Idan and Ramadhan
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An experimental study to show the effect of forced vertical vibrations on the thermal heat transfer coefficient of a flat plate

Mahmoud Fadhel Idan[1*] and Amer Abbas Ramadhan[2]

Abstract

The objective of this study is to conduct an experiment that considers the influence of vertical oscillations on the heat transfer coefficient of free convection in an aluminum flat plate component measuring $3\times100\times300$ mm. The plate is subject to a steady-state heat transfer; whereby it experiences a sustained heat flux ranging from (250–1500) W/m^2. The orientation of the flat plate can be either horizontal or inclined at particular angles, specifically at 0°, 30°, 45°, 60°, and 90°. The experimental tests conducted were characterized by an expanded frequency spectrum ranging from 2 to 16 Hz, a variable amplitude range spanning from 1.63 to 7.16 mm, and a range of Rayleigh number values upon activation of the system, with minimum and maximum thresholds of 138.991 and 487.275, respectively. The impact of vibration frequency upon both the amplitude and velocity of vibrations for a heat flow of 250 W/m^2, situated at an angle of $\theta=0°$, was examined. The impact of the Reynolds number upon the total vibrational heat transfer coefficient, as well as the total Nusselt number, was investigated with and without the presence of angle vibration $\theta=0°$, across diverse degrees of heat flux. This study investigates the impact of the Rayleigh number on the overall Nusselt number under varying conditions of thermal flux, with and without the application of vibration at angles of $\theta=30°$, 45°, 60°, and 90°. The findings of this analysis demonstrate that there exists a discernible correlation between the incremental amplitude of vibration and the coefficient of heat transfer, manifesting as a negative slope within the range of 0° to 60°. Such correlation reaches its optimal magnitude of 13.2894% under the condition of flat vibration mode, whereas the coefficient of heat transfer declines progressively as vertical vibration is augmented, culminating in a maximum decline of 7.6475%. The present study reports a decrease in the overall vibrational heat transfer coefficient with increasing vibrational Reynolds number. The total Nusselt number was found to increase with or without vibration as the Rayleigh number increased.

Keywords Vertical vibration, Free convection, Flat plate, Rayleigh number, Nusselt

1 Background

This work aims to conduct a test that considers the effect of vertical vibrations on the free convection heat transfer coefficient of flat aluminum sheets. Heat transfer by natural convection of oscillating vertical plates is associated with industrial and technological applications. Several researchers have been concerned with the topic of using mechanical vibration to increase the rate of convective heat transfer, which is of great interest [1, 2], including a numerical study of the load on a periodically oscillating vertical flat plate heated at a constant temperature [3].

*Correspondence:
Mahmoud Fadhel Idan
dr.mafa57@gmail.com
[1] Department of Civil Engineering, Al-Maarif University College, Anbar, Iraq
[2] Physics Department, Science College, University of Baghdad, Baghdad, Iraq

