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Experimental Study of Effect Vertical Vibration on Heat Transfer of Vehicle Radiator

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Abstract: External dynamic circumstances, especially vertical vibrations brought on by uneven road surfaces and engine activity, have a major impact on a vehicle's radiator performance. To increase cooling effectiveness and improve thermal management in automobiles, it is essential to comprehend how these vibrations affect heat transmission. This paper proposes using methods to enhance vibration-enhanced heat transfer and increase volumetric flows on a finned-tube car radiator. The radiator's thermal performance is improved through heat dissipation. The experiment was conducted at volumetric flows (0.5, 0.75, 1, and 1.25 liters per minute (LPM)) and frequencies (0, 5, 10, and 15 Hz). In terms of enhancing vibration-enhanced thermal performance, this study varies from other experimental investigations, particularly with regard to the frequency range employed and volumetric flow. We investigated the impact of vibration coinciding with volumetric flow and pellet behavior under operating settings more similar to those in which cooling systems function. This topic has not been fully explored before and does not constitute redundancy; instead, it solves limits by experimentally examining how vibration and realistic operating circumstances work together to improve thermal performance. The highest increase in Nusselt number enhancement was 23.4% observed on the water side, while the highest enhancement was 12.99% observed on the air side. Increased vibration led to increased heat flow, reaching its maximum 773.85 W/m^2 at frequency 15 Hz and volumetric flow 1.25 LPM. The vibrational disturbance further enhanced heat exchange between adjacent surfaces.

Keywords: Heat transfer; Fin-tube radiator; Vibration; Forced and free convection

1 Introduction

Due to the paucity of prior research on cooling system optimization, which frequently concentrated on enhancing thermal performance under optimal operating circumstances while ignoring the combined effects of these elements, this study was selected. In order to handle vibrations and sustain thermal performance under a variety of operating conditions, cooling systems must be designed and optimized. This clearly causes a research gap. As a result of the temperature difference between two adjacent bodies, heat transfer occurs from the hotter surface to the cooler surface to reach thermal equilibrium. There are three types of heat transfer: conduction, convection, and radiation [1]. Convection heat transfer has received widespread attention from researchers and is the most frequently used in industrial application.

Heat transfer enhancement methods are classified, based on their energy requirements, into active, passive, and composite-enhanced heat relies on surface vibration [2], magnetic field [3], spraying [4], and mechanical movement for heat transfer [5]. Passive technology relies on the use of a rough, extended surface [6], the jet [7], effect of surface treatment [8], and composite reinforcement of active and passive processes is achieved using various method.

Engineering applications have shown that heat transfer is of great importance in the design of bridges, buildings, vehicles, and digital devices, as well as in the development of heat transfer systems such as heaters, radiators, and heat exchangers [9]. Heat generation in these systems can lead to overheating and consequent system failure [10]. To eliminate this problem, practical studies are required on the transfer of heat from a solid surface to the fluid in contact with it [11].

In recent years, due to global advancements, car models have evolved and become more complex, leading to a need for larger radiators and improved performance [12]. The radiator is a crucial component of cooling systems, dissipating excess engine heat through heat transfer [13].

Due to rough roads or internal car design problems that cause vibrations, and because studies in this area were insufficient, this research idea was applied to determine the effect of vibrations on heat transfer. Vibrations disrupt the fluid surface in the boundary layer, leading to increased mixing between surfaces, which in turn increases heat transfer via convection.

Vibration is an effective and successful method for increasing heat transfer, as it confuses the particles in the fluid layers, leading to increased heat transfer [14]. There are two methods for vibration: the first is to keep the surface stationary, and to apply vibration within the liquid medium around the surface. The second is the movement of the surface itself as a result of placing a mechanism that forces the surface to vibrate, while the surrounding medium remains constant [15]. In industrial applications, when exposed to vibration (vibration resulting from ultrasonic waves and pulsating flow), despite its negative effects on the life and durability of the devices, the improvement of thermal transfer is achieved many times without vibration [16, 17]. The acoustic field [18] and nano particles [19–22] are considered important methods for increasing thermal transfer It is considered the best way to cool the computer [23]. Among the negative effects are concerns about the effect of vibration when designing machines under dynamic conditions due to their operation [24]. The effect of Nusselt number and Rayleigh number on improving thermal performance was investigated when heat was added using two shaped fins, one perforated and the other non-perforated. Heat transfer rate and Nusselt number increased with increasing heat addition, and increasing Rayleigh number resulted in a decrease in thermal resistance. It was confirmed that the non-perforated fin performed better than the perforated fin in improving thermal performance Also, injecting air bubbles into the U-shaped two-tube heat exchanger resulted in an increase in the flow rate and an increase in the heat transfer coefficient [25, 26]. Sheikh et al. [27] studied the effect of heat exchangers on the heat transfer process of thermoelectric generators using nine heat exchanger models. The results showed that reducing the barrier in the middle of the heat exchanger to 2.3 mm reduces the energy by a certain percentage 10.83%. Masoud Hosseini et al. [28] presented a study on improving thermal performance using low-concentration nanofluids in a long-tube heat exchanger. They found that when a concentration of 0.055% of the nanofluid is applied, the heat transfer process increases significantly and noticeably.

Eid and Gomaa [29] used a heat sink to demonstrate the effect of vibrations on heat transfer. The sink consisted of thin, flat fins. The sample was heated by a heater at the bottom and then subjected to vibration via a cam disc in random directions. The results showed that the Reynolds and Nusselt numbers were correlated, and the highest increase in the heat transfer rate was 85% compared to the static state.

Also, using a diffuser consisting of long fins, Sarhan [30] investigated the effect of vibrations occurring in a range (12–16 Hz) in the horizontal and inclined positions at angles (30°, 60°, and 90°). The results showed that the heat transfer coefficient at the angle 30° was higher than at the angle 60° by a certain amount 19.27%, and that the greatest increase at the angle 90° was 31.49% the increase in the heat transfer coefficient. Through practical and theoretical application, Kadhim and Mery [31, 32] conducted a study to clarify the effect of forced vibrations on the heat transfer coefficient of a wave-shaped copper surface subjected to vibration ranges (5 to 25 Hz) with varying amplitudes (3, 4, and 5 mm). The Rayleigh number ($1.5 \times 10^8 - 4 \times 10^8$) was heated in three ways: vertically, horizontally, and from above. It was found that increasing vibration increases the Nusselt number for the applied conditions, but this depends on the position of the wave surface. The transfer coefficient depends on the ratio between the vibration amplitude and the wavelength, with the best increase occurring at a ratio of 0.3.

Due to the phenomenon of reverse flow on inclined surfaces, the flow at lower Reynolds numbers is less stable. This was demonstrated by T'Joen et al. [33] using an inclined fin with a long tube, and he found that the best heat transfer occurs when the flow is along the fin. Biswas et al. [34] presented a review of the use of long vortex generators and how they improve thermal performance by disrupting the thermal boundary layer. The study of heat transfer enhancement has always been linked to pressure loss, and both lead to a good balance. In his scientific study, Li et al. [35] proposed the effect of vertical vibration on a radiator and how it impacts thermal performance. The experiment was conducted at a specific frequency, and it was found that the heat transfer coefficient increased with the gas side to a maximum of 16.82%, and with the air side to a maximum of 11.71%. Increasing the vibration increases heat transfer and results in pressure loss. However, despite the pressure loss, the improvement in thermal performance outweighs the pressure loss, and the highest increase in heat flow was found to reach 51.50%. The addition of nanoparticles and their ability to further enhance heat transfer. Sarafraz et al. [36] presented a study on the use of an iron oxide nanofluid, finding that despite a 37.5% pressure reduction, heat transfer increased by 46.3%. This suggests that nanofluids significantly contribute to increased heat transfer rates. Furthermore. Li et al. [37] demonstrated that adding an acetone and carbon nanofluid to heat exchangers increased heat transfer by up to 73%. Similarly, Goodarzi et al. [38] used counter-current heat exchangers and found that the presence of nanomaterials increased the Reynolds number, which in turn improved heat transfer efficiency using nanofluids. Using graphene nanosheets, researchers Bahiraei et al. [39] and Sarafraz et al. [40] have improved thermal performance through convection. Bahiraei demonstrated that increasing the Reynolds value from 1000 to 3000 resulted in up to 142% improvement in the performance of the nanofluid, while Sarafraz found a 32.1% improvement.

