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Evaluation of Heat Transfer Enhancement from an Oscillation Heat Sink Under Free Convection Heat Transfer

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ABSTRACT

Enhancing heat dissipation in passive cooling systems remains a critical challenge for modern electronic and thermal devices. This study introduces an innovative approach that integrates forced vibration with a rectangular-finned heat sink to enhance free-convective thermal performance. The research investigates the influence of vibration frequency and amplitude on the heat transfer coefficient, fin efficiency, and air mass flow rate under various heat fluxes. Experiments were conducted within a controlled vertical duct test rig equipped with a data logger, anemometer, and electrical instrumentation. Three heat flux levels, 150, 230, and 360 W/m², were examined across vibration frequencies ranging from 0 to 50 Hz and amplitudes between 0.07- and 6.99-mm. Results revealed a direct correlation between the heat transfer coefficient and the modified Rayleigh number, with maximum enhancement observed at 50 Hz. Compared to static conditions (0 Hz), the overall heat transfer coefficient increased by 160%, 59.5%, and 55.2% for the respective heat fluxes, accompanied by air mass flow rate rises of 8.8%, 12.7%, and 25%. Despite these gains, fin efficiency decreased marginally by 9.8t o11.8% due to intensified convective mixing. The findings highlight the novel contribution of mechanical vibration as an effective means to augment natural convection without additional energy input for fluid motion, offering a practical enhancement strategy for passive aluminum-finned heat sinks used in electronic cooling and thermal management systems.

Introduction

Improving thermal efficiency hinges significantly upon raising the disparity in temperatures between an object being heated and its environment. It is possible through enhancing the heat exchange rate or expanding the contact space between objects involved in thermal interaction. A multitude of research has explored diverse methods for improving the performance of cooling devices through passively induced convective flows in ambient environments. Various designs for geometrical structures have been suggested in an effort to enhance cooling efficiency within such setups. Convection methods typically offer faster heat dissipation but frequently entail greater power usage and more audible disturbances compared to other techniques.

Optimizing the surface area or adding extended elements like fins could resolve these problems. Unlike forced convection, which relies solely on external energy input for movement, natural convection is driven by internal forces such as temperature differences leading to buoyancy effects within fluids. During mechanical convective flow, liquid movement happens through physical forces like fans or pumps; conversely, natural convective currents arise naturally as fluids move because of differences in their densities caused by varying temperatures. This occurrence commonly finds application within electronic cooling mechanisms, especially for use in heat sinks [4]. Thickened areas frequently appear in technological setups like manufacturing equipment to enhance cooling efficiency through enhanced air circulation contact points. These materials play crucial roles in managing temperature, such as within air conditioning units, electronics cooling devices, heat transfer elements like those found in reactors and collectors of renewable energies [5].

As the temperature nears the bottom of the fin, convection decreases due to an obstructed airflow zone hindering both flow and heating efficiency. Despite being higher up, the top parts of the fin face greater exposure to air currents around it, leading to enhanced convective cooling effects. Substances like steel exhibit heightened air flow-induced friction at their surfaces, thereby diminishing localized thermal exchange. [6]. Consequently, an ideal fin configuration should strike a delicate equilibrium between enhancing heat transfer efficiency while adhering to real-world limitations like material density, size dimensions, and production expenses. Scientists frequently resolve such issues through methods of enhancing cooling efficiency relative to available fins or reducing fin sizes while maintaining set thermal output requirements [7]. The authors Rasangi et al. Experimental research was carried out by [8], examining how forced vibrations affect heat dissipation through longitudinally finned heatsinks when subjected to constant thermal load and in the presence of free convective flow conditions. The results showed that the heat conduction rate was higher when measured at an incline of 30 degrees compared to 60 degrees, differing by about 19%. Three percent, increasing to thirty-one percent over time. At an angle of ninety degrees, this figure illustrates how significantly the direction of fins impacts convection-enhancing effects.