Scientific research has been conducted in all disciplines of engineering, with an emphasis on this topic, in the past decades. He also focused on increasing the rate of heat transfer in industrial units, to avoid heat transfer above the design value of the elements [4]. Scientific studies confirmed the subject of machine exposure to vibration and its impact on its performance under harsh operating conditions such as missiles, due to a lack of knowledge of the mechanical principles of heat transfer in the presence of vibration [5]. In addition to problems with engines and spacecraft, this has attracted researchers to study the effect of vibrations on heat transfer in propulsion engines. As a result, the temperature of the engine and its wall may reach a breaking point, i.e., the rocket engine will fail [6]. Research also tends to examine the complex forces acting on objects that can affect the increase in convective heat transfer, which requires extensive study in space technology. Research has been carried out to discover the extent to which forces are affected by magnetic vibrations and oscillations [7]. For this reason, the effect of vibrations on industrial equipment when these vibrations are not controlled has been studied. Vibrations and pulsations increase the heat transfer coefficient, which leads to the spontaneous destruction of some heat transfer devices and equipment [8]. Many researchers studied the heat transfer process for different models with freeloading and found empirical and numerical relationships that determine the relationship between the Rayleigh number (Ra) and the Nusselt number (Nu) [9]. In 2018, an experimental and theoretical study was presented to verify the effect of vertical forced vibration on the heat transfer coefficient of the laminar internal flow in a grooved spiral tube. During this, the tube is heated under constant heat flux levels of 618–3775 W/m^2. Vibration frequencies ranged from 13 to 30 Hz, and vibration amplitudes ranged from 0.001 to 0.002 mm. The results showed that the heat transfer coefficient was significantly affected by the mechanical vibration at the forced flow in a heated tube. When the vibration amplitude is increased, the Nusselt number increases significantly, with a maximum increase of 8.4% with vibration amplitude of 0.0022 mm, and a frequency of 13 Hz [10]. The researchers found that the objective Nusselt number does not depend on the rate of change of heat flow or laminar flow [11]. In 2013, an experimental and theoretical study was conducted on the effect of forced vertical vibrations on convection heat transfer using a plate with longitudinal fins made of aluminum with dimensions (100, 300, 3 mm). The test sample was heated under the condition of continuous heat flow. The relationship between heat transfer coefficient and vibration amplitude was directly proportional to the inclination angle (0°, 30°, 60°) [12]. The researchers concluded that the heat transfer coefficient of free convection increases with the increase in the heat flow rate and the increase in wall length [13]. They derived the empirical equation for turbulent and laminar flow [14]. In 2020, the researchers presented an experimental study showing the effect of vertical vibration on the convective heat transfer coefficient. The researchers used a cylinder with circumferential fins made of aluminum. The cylinder was heated under the condition of a constant convection flow resulting from the application of an alternating voltage to a fixed resistor fixed within the internal space of the cylinder, which was located horizontally or inclined at various angles in the range of 0°–45°. The effect of vibration was studied over a range of 2 to 16 Hz and a range of vibration condensers from 0 to 2.2 mm, with a different heat flow range of 500 to 1500 W/m^2. The researchers found that the relationship between the heat transfer coefficient and the vibration amplitude increases gradually for all inclination angles from (0°–45°) to reach the maximum percentage (13.34%) [15]. Increasing the angle of inclination leads to a decrease in the coefficient of forced convection heat transfer [16]. In 2016, researchers presented a pilot study to experimentally investigate the effect of forced vibration on convective heat transfer from a