Mohammed et al. [41] used a rectangular channel heat exchanger to demonstrate the effect of vibration on improving thermal performance. They conducted experiments at three different frequencies and found that increasing vibration led to increased heat transfer. Similarly, Pandey et al. [42] used a horizontal heat exchanger and conducted their experiment with and without vibration. They found that the presence of vibration increased heat transfer, but only to a certain extent. Using very high frequencies can cause problems in the heat exchanger, potentially leading to its damage, such as noise, leakage, and reflections. In heat transfer Tian et al. [43] using a helical twin-tube heat exchanger, heat transfer was increased by converting the fluid's motion into a secondary, slower motion via forced convection. Bahmani et al. [44] also demonstrated increased heat transfer of nanofluids by increasing the Reynolds number.

The purpose of this study is to find strategies to improve thermal performance in finned-tube car radiators by increasing volumetric flow rates. Analyzing how vibrations improve heat transfer inside the radiator is another goal. The evaluation of heat dissipation's contribution to lower operating temperatures and improved heat exchange efficiency is the main goal of the study. Additionally, it aims to assess the radiator's thermal performance before and after implementing the suggested improvement methods.

Lastly, the study attempts to offer workable methods that might be applied to enhance automobile radiator efficiency and design.

2 Materials and Methods

2.1 Design Vibration Test Platform

The Figure 1 shows the design of the test platform under vibration conditions.

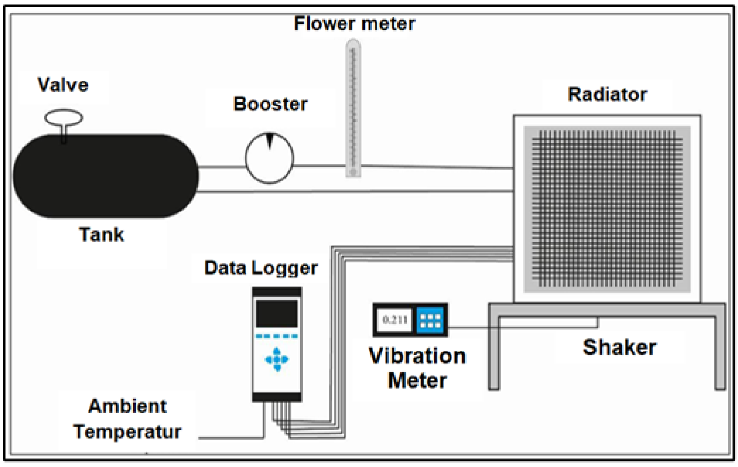

Figure 1. Schematic of a vibration-enhanced heat transfer

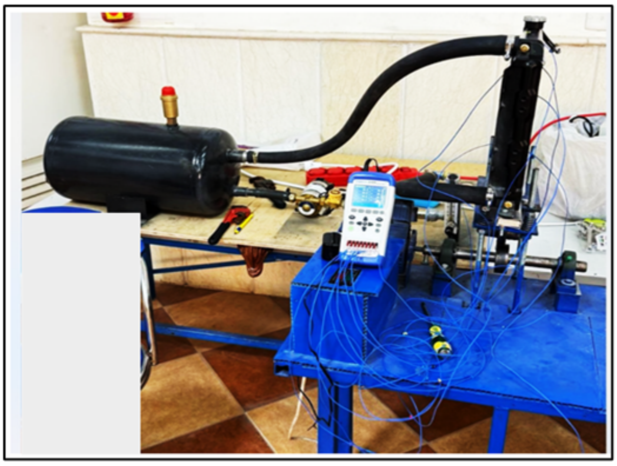

Figure 2. Schematic of vibration state of radiator under the vibration conditions

The platform consists of a radiator, a vibration shaker, and a tank equipped with a heater connected to a booster and flow meter. The radiator is placed on the vibration shaker platform, and vertical mechanical frequencies are generated. The frequency used in this experiment is (5, 10, and 15 Hz), which is similar to the vibrations experienced by vehicle radiators due to road roughness or internal engine vibrations. The forced frequencies generated by the vehicle are often low, hence the use of this vibration range. Flexible pipes circulate the water between the radiator and the tank, a principle similar to how cars operate. The water circulates between the engine, becoming hot, and returns to the radiator where the heat is dissipated by convection between the water and air. Temperature and flow data obtained during the experiment were collected. The Figure 2 illustrates the device used under vibration conditions, and the Table 1 shows the engineering specifications used for the radiator.

Table 1. Geometrical characteristics the radiator

No.	Description	Specification
1	Radiator Length (RL)	32 cm
2	Radiator Width (RW)	43 cm
3	Radiator Height (RH)	24.5 cm
4	Fin Width (FW)	26 mm
5	Fin Height (FH)	1.5 mm
6	Fin Thickness (FT)	28 mm
7	Total Area Surface	0.88 m
8	Number of Tubes (TN)	39

2.2 Vehicle Radiator Heat Transfer Test Parameters

Flow and vibration parameters and physical properties are as follows:

Water flow was measured using a flow meter consisting of two scales: gallons per minute (GPM) and liters per minute (LPM). The standard was LPM, and the water flow values used were 0.5, 0.75, 1, and 1.25 LPM.

Temperature sensors are measured using a Data Logger device with 8 temperature measurement channels: two at the water inlet and outlet of the radiator, five pairs distributed on either side of the radiator, and one free to measure ambient temperature. The device features a digital display showing the temperatures.

Vibration Meter is a device (SinometerVM-6360) was used to measure the acceleration and speed of vibration. It is attached to a magnetic compass placed on the vibration meter platform. The shaker converts the physical sensor into signals that are recorded on its digital screen. It works vibration for range (0–1 kHz). A heater was installed on the water tank to heat the water and set the temperature at 55°C.

The parameters obtained include the water inlet and outlet temperatures of the radiator, the ambient temperature of the radiator, and measurements. The parameters obtained included the inlet and outlet temperatures of the radiator water, the ambient temperature of the radiator, water flow rate, and vibration intensity. The radiator was placed on a vibration platform and kept vibrating for 30 minutes for each operating reading. The average values of the readings were obtained, and the difference between the inlet and outlet temperatures was approximately 6 to 10 degrees Celsius.

The principle of vibration involves converting electrical energy into mechanical energy using a motor. This utilizes the principle of hydro mechanical force, creating precise vibrations by introducing an electric current into a magnetic field to generate a kinetic force. The vibration intensity can be adjusted via a control panel, and the signal is controlled by the vibration frequency, Table 2 shows the accuracy of the measurement and sensors used in this research.

Table 2. Accuracy of the measurements and sensors utilized in this study

Parameter	Instrument	Uncertainty
Liquid temperature	K-type thermocouple	$\pm$0.5 K
Liquid flow rate	Flowmeter	$\pm$1% of max. displayed value
Nusselt number	Calculated	$\pm$0.4

In order to increase accuracy, a total of 16 measurement points were carried out under four volumetric flow rates 0.5/0.75/1/1.25 LPM in a steady-state environment free of vibrations and excitation frequencies 5/10/15 Hz. Each measurement was repeated 4 times. Excellent repeatability was shown by the deviation among repetitions not passing one unit (STDEV.S $<$ 1).

In order to prevent unintentional interference with the natural convection process, which is primarily driven by free convection, the experiments were carried out in a closed room with still air. No forced ventilation or external air flow was present during the tests, and there was no air conditioning system nearby. The updated manuscript now includes this clarification.