Moreover, researchers Sathe and Sanap [9] analyzed the efficiency of slit-shaped flat plates in rising fluids for studying how adding transverse slots affects thermal conductivity characteristics. Their study revealed that altering flat fins into slit ones resulted in enhanced convective heat exchange efficiency and increased total cooling capacity when subjected to varying input powers between 25 and 125 watts, demonstrating how optimizing fin geometries can significantly boost thermal management capabilities. Researchers Rahman and Tafti [10] performed computational studies aimed at evaluating and improving convective cooling of a linearly oscillating plate within unsteady, inviscid media. The outcomes showed an increase in the vibration frequency resulted in a parallel enhancement of the Nusselt number, indicating better convective efficiency. Moreover, as per Azzawi et al. A research project was conducted examining how external vibrations affect the rate at which hot fluids rise in a cylindrical tube surrounded by cooler ones vertically aligned.

Heat transfer measurements spanned an interval from 35 to 75 watts per square meter; meanwhile, vibration intensities oscillated within the range of 90 to 180 hertz consistently at levels not exceeding 0 units. Al-Shorafa's study revealed that reducing both the surface temperature and the size of the cylindrical object led to an enhancement in heat exchange efficiency under conditions involving vertical vibrations. Moreover, it was evident that the Reynolds number significantly influenced heat transfer efficiency. The researchers Saini and Kumar [13] evaluated how adding vibrations improved convection-based heating efficiency within a horizontally oriented rectangle-shaped cooling system using experiments. Their conclusion was that incorporating mechanical vibrations into extensive heat exchange systems introduces significant difficulties such as material degradation due to wear, potential for leaks under pressure fluctuations, and increased operational noise levels associated with higher amplitude movements. Khadim et al.

The study [14] investigated how vertical vibrations impact forced convective heat transfer within a longitudinally finned pipe. The study's results indicated that the mean Nu value for fins oriented at an angle of 45 degrees surpassed values obtained under other angles such as 30 degrees and zero degree, showing increases of approximately fourteen percent and sixteen percent compared to these baseline conditions. Khadir et al. A study examined how vibrations affect natural airflow within a cubical container containing air, discovering that increased frequency led to substantial enhancements in thermal conductivity due primarily to buoyant effects, alongside insulation provided by only one side.

Khan et al. Numerical analysis was conducted on the study of natural convective heat exchange around a vertical oscillating cylinder. The results indicated that when the Brinkman number grew larger, temperatures fell, whereas the Nusselt numbers climbed during situations of lower frequency. Additionally, faster flow rates were observed when the Grashof ratio was higher, while slower velocities appeared at greater values of the Brinkman coefficient. Researchers Gururatana and Li [17] explored micro-scale heat conduction through vibrations on a square wedge shape fin, demonstrating significant improvements in thermal efficiency alongside an observable rise in resistance levels. Researchers Nag and Bhattacharya investigated how vibrations impact natural air currents around vertically arranged square fins whose dimensions changed. Their conclusion was that any vibration lower than 15 millimeters per second did not significantly enhance temperature control. Researchers Eid and Gomaa investigated a computer-aided cooling system composed of fins arranged in four sectors, analyzing how vibrations affect thermal conductivity within this design. The findings revealed an empirical connection between the Nusselt, Strouhal, and Reynolds numbers, showing uniformity in their behaviors under comparable average speeds. [Kadhim 20] conducted an experimental study examining how periodic movement affects heat exchange in natural convective flow conditions. Research revealed that augmenting horizontal vibrational force boosts not only the convection-induced thermal conductivity but also increases overall heat flow rates significantly. Additionally, it was observed that vibrations increased in direct proportion as their direction became more horizontal, while they decreased at lower inclinations relative to vertical axes. Comparative research found Kadhim and Nasif [21], who studied a finned cylindrical object exposed to longitudinal heating under vibratory conditions. Their findings indicated an increase in the heat transfer rate as the vibrational intensity grew across various angle ranges of zero through forty-five degrees; however, higher inclinations led to diminished total coefficients. The authors Sertkaya et al. A new plate design was suggested by [22], focusing on enhancing convective cooling through increased air flow around spaced-out heating elements; this approach reduces overall thermal impedance when compared to traditional configurations where closer proximity of heaters and plates minimizes airflow separation. Instead, adding more fin structures had little effect on improving cooling efficiency.