sinusoidal surface. A copper plate with a length, width, and thickness of [$350\times150\times10$ mm], respectively, was used as a test sample. This plate is heated by an electric heater under constant heat flow conditions in the order (250, 500, 750, 1000, 1250, and 1500 W/m^2). Subjected to vertical forced vibration at frequencies [5, 10, 15, 20, 25 Hz] and [3, 4, 5 mm], peak-to-peak vibration amplitude, Rayleigh number (Ra) ranging from (1.5×10^8–4.0×10^8), the vibrational Reynolds number (Rev) ranges from (2×10^3, 4×10^3, 6×10^3, 8×10^3, 10×10^3), and the PR number ranges approximately from 0.707 to 0.710, under 25 °C, and pressure 1 bar [17]. Increasing the inclination angle leads to lower values of the vibrational heat transfer coefficient; this causes the fins to clog in the inclined state of the convection currents. In the horizontal position, the fins act as paths that help increase the movement of convection currents and thus increase heat transfer coefficient rates [18]. Many researchers have conducted numerical theoretical and experimental studies [19] on normal stratified load. They used flat plates with arrays of vertical or oblique rectangular fins with different inclination angles, oscillating periodically. The researchers examined two types of test models, one with a single fin and the other with a triple fin mounted on a square copper plate [20]. Based on the aforementioned literature survey, it was observed that the effect of vibration on the amount of heat transferred was significant in cases of natural convection, while the effect of vibration on the amount of heat transferred was little in forced convection and for much geometry [21]. Many researchers conducted studies [22] that focused in their entirety on the numerical effect of a cylinder oscillating around its axis on the amount of heat transferred from its surface to the adjacent surface, after placing a hot air stream inside it. The research included various studies on the effect of Reynolds number, oscillatory velocity on flow structures, and heat transfer properties. As these studies have shown, there is a significant improvement in the heat transfer performance of the plate when the oscillation frequency approaches the natural incident frequency, and an increase in heat transfer performance is seen when the plate oscillates faster, and then, the Reynolds number increases. Several studies have been published [23–25], to show the effects of transverse oscillation on heat transfer in a circular cylinder, with tangential hot air flow inside it, and to determine the heat transfer coefficient of an exposed cylinder within a wide range of frequencies and amplitudes [26]. In these studies, the following results were obtained: that the increase in the amount of heat transferred depends on matching with the harmonics of the natural separation frequency and that the relationship between the heat transfer coefficient and the vibration amplitude is intended for all tilt angles [27–29]. It was also observed that the increase in the angle of inclination leads to a decrease in the values of the forced convection heat transfer coefficient because the fins act as path lines that help increase the thermal movement of the currents in the horizontal state. But in the inclined position, the fins act as a barrier against thermal currents and then reduce the heat transfer coefficient range. Generally, the heat transfer coefficient increases with the Reynolds number. Many researchers [30–35] devised experimental equations to calculate the heat flow of stratified and turbulent air currents. The great importance of the researchlies in the knowledge of the basic mechanical principles, especially the study of the effect of forced vertical vibrations on the thermal heat transfer coefficient of a heated flat plate, and its effect on the rate of convective heat transfer, to avoid heat transfer higher than the design value of the components, especially in spacecraft, missiles and industrial units. To address the problem of measuring the variable values several times for the same case, the uncertainty analysis method is followed, to find the uncertainty, using the Burgers–Huxley equation [36]. It is known that the Berger–Huxley equation is a nonlinear partial differential mathematical equation [37].