The periodic acceleration of the fluid caused by vertical vibration results in secondary flows. By encouraging mixing between near-surface and far-surface fluid layers, these fluxes lessen the thickness of the boundary layer and enhance heat transfer efficiency. Since the predominant fluid movement in this instance is mostly vertical, shear effects are less noticeable.

A vibration measurement instrument was used to directly measure all vibration frequencies; no values were estimated. A mechanical shaker that was intended to produce a vertical sinusoidal vibration was used to vibrate the radiator. To guarantee precise vibration transmission, the radiator was securely fixed on the shaker platform.

The vibration measurement device's sensor was used to detect the vibration frequency, and the reported data indicated the average vibration level. Table 3 summarizes the vibration parameters and classifies them as either measured or estimated.

Table 3. Summary of vibration parameters with classification as measured or estimated

No.	Parameter	Value	Method of Determination
1	Frequency (Hz)	0, 5, 10, and 15	Measured
2	Volumetric flow rate (L/min)	0.5, 0.75, 1, and 1.25	Measured
3	Waveform type	Sinusoidal	Measured
4	Vibration amplitude	–	Not measured
5	Vibration acceleration	–	Not measured
6	Vibration direction	Vertical	Measured

3 Calculation

3.1 Evaluation Method for Vibration-Enhanced Heat Transfer Effect

To determine heat transfer, it is necessary to find the relationships obtained experimentally, such as Nusselt's number, Reynolds number, and the heat transfer coefficient [45].

3.1.1 Radiator parameters

Cross-sectional area of flow:

$$A_c = l \times w \tag{1}$$

The surface area between the liquid and the wall:

$$A_s = P \times L \times N_t \tag{2}$$

Characteristic length of flat tube:

$$D_H = \frac{4A_c}{P} = \frac{4(l \times w)}{2(l+w)} \tag{3}$$

Reynolds number has been found by:
Convert flow rate from LPM to m^3/s:

$$\dot{v} = LPM \times \frac{0.001\left(m^3\right)}{60(s)} = \frac{m^3}{s} \tag{4}$$

Find mass flow rate:

$$\dot{m} = \rho \times \dot{v} \tag{5}$$

$$G = \frac{\dot{m}}{N \times A_c} \tag{6}$$

$$Re = \frac{G \times D_h}{\mu} \tag{7}$$

In this investigation, a vibration meter installed on the shaker platform was used to measure vibration frequency directly. Acceleration and vibration amplitude were not directly measured due to equipment constraints. As a result, frequency-controlled vibration conditions are the main focus of the experimental analysis. When interpreting the vibration intensity, this restriction should be taken into account.

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A digital vibration meter was used to measure the vibration. In order to record motion in the same direction as the applied vibration (vertical), the sensor was positioned vertically on the shaker base. Due to equipment restrictions, amplitude and acceleration could not be measured, hence the presented data represents the average frequency. Throughout every experiment, the vibration signal's waveform remained sinusoidal.

3.1.2 Heat transfer coefficient of the radiator

Heat rate transfer has been found by:

$$Q_{rate} = \dot{m} \times cp \times \Delta T \tag{8}$$

The heat transfer coefficient of the water side is calculated from the temperature difference between the water inlet and outlet from the radiator, in addition to its physical properties.

$$h_{exp} = \frac{Q_{rate}}{A_s \left(T_{ave} - T_b\right)} \tag{9}$$

A portion of the energy is lost through radiation, calculated as follows [46]:

$$Q_{rad} = \sigma \times \varepsilon \times A \times \left(T_{ave}^4 - T_{amb}^4\right) \tag{10}$$

A portion of the energy is lost through radiation, calculated as follows [47]:

$$h_{out} = \frac{Q_{rate} - \mathrm{Q}_{rad}}{A \left(T_{ave} - T_{amb}\right)} \tag{11}$$

The manuscript has been updated to present the governing equations in full form, and all symbols are defined at their first appearance to improve clarity and allow replication of the results. To find Reynolds number (Re).

$$Re = \frac{G \times D_h}{\mu} \tag{12}$$

$$G = \frac{\dot{m}}{N \times A_c} \tag{13}$$

where, G is mass flux and measured by kg/(m^2·s)

And to find Prandtle number (Pr) used:

$$Pr = \frac{\mu \times cp}{k} \tag{14}$$

Physical explanation: The increase in vibration Reynolds number (Re_v) and excitation frequency, which exacerbate periodic disturbances within the thermal boundary layer, provides a physical explanation for the enhancement of heat transmission. Higher convective heat transfer coefficients and the observed rise in the Nusselt number result from these disruptions, which also encourage boundary layer thinning and cause secondary flow and micro-mixing close to the heated surface.

4 Results and Discussion

4.1 Effect of Vibration on Heat Transfer of Radiator Inside (Water Side)

Figure 3 shows the increase in the heat transfer coefficient with increasing volumetric flow rate and vibration intensity. Vibration increases turbulence, thus reducing the thickness of the boundary layer, which in turn increases collisions of water molecules, leading to heat transfer. Although the flow rate decreases the time it takes for water to enter and exit the radiator, the change in its physical properties and the increase in mass flow rate result in a higher temperature. The ratios below represent the increase in the heat transfer coefficient according to increasing volumetric flow rates at frequencies (0, 5, 10, and 15 Hz). When the volumetric flow rate was 0.5 LPM, the increase in the heat transfer coefficient was from 130.22 to 179.81 W/m^2·°C. At a volumetric flow rate of 0.75 LPM, the increase was from 189.08 to 279.67 W/m^2·°C. For volumetric flow rates at 1 and 1.25 LPM values were from 234.23 and 355.98 to 378.77 and 563.70 W/m^2·°C, respectively.

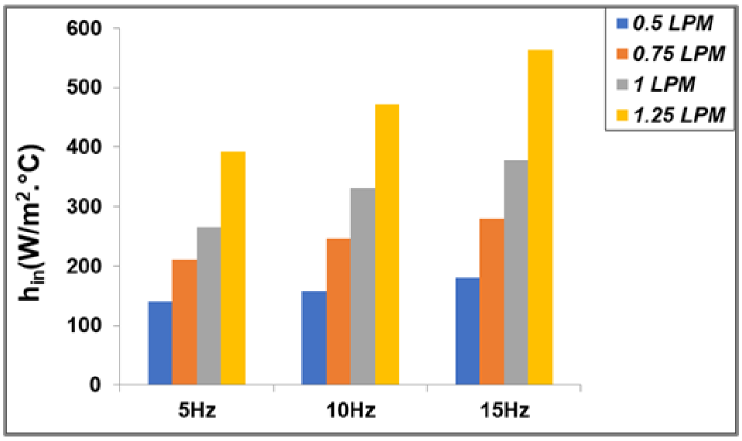

Figure 3. Effect vibration and flow rate on heat transfer coefficient (water side)

4.2 Effect of Vibration on Heat Transfer of Radiator Inside (Air Side)

Figure 4 shows the increase in air-side heat transfer between the radiator and the outside air. Increasing the volumetric flow and frequency causes disturbances in the water movement within the radiator, and the vibrations disturb the outer layer surrounding the radiator. This leads to changes in the density of the air layers, thus increasing heat transfer. The results, according to the increase in frequency intensity (0, 5, 10, and 15 Hz), were as follows: at a volumetric flow of 0.5 LPM, the heat transfer coefficient increased from 16.66 to 19.28 W/m^2·°C; at 0.75 LPM, the values decreased from 18.81 to 22.46 W/m^2·°C; and at volumetric flows of 1 and 1.25 LPM, the increase in the heat transfer coefficient was from 27.67 and 33.45 to 35.26 and 47.25 W/m^2·°C, respectively.