Researchers Rao and Babu examined how vibrations can boost fluid-based convective currents using substances like water, engine oil, diesel fuel, alcohol, and antifreeze. Their conclusion was that reduced conductivity of fluid materials showed minimal enhancement in thermal efficiency. Furthermore, their data indicated an ascending trend in the convective heat transfer rate throughout the height of the cylindrical vessel when subjected to increasing oscillatory conditions. The researchers Sultan et al. Analysis of free convection heat exchange on a vertical oscillating flat surface revealed that the vibrational frequency was found to be significantly influential whereas the amplitude had little impact. Moreover, as per Akçay et al. Investigations into mixed convection near a vertically vibrating plate revealed that the governing factor for the Rayleigh number is not the amplitude but its frequency. Liu et al. Experimental studies [26] revealed an increase in heat dissipation of up to twenty-two percent due to vibrations within a finned-tube automotive cooling system. Nine percent. Their investigation revealed an additional enhancement of 51% in heat dissipation through increased frequencies. Five percent.

The rate of thermal conduction enhanced by precisely 1 unit. Eighty-nine percent through eleven units has been completed. Seventy-one percent in relation to liquids saw an increase of three percentage points up to sixteen percent. An increase of 8 percentage points in gasoline prices was observed alongside an upward trend in pressure drops by approximately two units. Six percent and forty percent. A fifth of each party's contribution is allocated in this arrangement. Authors Akçay and Akdağ conducted numerical analysis of mixed convection flows on a dynamically oscillating horizontal surface employing ANSYS Fluent software.

The findings showed that temperature and heat transfer were highly influenced by both vibrational frequencies and amplitudes. At a heat flux rate of 250 watts per square meter, there is an intensity level of 1 unit. A thickness of 4 millimeters coupled with a frequency of 146 hertz yielded the greatest improvement in performance. The study was conducted by Xie et al. Numerical experiments were conducted on simulating thermal conduction within an oscillating duct featuring four equidistant cylindrical elements. In comparison to its static counterpart, the vibrational prototype demonstrated an improvement of 14%.

A notable enhancement of 7 percentage points in the convective heat transfer efficiency was observed compared to previous studies. Additionally, there is an increase by 16%. A 13 percent rise in total heat efficiency is observed. This study investigates how forced vibration affects the thermal performance of heat sinks equipped with flat longitudinal fins operating under steady-state free convection. The analysis compares the system's behavior under vibrational conditions with its performance at a static state (0 Hz). The focus of the investigation is to establish the relationship between the heat transfer coefficient and the modified Rayleigh number for stationary conditions, as well as the relationship between the heat transfer coefficient and the vibrational Reynolds number during oscillatory motion. These relationships are used to evaluate how vibration influences airflow characteristics and to assess its impact on the thermal efficiency of the finned heat sinks.

1. Experimental Setup

The experimental setup features a vertical channel with a rectangular cross-section measuring 137 mm by 142 mm and a height of 750 mm. It is constructed from transparent polycarbonate to allow for optical access. The channel is open at the bottom to facilitate unrestricted air inflow and has a circular outlet (50 mm in diameter) at the top, where a digital anemometer is installed to measure airflow velocity. An aluminum heat sink is positioned within a square opening measuring 100 mm by 100 mm on one side of the channel. Each heat sink consists of a base plate measuring 100 mm by 100 mm by 10 mm, along with nine longitudinal fins. Each fin is 130 mm long, 100 mm wide, and 2 mm thick, arranged uniformly with a spacing of 8.2 mm.

A 140 W electric heating element is embedded in the base of the heat sink and connected to a regulated power supply and measurement system. Additionally, the assembly is linked to a vibration generator and control unit to impose controlled oscillations. Experiments were conducted in line with the study objectives, ensuring that the system reached steady-state conditions at each applied heat flux level (150, 230, and 360 W/m²) before data acquisition began. A multi-channel temperature data logger, capable of recording eight channels, captured readings from K-type thermocouples; two located at the air inlet and outlet, and six distributed across the surface of the heat sink. Temperature and airflow data were automatically logged at five-minute intervals throughout each test for all vibration frequencies ranging from 0 Hz to 50 Hz, corresponding to amplitudes of 0.07 to 7.0 mm. Each experiment was repeated three times to ensure measurement accuracy and reduce experimental uncertainty. Figure 2 shows a photograph of the test rig components.