2 Materials and methods

2.1 Materials

The test sample was made from a rectangular aluminum plate with dimensions of $(30 \times 10 \times 0.3)$ cm^3, and thermocouples were installed on it, to measure its surface temperature as shown in Fig. 1. The thermocouples were attached to the holes in the aluminum plate using a high-temperature resistant adhesive. Electric heaters made of thin strips of chromium with a width of 0.3 mm and thicknesses of 0.06 mm were used to heat the surface of the heat exchanger. These slices were fixed longitudinally on a layer of mica with a thickness of 0.5 mm and were distributed sequentially to ensure homogeneous thermal distribution on the surface of the plate. The upper and lower sides of the heater were covered with two layers of mica to ensure electrical insulation. The mica layers (three layers) have as many holes as there are holes on the surface of the heat exchanger. The holes are distributed on the surface of the heat exchanger by passing two thermocouples over the surface. The bottom surface of the heat exchanger is covered with glass wool to reduce heat loss. The model is attached to a wooden frame with Teflon strips with dimensions of $33 \times 125 \times 1.8$ mm, isolated from the surface of the heat exchanger, and then installed on a U-shaped stand. Its sides and base are made of iron. Hold the template in its center so that it can be easily moved at different angles. An angle protractor is installed on it to adjust angles. The test sample is heated by passing an electric current through a 1000-W thermocouple wrapped around a layer of mica, sandwiched between two layers of mica, to ensure complete insulation. The voltage difference is changed by a power regulator. Both voltage and current are measured by a potentiometer and ammeter to obtain heat flux with different values. The temperatures were also measured using 30 K-type thermocouples, attached to the test form by a heat-resistant adhesive. It was connected to a selective switch and then to a digital thermometer. Temperature values were recorded with a thermometer after a steady state was reached after 3 to 3.5 h. The vibrations are generated by a functional random generator that generates sinusoidal signals of desired frequencies and sends them to a digital oscilloscope and power amplifier, which in turn amplifies this signal and then sends it to a vibrator mounted perpendicular to the platform, which vibrates at the desired frequency. Figure 2 presents an illustration of the testing system used in the research. Figure 3 shows a detailed schematic diagram of the test system used in the research showing how the power amplifier, the sinusoidal random generator, and the oscilloscope are connected to a power source. The figure also shows how the power amplifier and exciter are connected to the vibration meter and flat. The flat connects to both the electrical transformer and the selector switch. Finally, a selector switch and a thermometer are connected to measure the amount of heat. The basic procedures used in laboratory experiments were followed to conduct the tests, and the results were recorded for adoption in analyzing the effect of vibration on the free heat transfer coefficient.