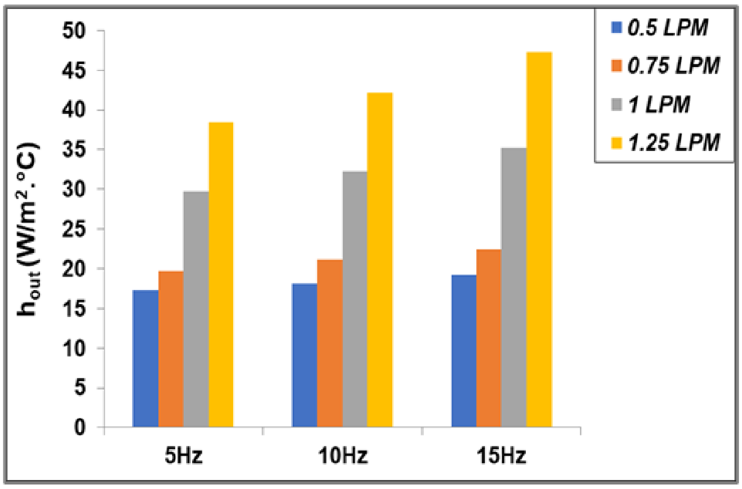

Figure 4. Effect vibration and flow rate on heat transfer coefficient (air side)

4.3 Effect of Vibration on Nusselt Number (Water Side)

The observed rise in Nusselt number can be converted into an estimated decrease in outlet fluid temperature or an increase in heat dissipation under normal operating circumstances to illustrate the data's practical implications for vehicle cooling. This quantitative analysis demonstrates the actual effects of improved heat transfer on the cooling system's effectiveness and performance.

To calculate the number of Nusselt units on the water side, the results obtained from the experiment were used according to Eq. (15). When comparing the experimental results with those obtained mathematically by Eq. (16) using the Sieder-Tate Equation [48], the results were very close.

$$Nu_{exp} = \frac{h_{exp} \times D_h}{k_{(Tb)}} \tag{15}$$

$$Nu_d = 0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.333}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{16}$$

Figure 5 shows the increase in Nusselt number with volumetric flow and frequency from the water side. The values according to the frequencies (0, 5, 10, and 15 Hz) were as follows: at a volumetric flow rate of 0.5 L/min, the Nusselt number increased from 0.57 to 0.79 W/m^2·°C; at a volumetric flow of 0.75 LPM, the increase in Nusselt number was from 0.84 to 1.23; and at volumetric flows of 1 and 1.25 LPM, the increase in Nusselt numbers were from 1.04 and 1.58 to 1.67 and 2.48, respectively.

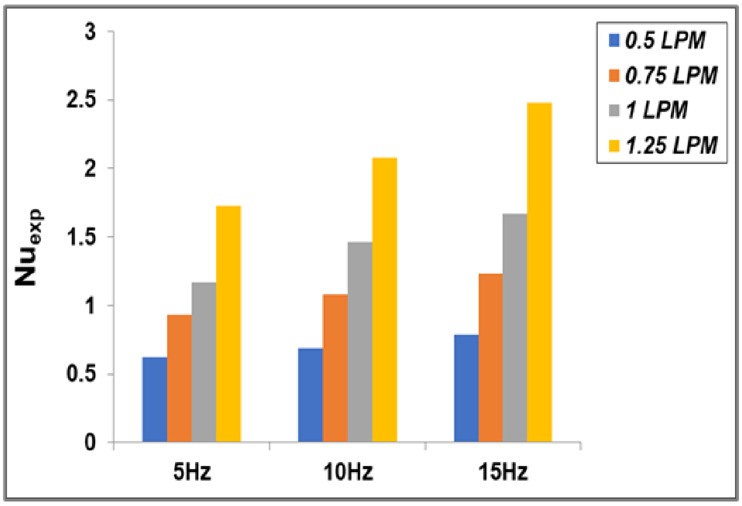

Figure 5. Effect vibration and flow rate on Nusselt number (water side)

To calculate the Nusselt number from the air side, where heat exchange occurs between the refrigerant and the outside air, heat transfer occurs due to the density difference between the layers, thus increasing heat transfer. The Nusselt number is a function of convection heat transfer; as heat transfer increases, the Nusselt number also increases.

$$Nu_{out} = \frac{h_{out} \times L}{k_{(Tf)}} \tag{17}$$

Figure 6 shows the increase in Nusselt number with volumetric flow and frequency from the air side. The values were as follows: at a volumetric flow of 0.5 LPM, the increase in Nusselt number according to the frequencies (0, 5, 10, and 15 Hz) was from 197.74 to 227.39 W/m^2·°C; at a volumetric flow of 0.75 LPM, the increase in Nusselt number was from 223.02 to 263.35; and at volumetric flows of 1 and 1.25 LPM, the increase in Nusselt numbers were from 327.25 and 396.51 to 414.03 and 556.31, respectively.

The Sieder-Tate Equation was used to determine the Nusselt number as a function of the Reynolds and Prandtl numbers according to the following relation:

$$N_u = 0.027 R_e^{0.8} P_r^{0.33}\left(\frac{\mu}{\mu_u}\right)^{0.11} \tag{18}$$

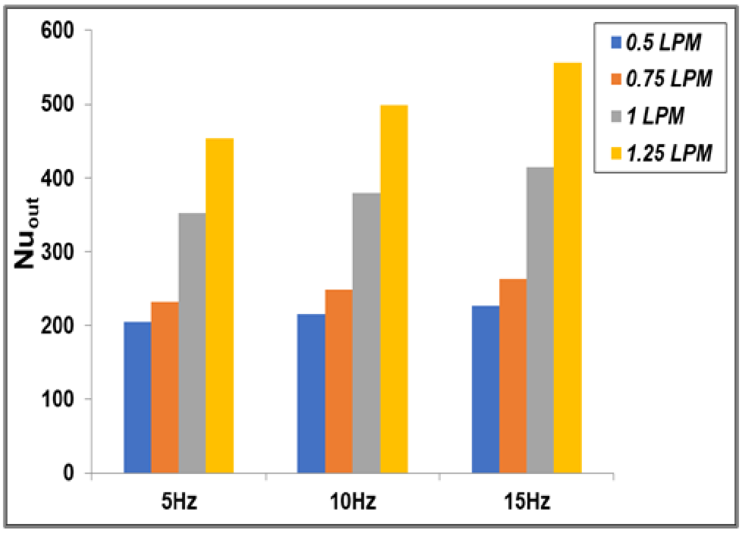

Figure 6. Effect vibration and flow rate on Nusselt number (air side)

The results showed that the Nusselt number increases with increasing Reynolds and Prandtl numbers. When comparing the experimentally obtained results from direct measurements with those calculated using the mathematical correlations, the difference between the results was found to be very small, indicating good agreement.

The volumetric flow rates used were 0.5, 0.75, 1, and 1.25 LPM, under vibration testing at frequencies of 5, 10, and 15 Hz, in addition to the stationary condition. The lowest Reynolds number recorded was 16.16, corresponding to the stationary condition at a volumetric flow rate of 0.5 LPM, while the highest Reynolds number was 47.25, recorded at a vibration frequency of 15 Hz and a volumetric flow rate of 1.25 LPM.

The results were also compared with those reported by another researcher in a study on improving the thermal performance of an automotive radiator. Although that study employed much higher volumetric flow rates (40 and 60 LPM) within a vibration frequency range of 0–20 Hz, it similarly achieved clear and satisfactory enhancement in vibration-assisted heat transfer.