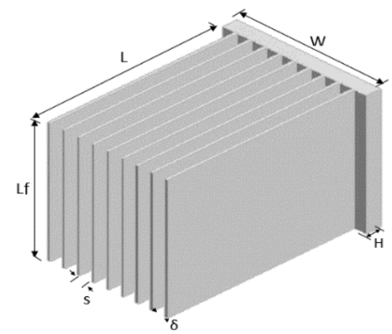


Fig.1 Sketch of a heat sink

Fig.2 Photo of the test rig used

2. Result and Discussion

a. The Relation Between h and Ra*

Fig.3 shows the relationship of the (h) to the (Ra*) when the heat sink was at rest state (0 Hz). It indicated an increase in both h and Ra* concerning heat flux increases. Additionally, it demonstrated that the relationship between them is linear. This is because the physical characteristics of the fluid (ρ, μ, c_p, k, and Pr) are all dependent on temperature. The results agreed with the researchers [21].

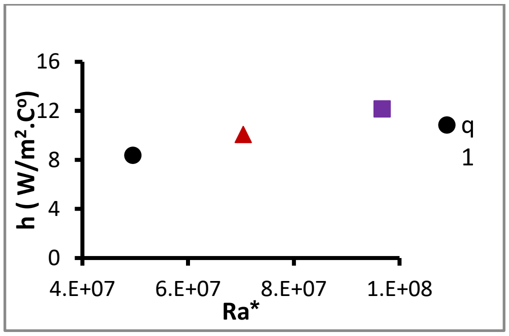
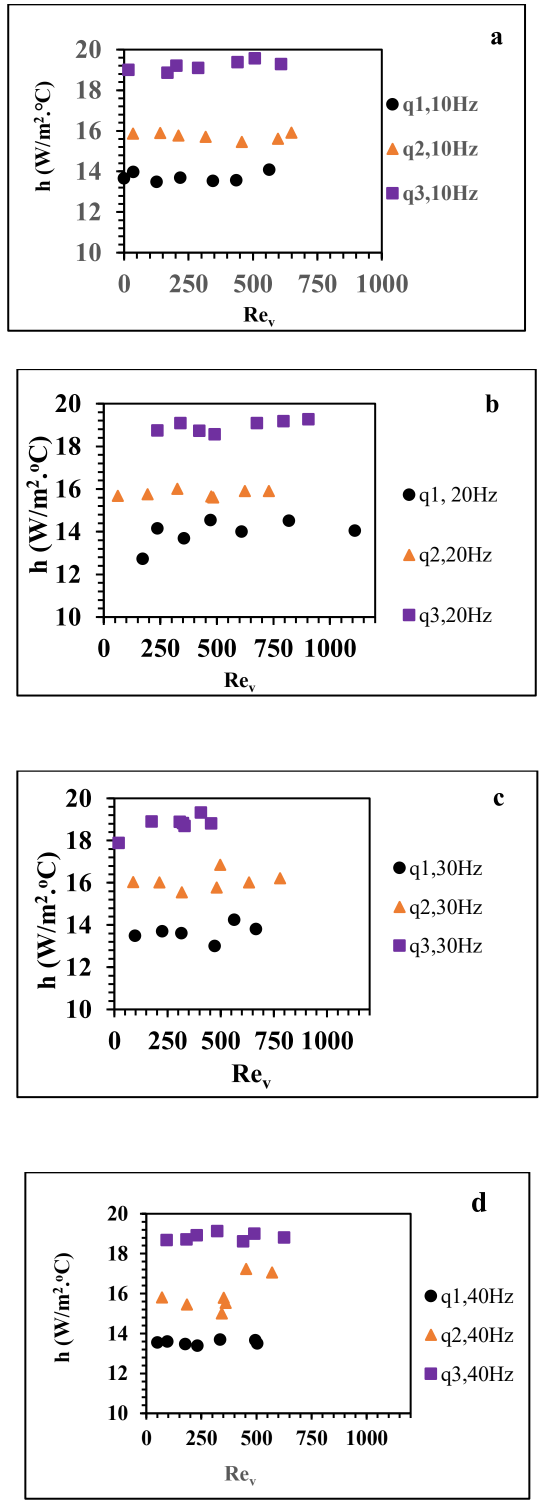