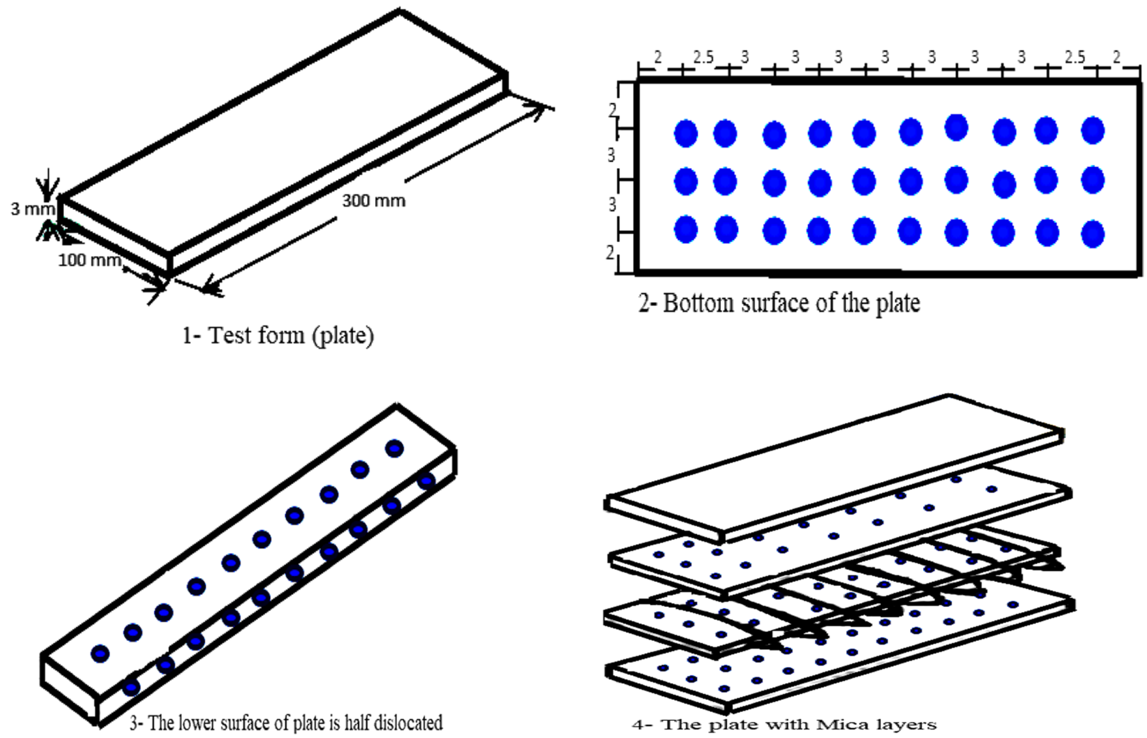

Fig. 1 This is a diagram illustrating the test model used in the research

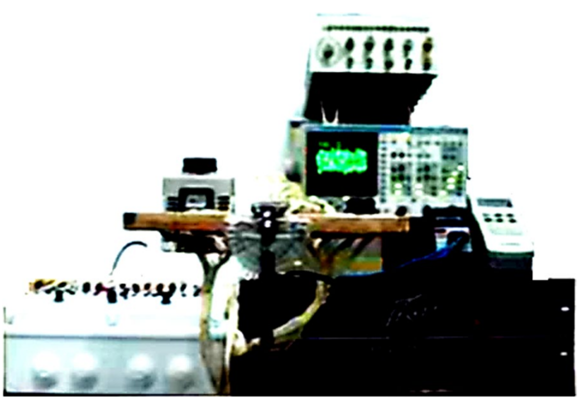

Fig. 2 A photograph of the test system

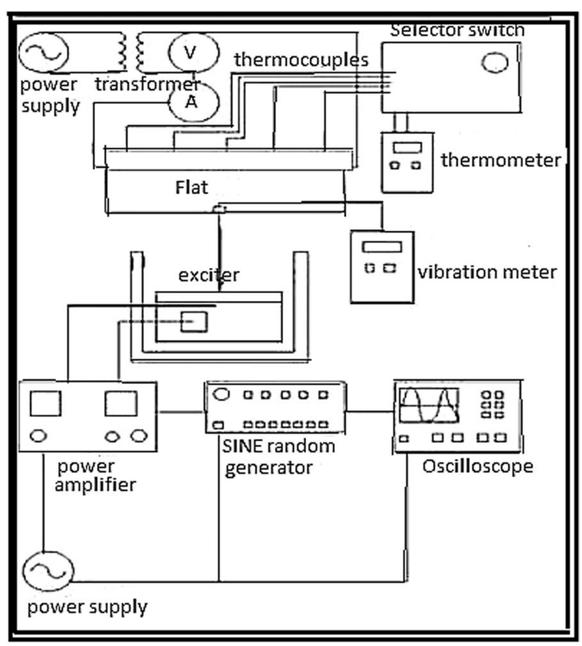

Fig. 3 The test system used in the research

2.2 Methods

The following equation was used to find the total amount of radiant heat transferred [12]:

$$
\begin{aligned}
Q_{\text{rad}} = {} & \sigma A_3 \epsilon_{\text{conv}} \left({T^4}_{\text{bv}} - {T^4}_{\infty} \right) \\
& + 2\sigma A_4 \epsilon_s \left({T^4}_{\text{tip}} - {T^4}_{\infty} \right) \\
& + 2\sigma A_4 \epsilon_s \left({T^4}_{\text{tip}} - {T^4}_{\infty} \right)
\end{aligned} \tag{1}
$$

The heat lost through heat insulation has been calculated by using the following equation:

$$Q_{\text{los}} = K_{\text{ins}\times} A_{\text{ins}} \times \frac{\Delta T_{\text{ins}}}{L} \tag{2}$$

It has been found that all energy lost by radiation and conduction does not exceed 3% of the electrical energy supplied to the system [12]. Thus, the heat load and the heat generated in the heating element by the electric coil were calculated, respectively, and as follows [17]:

$$Q_{\text{con}} = Q_{\text{gen}} - Q_{\text{rad}} - Q_{\text{los}} \quad (3)$$

The total amount of heat generated is calculated as follows [12, 17]:

$$Q_{\text{gen}} = I \times V \quad (4)$$

After completing the above steps, the convection coefficient can be calculated as follows [12]:

$$h = \frac{Q_{\text{con}}}{A_T(T_{\text{b}} - T_\infty)} \quad (5)$$

where T_{b} is the average temperature recorded by the thermocouples, which are placed at the base of the channel. The total amount of heat generated in the electric heater (Q_{gen}) is converted into heat transmitted through the plate by conduction, and to the external environment from the surface of the plate by convection (Q_{conv}), in addition to the heat lost by radiation (Q_{rad}) [17].