4.4 Relationship Between the Reynolds Number (Rea) and the Vibrational Reynolds Number (Rev) on Heat Transfer Coefficient

Figure 7 show the effect of the buoyancy-induced Reynolds number on the heat transfer coefficient was investigated in the absence and presence of vibration for the following volumetric flow rates: 0.5, 0.75, 1, and 1.25 LPM. As the temperature increases, the sample begins to heat up, and its height increases with the volumetric flow rate. This increases its velocity, thereby reducing the effect of viscosity, increasing mixing within the tube, and decreasing the boundary layer thickness. Consequently, the Reynolds number increases, which in turn increases heat transfer and the heat transfer coefficient. We observe an increase in the heat transfer coefficient with increasing Reynolds number (Rea) of 16.16, 18.81, 27.67, and 33.45 W/m^2·°C, respectively, depending on the volumetric flow rate. In the presence of vibration, mixing increases due to the oscillations, and a slight improvement in the vibrational Reynolds number (Rev) is observed. Correspondingly, heat transfer increases at a frequency of 5 Hz. The heat transfer coefficient increases at rates of 17.27, 19.67, 29.74, and 38.48 W/m^2·°C, at frequencies of 10 and 15 Hz. The increases in the heat transfer coefficients for volumetric fluxes are (18.18, 21.09, 32.25, 42.14) and (19.28, 22.46, 35.26, 47.25) W/m^2·°C, respectively. As vibration frequency and volumetric flow rate rise, the Nusselt number and Reynolds number increase proportionately. Both the Reynolds number and the Nusselt number rise when the fluid flow rate increases because of increasing water turbulence and the creation of more convection currents. By increasing fluid turbulence, vibration improves heat transmission. Since the rate of heat transfer determines the Nusselt number, the increased heat transfer brought about by vibration raises the Nusselt number.

4.5 Percentage Improvement in Nusselt Number (En%) (Air Side)

The effect of the enhancement ratio on the dimensional Nusselt number was studied along with the free convection air side for volume flows of 0.5, 0.75, 1, and 1.25 LPM in the presence and absence of vibration at frequency levels 5, 10, and 15 Hz. It is clear that with increasing frequency and volume flow, on the coolant side, the density of the hot air layer resulting from the temperature difference changes and is replaced by cold air. This disturbance increases as the vibration increases, and there is a difference between the cold and hot air layers. As a result, the difference occurs, free heat transfer increases as the frequency and volume flow increase, which increases the heat transfer, especially the Nusselt number, because it is a function of the heat transfer by convection. The increase in the improvement percentages of the heat transfer coefficient at frequencies 5 and 10 Hz and according to the adopted volumetric flows were as follows (3.50%, 4.26%, 7.73%, 7.82%) and (4.99%, 6.85%, 8.53%, 9.82%) respectively. The highest increase in the improvement percentage was 6.42%, 7.61%, 8.90%, and 12.99% at frequency of 15 Hz, as shown in Figure 8.

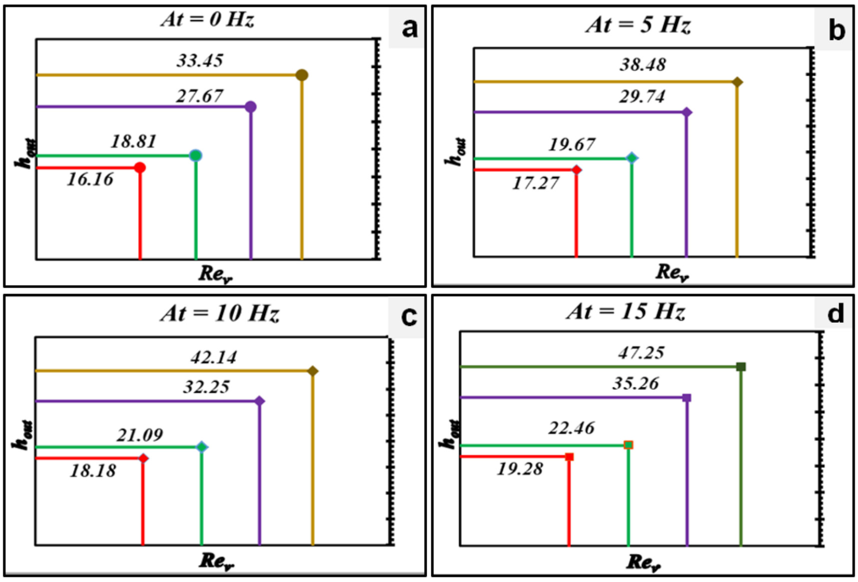

Figure 7. The relationship between Nusselt number and Reynolds number: (a) at 0 HZ; (b) at 5 HZ; (c) at 10 HZ; (d) at 15 HZ

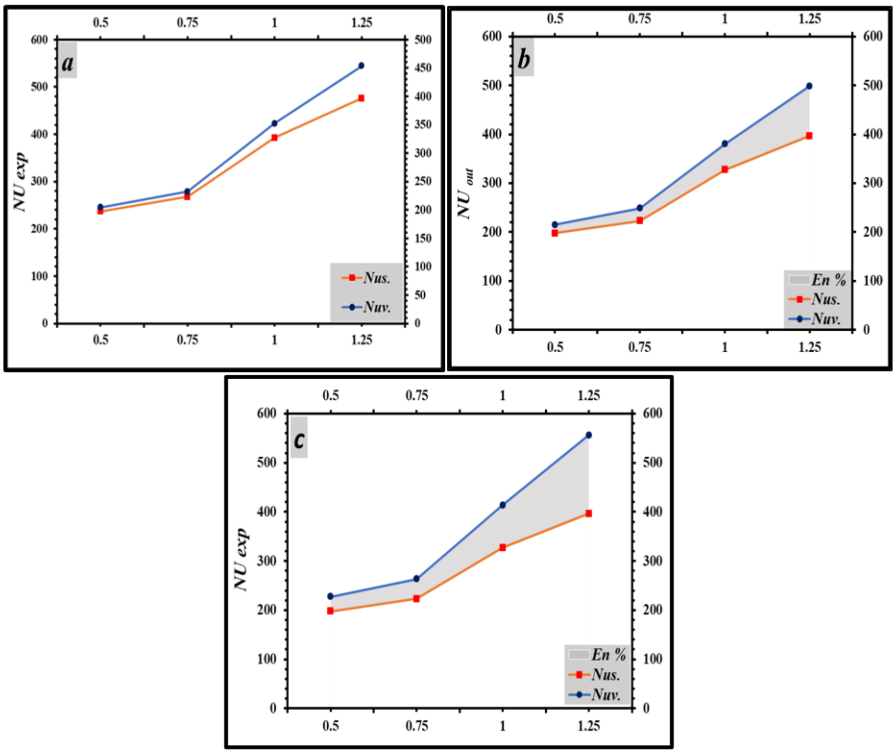

Figure 8. (a) The improvement ratio in the dimensionless Nusselt number at a frequency of 5 Hz (air side); (b) the improvement ratio in the dimensionless Nusselt number at a frequency of 10 Hz (air side); (c) the improvement ratio in the dimensionless Nusselt number at a frequency of 15 Hz (air side)

4.6 Percentage Improvement in Nusselt Number (En%)

The improvement in the dimensionless Nusselt number was studied for volumetric flows of 0.5, 0.75, 1, and 1.25 LPM, in the presence or absence of vibration at frequencies of 5, 10, and 15 Hz. It is evident that with increasing frequency and volumetric flow, the flow velocity increases, mixing increases, and the boundary layer penetrates and becomes thinner. As a result, eddy currents form, increasing heat transfer, which in turn increases convection. The Nusselt number, which represents the convection function, increases with increasing transfer. The increase in the improvement percentages of the heat transfer coefficient at frequencies 5 and 10 Hz, according to the adopted volume flows, was as follows: (7.67%, 11.07%, 12.75%, 12.95%) and (11.92%, 17.08%, 17.79%, 19.73%) respectively. The highest increase in the improvement percentage was 14.05%, 17.85%, 18.73% and 23.40% at frequencies of 15 Hz, as shown in Figure 9.