Fig.3 Variation of *h* vs *Ra concerning the heat sink at 0 Hz.**

b. The Relation Between *h* and *Rev*

When a heat sink experience forced vibrations, the oscillatory motion of its fins disturbs the thermal boundary layer that surrounds the surfaces. This continuous disturbance helps to prevent the formation of thick thermal and velocity boundary layers, thereby enhancing convective mixing between the heated surface and the cooler surrounding air. As a result, heat transfer transitions from a natural (buoyancy-driven) regime to one dominated by forced convection, influenced by inertial and vibrational effects. As illustrated in Figure 4, the convective heat transfer coefficient increases almost linearly with the Reynolds number for vibration frequencies ranging from 10 Hz to 50 Hz and for heat fluxes of 150, 230, and 360 W/m². The increases in of 63.9%, 58.9%, and 57.9%, respectively, reflect the enhanced turbulence intensity and mixing caused by the periodic motion of the fins. At lower frequencies, the vibration amplitude creates larger displacements and more effectively entrains surrounding air, thereby amplifying natural convection effects. However, as the frequency increases, the flow becomes quasi-steady and is largely governed by forced convection, which leads to a reduced incremental enhancement, consistent with findings reported in [23]. Additionally, as shown in Figure 5, the effect of amplitude is most significant up to about 30 Hz. Beyond this point, further increases in vibration energy contribute minimally to disrupting the boundary layer. This saturation behavior corresponds with trends noted in [20] and suggests that excessive frequency primarily adds mechanical vibration without significantly improving convective heat transfer.



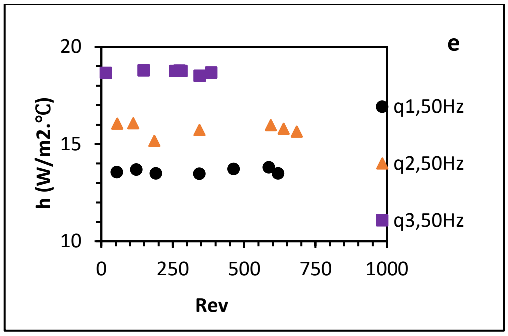


Fig.4 (a,b.c.d.e)Variation of the heat transfer coefficient with Reynolds number under different heat flux values in the frequency range of 10–50 Hz.

c. Air mass flow rate

When the heat sink operates under natural convection (0 Hz), heat transfer mainly occurs due to buoyancy-driven flow. Hot air near the heated surface becomes less dense and rises, allowing cooler air to replace it. This process generates a modest air mass flow rate, which primarily depends on the temperature difference and density gradient in the surrounding fluid. When the heat sink is subjected to vibration, as in forced-vibration scenarios, the oscillatory motion adds a mechanical acceleration component to the buoyant forces. This periodic shaking enhances air mixing and momentum exchange, increasing the velocity of air particles near the fins and intensifying the convective flow. As illustrated in Figure 5, the air mass flow rate increases with both heat flux and vibration frequency. At 0 Hz, the air mass flow rate rises from approximately 0.091 g/s at 150 W/m² to 0.501 g/s at 360 W/m², indicating stronger buoyancy effects with higher heat input. When vibration is applied at 50 Hz, the average air mass flow rate further increases by about 8.7% compared to the non-vibrating case at the same heat flux. This enhancement confirms that vibration-induced inertial forces contribute to additional fluid motion beyond natural convection, thereby improving convective heat removal efficiency. This behavior can be attributed to the periodic acceleration imparted by the vibrating fins, which disrupts thermal and velocity boundary layers, reduces flow stagnation zones, and promotes a more uniform air circulation pattern around the heat sink.

