vibration improved fin heat transfer
[62] Zhou <i>et al.</i> (2024)	Vibration effect on cold plates	Frequency, amplitude	Water	Vibration significantly influenced flow and HTC

4. Conclusion

The reviewed studies demonstrate that mechanical vibration, whether vertical, horizontal, transverse, or oscillatory is highly effective in enhancing convective heat transfer. It has been proven across various geometries, including cylinders, plates, fins, heat sinks, radiators, microchannels, and cold plates, by disturbing boundary layers, reducing stratification, and promoting mixing, which significantly boosts heat transfer coefficients. Research has also verified its effectiveness in phase-change processes and with advanced fluids, such as nanofluids, where vibration enhances stability, reduces fouling, and increases critical heat flux. However, several key gaps still exist. Most current correlations are system-specific and lack broad applicability. Few studies have evaluated the balance between the energy required for vibration and the resulting thermal benefits, an essential factor for practical applications. Scaling laws to adapt laboratory results to industrial systems are not well-defined. Additionally, the long-term effects of vibration on structural integrity and noise, as well as its integration with hybrid fluids, phase-change materials, and innovative fin designs, require further investigation. Overall, vibration has demonstrated itself as a versatile and efficacious technique for enhancing heat transfer, although additional research is requisite to translate its potential into widespread practical application. Future endeavours should focus on developing unified predictive models that precisely capture the influence of vibration parameters across different geometries and fluids. Equally vital are strategies to optimize energy efficiency, ensure long-term structural reliability, and explore synergies with advanced materials and multiphase working fluids. Addressing these challenges will be crucial for advancing vibration-assisted convection from laboratory-scale demonstrations to scalable,

durable, and energy-efficient technologies that can fulfil the requirements of sophisticated thermal management systems

Nomenclature

A_o – dimensionless oscillation amplitude

Gr – Grashof number

h_v – vibrational heat transfer coefficient ratio $[W / m^2 .K]$

h_o – heat transfer coefficient ratio without vibration $[W / m^2 .K]$

Nu – Nusselt number

Pr – Prandtl number

q'' – heat flux $[W / m^2]$

Ra – Rayleigh number

Re_v – vibrational Reynolds number

Wo – dimensionless oscillation frequency

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