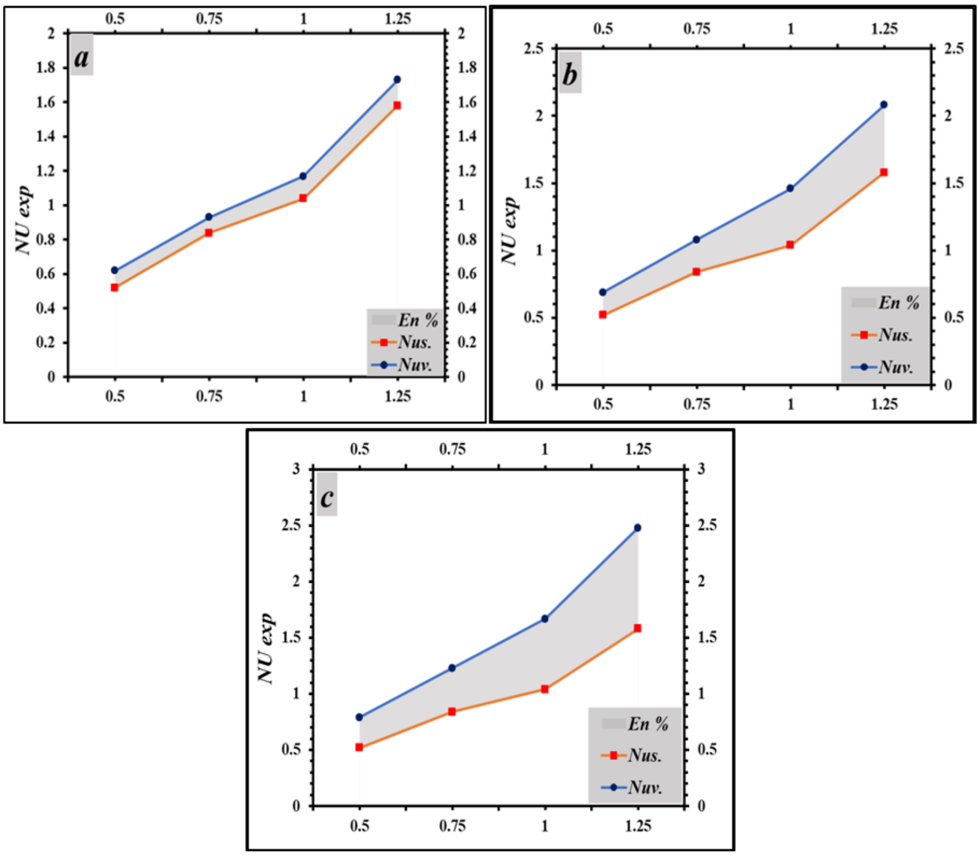

Figure 9. (a) The improvement ratio in the dimensionless Nusselt number at a frequency of 5 Hz; (b) the improvement ratio in the dimensionless Nusselt number at a frequency of 10 Hz; (c) the improvement ratio in the dimensionless Nusselt number at a frequency of 15 Hz

Our findings and those published by Li et al. [35] have been quantitatively compared. This comparison draws attention to the two research's similarities and differences. Vibration caused an overall increase in the heat transfer coefficient in Li's experiments: for the liquid phase, this increase ranged from roughly 1.9% to 11.7%, with an average enhancement of about 6.8%; for the gas phase, it ranged from roughly 3.0% to 16.8%, with an average of roughly 9.9%. These results show the degree of agreement or improvement in thermal performance when compared to previously published data and offer a clear reference for positioning our findings.

The improvement in the dimensionless heat transfer coefficient (Nusselt number) is represented by the percentage. According to the improvement ratio law, these percentages not only show theoretical improvement but also improve operating margins in a scientific manner. The difference in heat transfer improvement with higher vibration is what causes this improvement.

By assessing the combined impact of vibration frequency and volumetric flow rate on the thermal performance of the water-air heat exchanger, this study offers a novel approach in comparison to earlier research, connecting improved heat transfer to mixing and a decrease in the thickness of the boundary layer. Additionally, it offers exact quantitative measures of the increase in heat transmission, which can reach up to 23.4% and 12.99%, respectively—findings not addressed in earlier research.

4.7 Empirical Analysis of Vibration's Impact on Heat Transfer

An empirical correlation based on an approximation (regression analysis) of experimental data was obtained in order to quantitatively characterize the impact of mechanical vibration on convective heat transfer. This is the suggested relationship:

$$C^c R_e^a P_r^b f = N_u \tag{19}$$

where,

Nu is the Nusselt number;

Re is the Reynolds number;

Pr is the Prandtl number;

f is the vibration frequency (Hz);

C, a, b, and c are empirical coefficients determined by nonlinear regression.

Based on the processing of the experimental data from this study, the following coefficient values were obtained: C = 0.018, a = 0.84, b = 0.36, c =0.12.

An increase in vibration frequency results in a higher Nusselt number, or more intense heat transfer, if the exponent c is positive. Increased flow mixing and disruption of the thermal boundary layer provide an explanation for this. The model's validity is confirmed by the suggested correlation, which shows good agreement with experimental results: the average relative error is 7.11% and the determination coefficient R^2 = 0.94.

The correlation is applicable in the following parameter ranges: $4000 \leq Re \leq 18000$; $Pr \approx 0.7$ (air); Volumetric flow: 1.5–4.5 LPM; $0 \leq f \leq 25$ Hz.

The suggested association predicts greater Nusselt numbers in the presence of vibration as opposed to the traditional Sieder-Tate correlation, which disregards its impact. This demonstrates that vibration improves heat transmission by enhancing turbulent disturbances and decreasing the thickness of the thermal barrier layer.

5 Conclusions

This study investigates how vibration and volumetric flow rate can enhance a composite heat exchanger's thermal performance, with an emphasis on the water-inside and air-sides.

1. The investigation showed that as vibration frequency and volumetric fluid flow rate increase, the composite heat exchanger's thermal performance greatly improves.
2. The approach was effective on both sides of the exchanger, as evidenced by the maximum heat transfer increment of 23.4% on the water-inside and 12.99% on the air-side.
3. By interfering with the uniform water flow, vibration increases forced convection heat exchange by reducing the thickness of the boundary layer and promoting layer mixing.
4. The findings demonstrate that when vibration and a higher flow rate are combined, the effects are better than when each component is used separately.
5. Compared to other methods for enhancing heat transmission, the vibration-based approach is easy to use and effective.
6. Despite the encouraging outcomes, there are still few real-world uses for this method, which highlights the need for more research to assess the impact of vibration under various operating circumstances.
7. Future study should broaden its focus to include precise heat exchange measurements under industrial operating settings, examination of the impact of higher frequencies, and evaluation of thermal performance in multi-layer systems.

Author Contributions

Conceptualization, N.M.A.; methodology, N.M.A. and Y.H.A.; validation, Y.H.A. and Q.A.Y.; formal analysis, N.M.A.; investigation, N.M.A.; resources, Y.H.A.; data curation, Q.A.Y.; writing—original draft preparation, N.M.A.; writing—review and editing, Y.H.A. and Q.A.Y.; visualization, N.M.A.; supervision, Y.H.A.; project administration, Y.H.A. All authors were actively involved in discussing the findings and refining the final manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Y. L. He and W. Q. Tao, "Convective heat transfer enhancement: Mechanisms, techniques, and performance evaluation," in *Advances in Heat Transfer*. Elsevier, 2014, pp. 87–186. https://doi.org/10.1016/bs.aiht.2014.09.001

[2] B. Grabas, "Vibration-assisted laser surface texturing of metals as a passive method for heat transfer enhancement," *Exp. Therm. Fluid Sci.*, vol. 68, pp. 499–508, 2015. https://doi.org/10.1016/j.expthermflusci.2015.06.006

[3] S. Roy, P. Saikrishnan, and R. Ravindran, "Role of non-uniform slot injection (suction) model on the separation of a laminar boundary layer flow," *Math. Comput. Model.*, vol. 50, no. 1–2, pp. 45–52, 2009. https://doi.org/10.1016/j.mcm.2008.12.016

[4] M. Gao, L. S. Zhang, D. Zhang, and L. X. Zhang, "Experimental study on the enhancement of free convection heat transfer under the action of an electric field," *Exp. Therm. Fluid Sci.*, vol. 104, pp. 9–14, 2019. https://doi.org/10.1016/j.expthermflusci.2019.02.006