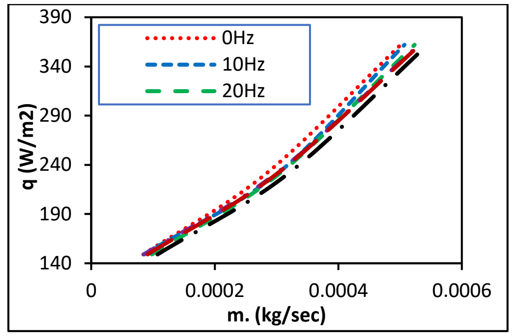


Fig.5 Variation in air mass flow rate versus heat flow and vibration frequency

d. Effect of vibration on fin efficiency (η_f)

As illustrated in Figure 6, the fin efficiency decreases linearly with increasing heat flux under stationary conditions (0 Hz). Specifically, it declines from approximately 81% to 75% as the heat flux rises from 150 to 360 W/m². This trend occurs because a higher heat flux raises the fin-base temperature, which increases the temperature gradient along the fin. This enlarging gradient intensifies heat losses through conduction and convection, ultimately reducing overall efficiency. In contrast, when the heat sink is subjected to forced vibration (as shown in Figure 7), there is a significant reduction in fin efficiency compared to the stationary case. The efficiency drops by about 10-11% as the vibration frequency increases from 10 Hz to 50 Hz. This reduction can be attributed to enhanced convective heat transfer caused by the vibration. The fin surface temperature becomes less uniform, resulting in increased local heat transfer coefficients. This non-uniformity leads to larger temperature variations along the length of the fin, consequently decreasing the ratio of actual heat transfer to ideal (isothermal) heat transfer—this ratio defines fin efficiency. Although vibration enhances the overall heat dissipation rate and increases the convective coefficient, it simultaneously leads to a decrease in fin efficiency due to the non-uniform temperature distributions that the fins experience. as the heat transfer coefficient increases due to vibration, the value of m also increases, resulting in a lower fin efficiency.

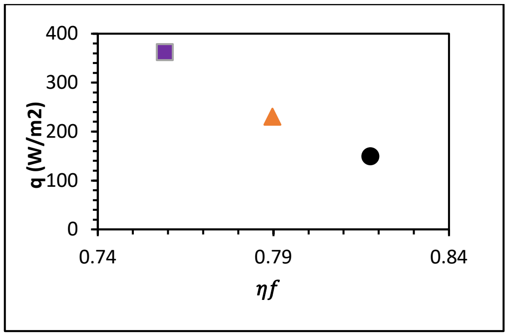


Fig. 6 Variation of fin efficiency vs. heat flux at zero Hz

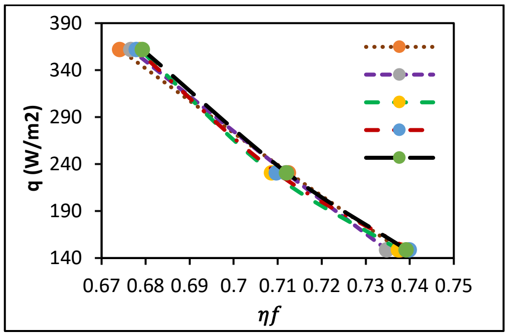


Fig. 7 Variation of fin efficiency with respect to heat flux at a vibration station

Conclusion

This study found that applying forced vibration to a finned heat sink significantly improves convective heat transfer by switching the mechanism from natural to forced convection. This change results in measurable increases in both the heat-transfer coefficient and the air mass flow rate. Although the vibration slightly reduces fin efficiency due to increased temperature non-uniformity, the overall thermal performance of the system improves substantially.

These results are valuable for optimizing compact cooling systems in power electronics and lubrication applications, where space, cost, and efficiency are crucial. The findings will assist researchers in identifying and exploring key areas, such as vibration-induced boundary-layer disruption, thermal–fluid coupling effects, and the optimization of vibration frequency for maximum thermal enhancement. This research introduces a new theoretical perspective that links dynamic surface motion with fin-array convection, providing a foundation for the development of advanced vibration-assisted thermal management systems in future studies.