[5] G. Metcalfe and D. Lester, "Mixing and heat transfer of highly viscous food products with a continuous chaotic duct flow," *J. Food Eng.*, vol. 95, no. 1, pp. 21–29, 2009. https://doi.org/10.1016/j.jfoodeng.2009.04.032

[6] K. Posew, S. Laohalertdecha, and S. Wongwises, "Evaporation heat transfer enhancement of R-134a flowing inside smooth and micro-fin tubes using the electrohydrodynamic technique," *Energy Convers. Manag.*, vol. 50, no. 7, pp. 1851–1861, 2009. https://doi.org/10.1016/j.enconman.2009.02.003

[7] A. L. Goh and K. T. Ooi, "Nature-inspired inverted fish scale microscale passages for enhanced heat transfer," *Int. J. Therm. Sci.*, vol. 106, pp. 18–31, 2016. https://doi.org/10.1016/j.ijthermalsci.2016.03.010

[8] J. W. Zhou, Y. G. Wang, G. Middelberg, and H. Herwig, "Unsteady jet impingement: Heat transfer on smooth and non-smooth surfaces," *Int. Commun. Heat Mass Transfer*, vol. 36, no. 2, pp. 103–110, 2009. https://doi.org/10.1016/j.icheatmasstransfer.2008.10.020

[9] Z. K. and H. O., "Influence of vibration on free convection heat transfer from sinusoidal surface," *Int. J. Comput. Appl.*, vol. 136, no. 4, pp. 1–6, 2016. https://doi.org/10.5120/ijca2016908252

[10] W. H. A. R. Al-Doori, "Enhancement of natural convection heat transfer from the rectangular fins by circular perforations," *Int. J. Automot. Mech. Eng.*, vol. 4, pp. 428–436, 2022. https://doi.org/10.15282/ijame.4.2011.5.0035

[11] M. R. Shaeri and M. Yaghoubi, "Thermal enhancement from heat sinks by using perforated fins," *Energy Convers. Manag.*, vol. 50, no. 5, pp. 1264–1270, 2009. https://doi.org/10.1016/j.enconman.2009.01.021

[12] Q. Zhang, L. Xu, J. Li, and M. Ouyang, "Performance prediction of plate-fin radiator for low temperature preheating system of proton exchange membrane fuel cells using CFD simulation," *Int. J. Hydrogen Energy*, vol. 42, no. 38, pp. 24 504–24 516, 2017. https://doi.org/10.1016/j.ijhydene.2017.07.210

[13] Z. Said, M. E. H. Assad, A. A. Hachicha, E. Bellos, M. A. Abdelkareem, D. Z. Alazaizeh, and B. A. Yousef, "Enhancing the performance of automotive radiators using nanofluids," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 183–194, 2019. https://doi.org/10.1016/j.rser.2019.05.052

[14] H. Shokouhmand, S. M. A. Noori Rahim Abadi, and A. Jafari, "The effect of the horizontal vibrations on natural heat transfer from an isothermal array of cylinders," *Int. J. Mech. Mater. Des.*, vol. 7, no. 4, pp. 313–326, 2011. https://doi.org/10.1007/s10999-011-9170-6

[15] H. Al sultan, A. Soltan, and H. El-Tahan, "Natural convection heat transfer from vibrated vertical flat plate," *Bull. Fac. Eng. Mansoura Univ.*, vol. 40, no. 1, pp. 22–31, 2021. https://doi.org/10.21608/bfemu.2020.96277

[16] A. Bash, A. Alkumait, and H. Yaseen, "Experimental investigation of the influence of mechanical forced vibrations and heat flux on coefficient of heat transfer," *Sci. J. Univ. Zakho*, vol. 6, no. 3, pp. 124–129, 2018. https://doi.org/10.25271/sjuoz.2018.6.3.519

[17] S. K. Mishra, A. Arora, and H. Chandra, "Application of vibration on heat transfer: A review," *i-Manager's J. Future Eng. Technol.*, vol. 15, no. 1, pp. 72–81, 2019. https://doi.org/10.26634/jfet.15.1.15877

[18] R. C. Martinelli and L. M. K. Boelter, "The effect of vibration upon the free convection from a horizontal tube," in *Proceedings of the 5th International Congress of Applied Mechanics*, Cambridge, Massachusetts, USA, 1938, p. 578.

[19] B. A. Bhanvase, S. D. Sayankar, A. Kapre, P. J. Fule, and S. H. Sonawane, "Experimental investigation on intensified convective heat transfer coefficient of water based PANI nanofluid in vertical helical coiled heat exchanger," *Appl. Therm. Eng.*, vol. 128, pp. 134–140, 2018. https://doi.org/10.1016/j.applthermaleng.2017.09.009

[20] R. V. Pinto and F. A. S. Fiorelli, "Review of the mechanisms responsible for heat transfer enhancement using nanofluids," *Appl. Therm. Eng.*, vol. 108, pp. 720–739, 2016. https://doi.org/10.1016/j.applthermaleng.2016.07.147

[21] N. S. Pandya, H. Shah, M. Molana, and A. K. Tiwari, “Heat transfer enhancement with nanofluids in plate heat exchangers: A comprehensive review,” *Eur. J. Mech. B Fluids*, vol. 81, pp. 173–190, 2020. https://doi.org/10.1016/j.euromechflu.2020.02.004

[22] P. Kumar and R. M. Sarviya, “Recent developments in preparation of nanofluid for heat transfer enhancement in heat exchangers: A review,” *Mater. Today Proc.*, vol. 44, pp. 2356–2361, 2021. https://doi.org/10.1016/j.matpr.2020.12.434

[23] H. T. Ali, A. M. Hussein, and J. A. Yagoob, “Heat transfer enhancement using nanofluids for cooling computer device: A review,” *NTU J. Eng. Technol.*, vol. 1, no. 1, pp. 25–34, 2021. https://doi.org/10.56286/ntujet.v1i1.82

[24] A. Rahman and D. Tafti, “Characterization of heat transfer enhancement for an oscillating flat plate-fin,” *Int. J. Heat Mass Transf.*, vol. 147, p. 119001, 2020. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119001

[25] M. S. Hassan, T. A. Tahseen, and M. M. Weis, “Natural convection from a radial heat sink with triangular fins,” *NTU J. Eng. Technol.*, vol. 1, no. 2, pp. 40–49, 2022. https://doi.org/10.56286/ntujet.v1i2.81

[26] M. F. Albayati and R. A. Khalefa, “The performance of the U shape double pipe heat exchanger under effect of using active techniques,” *NTU J. Eng. Technol.*, vol. 1, no. 3, 2022. https://doi.org/10.56286/ntujet.v1i3.61

[27] R. Sheikh, S. Gholampour, H. Fallahsohi, M. Goodarzi, M. Mohammad Taheri, and M. Bagheri, “Improving the efficiency of an exhaust thermoelectric generator based on changes in the baffle distribution of the heat exchanger,” *J. Therm. Anal. Calorim.*, vol. 143, no. 1, pp. 523–533, 2021. https://doi.org/10.1007/s10973-019-09253-x

[28] S. Masoud Hosseini, M. R. Safaei, P. Estellè, and S. Hadi Jafarnia, “Heat transfer of water-based carbon nanotube nanofluids in the shell and tube cooling heat exchangers of the gasoline product of the residue fluid catalytic cracking unit,” *J. Therm. Anal. Calorim.*, vol. 140, no. 1, pp. 351–362, 2019. https://doi.org/10.1007/s10973-019-08813-5

[29] E. I. Eid and M. E. Gomaa, “Influence of vibration in enhancement of heat transfer rates from thin plannar fins,” *Heat Mass Transf.*, vol. 45, no. 6, pp. 713–726, 2009. https://doi.org/10.1007/s00231-008-0470-9

[30] A. R. Sarhan, “Vertical forced vibration effect on natural convective performance of longitudinal fin heat sinks,” *Tikrit J. Eng. Sci.*, vol. 20, no. 2, pp. 60–69, 2013. https://doi.org/10.25130/tjes.20.2.06

[31] Z. K. Kadhim and H. O. Mery, “Free convection from optimum sinusoidal surface exposed to vertical vibrations,” *Int. J. Mech. Eng. Technol.*, vol. 7, no. 1, pp. 214–224, 2016.

[32] Z. K. Kadhim and H. O. Mery, “Influence of vibration on free convection heat transfer from sinusoidal surface,” *Int. J. Comput. Appl.*, vol. 136, no. 4, pp. 1–6, 2016.

[33] C. T’Joen, H. Huisseune, H. Canière, H. J. Steeman, A. Willockx, and M. De Paepe, “Interaction between mean flow and thermo-hydraulic behaviour in inclined louvered fins,” *Int. J. Heat Mass Transf.*, vol. 54, no. 4, pp. 826–837, 2011. https://doi.org/10.1016/j.ijheatmasstransfer.2010.10.020

[34] G. Biswas, H. Chattopadhyay, and A. Sinha, “Augmentation of heat transfer by creation of streamwise longitudinal vortices using vortex generators,” *Heat Transf. Eng.*, vol. 33, no. 4–5, pp. 406–424, 2012. https://doi.org/10.1080/01457632.2012.614150

[35] D. Li, X. Yang, S. Wang, D. Duan, Z. Wan, G. Xia, and W. Liu, “Experimental research on vibration-enhanced heat transfer of fin-tube vehicle radiator,” *Appl. Therm. Eng.*, vol. 180, p. 115836, 2020. https://doi.org/10.1016/j.applthermaleng.2020.115836

[36] M. M. Sarafraz, A. Dareh Baghi, M. Safaei, A. S. Leon, R. Ghomashchi, M. Goodarzi, and C. X. Lin, “Assessment of Iron Oxide (III)—Therminol 66 Nanofluid as a novel working fluid in a convective radiator heating system for buildings,” *Energies*, vol. 12, no. 22, p. 4327, 2019. https://doi.org/10.3390/en12224327

[37] Z. X. Li, U. Khaled, A. A. A. A. Al-Rashed, M. Goodarzi, M. M. Sarafraz, and R. Meer, “Heat transfer evaluation of a micro heat exchanger cooling with spherical carbon-acetone nanofluid,” *Int. J. Heat Mass Transf.*, vol. 149, p. 119124, 2020. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119124

[38] M. Goodarzi, A. Amiri, M. S. Goodarzi, M. R. Safaei, A. Karimipour, E. M. Languri, and M. Dahari, “Investigation of heat transfer and pressure drop of a counter flow corrugated plate heat exchanger using MWCNT based nanofluids,” *Int. Commun. Heat Mass Transf.*, vol. 66, pp. 172–179, 2015. https://doi.org/10.1016/j.icheatmasstransfer.2015.05.002

[39] M. Bahiraei, H. Kiani Salmi, and M. R. Safaei, “Effect of employing a new biological nanofluid containing functionalized graphene nanoplatelets on thermal and hydraulic characteristics of a spiral heat exchanger,” *Energy Convers. Manag.*, vol. 180, pp. 72–82, 2019. https://doi.org/10.1016/j.enconman.2018.10.098

[40] M. M. Sarafraz, M. R. Safaei, Z. Tian, M. Goodarzi, E. Bandarra Filho, and M. Arjomandi, “Thermal assessment of nano-particulate graphene-water/ethylene glycol (WEG 60:40) nano-suspension in a compact heat exchanger,” *Energies*, vol. 12, no. 10, p. 1929, 2019. https://doi.org/10.3390/en12101929

[41] A. M. Mohammed, S. Kapan, M. Sen, and N. Çelik, “Effect of vibration on heat transfer and pressure drop in a heat exchanger with turbulator,” *Case Stud. Therm. Eng.*, vol. 28, p. 101680, 2021. https://doi.org/10.1016/j.

csite.2021.101680
[42] K. A. Pandey, C. P. Pant, S. O. Sastry, A. Kumar, and K. S. Tyagi, “Energy and exergy performance evaluation of a typical solar photovoltaic module,” *Therm. Sci.*, vol. 19, no. Suppl. 2, pp. 625–636, 2015. https://doi.org/10.2298/TSCI130218147P
[43] Z. Tian, A. Abdollahi, M. Shariati, A. Amindoust, H. Arasteh, A. Karimipour, M. Goodarzi, and Q. V. Bach, “Turbulent flows in a spiral double-pipe heat exchanger,” *Int. J. Numer. Methods Heat Fluid Flow*, vol. 30, no. 1, pp. 39–53, 2019. https://doi.org/10.1108/HFF-04-2019-0287
[44] M. H. Bahmani, O. A. Akbari, M. Zarringhalam, G. R. Ahmadi Sheikh Shabani, and M. Goodarzi, “Forced convection in a double tube heat exchanger using nanofluids with constant and variable thermophysical properties,” *Int. J. Numer. Methods Heat Fluid Flow*, vol. 30, no. 6, pp. 3247–3265, 2019. https://doi.org/10.1108/HFF-01-2019-0017
[45] A. Hasan, “Going below the wet-bulb temperature by indirect evaporative cooling: Analysis using a modified ε-NTU method,” *Appl. Energy*, vol. 89, no. 1, pp. 237–245, 2012. https://doi.org/10.1016/j.apenergy.2011.07.005
[46] J. C. Han and L. M. Wright, *Analytical Heat Transfer*. CRC Press, 2022.
[47] M. Zhang, X. Chen, K. Liang, Z. Li, X. Wang, J. Huang, Y. Qian, and H. Zhou, “Heat transfer mechanism of spray cooling under vibrational conditions: Effects of spray volume flow rate and nozzle inclination angle,” *Int. Commun. Heat Mass Transf.*, vol. 164, p. 108820, 2025. https://doi.org/10.1016/j.icheatmasstransfer.2025.108820
[48] C. G. Kirkbride, “Heat transfer by condensing vapor on vertical tubes,” *Ind. Eng. Chem.*, vol. 26, no. 4, pp. 425–428, 1934. https://doi.org/10.1021/ie50292a014

Nomenclature

A_c	Cross-sectional area of flow, m^2
A_s	The surface area between the liquid and the wall, m^2
A	Total surface area of the sample, m^2
C_P	Specific heat of water, J/kg·°C
D_H	Hydraulic diameter of radiator water channel
f	Vibration frequency, Hz
g	Ground acceleration, m/s^2
h_{in}	Forced convection heat transfer coefficient, W/m^2·°C
h_{out}	Free convection heat transfer coefficient, W/m^2·°C
GPM	Gallons per minute, GPM
l	The tube section length, m
L	Test sample length, m
LPM	Liter per minute, LPM
m	Mass flow rate, kg/s
N	Number of pipes
P	Wetted circumference, m
Q_{conv}	Heat transfer by convection, W
Q_{rate}	Heat transfer rate, W
Q_{rad}	Heat transfer by thermal radiation, W
t	The tube section width, m
T_{ave}	Average temperatures on the surfaces of the test sample, °C
T_{amb}	Ambient temperature, °C
T_b	Mean bulk temperature, °C
T_f	Film temperature on the surface of the two test specimens, K
$T_{water,in}$	Water inlet temperature, °C
$T_{water,out}$	Water outlet temperature, °C
V	Volumetric flow rate, LPM
w	The tube section height, m

Non-dimensional numbers

$En\%$	Improvement rate in the dimensional heat transfer coefficient
Nu_o	Nusselt number without vibration
Nu_v	Nusselt number with vibration
Pr	Prandtl number
Ra_s	Rayleigh number without vibration

Ra_v	Rayleigh number without vibration
Gr	Grashof number
Re_s	Reynolds number based on surface
Re_v	Reynolds number based on velocity

Greek symbols

β	Coefficient of volume expansion, 1/K
μ	Dynamic viscosity, kg/m·s
ν	Kinetic viscosity, m^2/s
ρ	Density, kg/m^3