Equations

To calculate the heat transfer coefficient, fin efficiency, modified Ra number, vibration, and Re number, the following steps must be taken:

1. The average temperature at the heat sink fin surface can be calculated as follows [29]:

$$T_{ave} = \frac{1}{n}\sum_{i=1}^{n} T_i \qquad ,n = 5 \tag{1}$$

and the film temperature is [30]:

$$T_{film} = \frac{T_{ave} + T_b}{2} \tag{2}$$

The overall water temperature is determined according to the method described in [31]

$$T_b = \frac{T_{in} + T_{out}}{2} \tag{3}$$

2. The heat flux generated by the electric power input is denoted by [8]:

$$q = \frac{Q}{A} = \frac{V * I}{A} \tag{4}$$

Thus, calculating each of the modified Rayleigh number , Nusselt number , and fin efficiency [31].

$$Ra_S^* = \frac{g\,\beta\,q_s\,(S)^4}{k\,v^2} \tag{5}$$

$$Ra_L^* = \frac{g\,\beta\,q_s\,(L)^4}{k\,v^2} \tag{6}$$

$$Nu_L = \left[\frac{48}{Ra_S^* * \frac{S}{L}} + \frac{2.51}{\left(Ra_L^* * \frac{S}{L}\right)^{0.4}}\right]^{-0.5} = \frac{h_L \times S}{k} \tag{7}$$

$$\eta_f = \frac{\sinh mL + \frac{h}{km}\cosh mL}{mL\left[\cosh mL + \frac{h}{km}\sinh mL\right]} \tag{8}$$

In order to investigate the effect of vibration on heat transfer enhancement, the amplitude and vibration Reynolds number must be calculated [32].

$$V = \frac{acc}{(2\pi)^2 * \sqrt{2} * F} \tag{9}$$

$$Re_v = \frac{V * L}{v} \tag{10}$$

Experimental uncertainty analysis

To estimate the precision of the experimental results, the error rate of the mechanical or electrical measuring devices used in this study was calculated using the uncertainty equation (11)[33]. EES software was used to evaluate their uncertainty. The results are shown in Table 1. It has been found that the maximum heat flux and transfer coefficient uncertainty are approximately (4.176 and 1.646) W/m^2, respectively.

$$w_r = \left[\left(\frac{\partial r}{\partial x_1} w_1\right)^2 + \left(\frac{\partial r}{\partial x_2} w_2\right)^2 + \cdots \left(\frac{\partial r}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (11)$$

Table 1. Uncertainty of the measuring devices used

Name of experiment	Resolution	Accuracy	$\pm$ *unceratainty*	%
Temprature datalogger	0.5	$\pm 0.2\%$	± 0.293°C	1.4%
Sine wave generator	0.01	$\pm 0.5\%$	± 0.20134 Hz	0.68%
voltmeter	0.1	$\pm 1.2\% + 3$	± 1.2 volt	1.23%
Ammeter	0.01	$\pm 2.5\% + 5$	± 0.02 amp	2.59%
Air speed	0.001	$\pm 3\% + 0.1$	± 0.03 m/s	4.28%
Vibration acceleration	0.01	$\pm 0.04\%$	± 0.005 m/s^2	1.25%
Vibration amplitude	0.01	$\pm$ 0.5%	± 0.007 mm	2.48%

Nomenclature

a	Amplitude (m)
A	Surface area (m^2)
acc	Acceleration (m/s^2)
f	Frequency (Hz)
g	Gravitational acceleration (9.81 m/s^2)
h_L	Heat transfer coefficient (W/m^2.°C)
hs	Heat transfer coefficient (W/m^2.°C)
L	Fin length
I	Current (A)
k	Thermal conductivity
$\dot{m}$	Mass flow rate (kg/s)
q	Heat flux (W/m^2)
Q	Heat transfer rate (W)
S	Fin space (m)
T_{ave}	Average temperature (°C)
T_b	Bulk temperature (°C)
T_{in}	Inlet temperature (°C)
T_{out}	Outlet temperature (°C)
T_{film}	Film temperature (°C)
Greek symbols	
β	Volumetric expansion coefficient
η_f	Fin efficiency
ν	Kinematic viscosity (m^2/s)
Dimensionless quantity	
Ra_L^*	Modified Rayleigh number
Ra_S^*	Modified Rayleigh number
Nu_L	Nusselt number

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