$$Q_{\text{gen}} = Q_{\text{conv}} + Q_{\text{rad}} \quad (6)$$

The amount of heat transferred by radiation is calculated as follows:

$$Q_{\text{rad}} = \sigma \varepsilon S_{\text{sur}} A_t \left(T_{\text{sav}}^4 - T_{\text{air}}^4 \right) \quad (7)$$

where the surface-emission factor (ε) is 0.04, the shape modulus (S_{sur}) is 1, and the Stefan–Boltzmann constant σ is 5.670373×10^{-8} W/m^2 K^{-4} [7]. Therefore, the free convective heat transfer coefficient was calculated from the following equation, which is known as Newton's cooling law [12].

$$h = \frac{Q_{\text{conv}}}{A_{\text{t}} \times \Delta T} \quad (8)$$

where (A_{t}) is the total plate area of the test specimen subjected to a load and is 0.003 m^2.

$$A_{\text{t}} = W \times L \quad (9)$$

where W is the width of the plate, and L is the length of the plate. The average temperature is calculated as follows:

$$T_{\text{Sav}} = \frac{T_1 + T_2 + \cdots + T_n}{N} \quad (10)$$

The average adjacent layer temperature T_f was calculated as:

$$T_f = \frac{T_{\text{Sav}} + T_{\text{air}}}{2} \quad (11)$$

This temperature was adopted in calculating the physical properties of the work material (air), after finding equations that enable us to obtain any property at any temperature. The volumetric expansion coefficient is also calculated from the following equation:

$$\beta = 1/\left(T_f + 273\right) \quad (12)$$

The calculation of the heat flux applied to the test sample requires the calculation of the energy generated by passing an electric current in the heating resistance, by applying Eq. 6, where the surface area exposed to this energy is the surface area of the slab and is calculated as in Eq. (10).

2.3 Dimensionless parameters

The membrane temperature was adopted in calculating the properties of the external fluid on which it depends in calculating the following non-dimensional values, which are the Reynolds number (Re_ν), the Rayleigh number (Ra), and the Nusselt number (Nu) [12]:

$$\text{Re}_\nu = \frac{2\pi f a \delta}{\vartheta} \quad (13)$$

$$\text{Ra} = \frac{\beta g (T_{\text{Sav}} - T_{\text{air}}) \delta^3}{\vartheta^2} \times \text{Pr} \quad (14)$$

$$\text{Nu} = \frac{h\delta}{K_f} \quad (15)$$

If the model is inclined from the horizon by an angle (θ) within the specified range, then the gravitational acceleration components on Earth are used to calculate the dimensionless parameters, as follows [17].

$$\text{Ra} = \frac{\beta g \sin\theta (T_{\text{Sav}} - T_{\text{air}}) \delta^3}{\vartheta^2} \times \text{Pr} \quad (16)$$

If the model is in the horizontal position, the plate characteristic length (δ) is calculated by the equation below [8]:

$$\delta = \frac{W \times L}{2(W + L)} \quad (17)$$

But if the model is inclined from the horizon at an angle greater than 0° and less than 90°, it is calculated according to the following equation:

$$\delta = \frac{W \times L\cos(\theta)}{2(W + L\cos(\theta))} \quad (18)$$

Table 1 The percentages of heat transfer coefficient values in the presence and absence of vibration

θ	$f = 2$Hz	$f = 6$Hz	$f = 10$Hz	$f = 16$Hz
0°	12.0977	13.2894	11.3854	11.4888
30°	10.6678	4.0475	5.0203	5.3860
45°	0.9670	1.3721	1.0203	3.0976
60°	3.5358	2.5849	4.1174	5.3575
90°	7.1267	6.6189	7.6475	7.0490

If the model is in portrait mode, it is calculated from the following equation:

$$\delta = L = 300\text{mm} \tag{19}$$

The Prandtl number (Pr) can be calculated from Eq. 20 as follows in refs. [12, 17]:

$$\text{Pr} = \frac{\mu C_P}{K_f} \tag{20}$$

The vibration velocity and vibration amplitude as listed in Ref. [12] are calculated as follows:

$$u_v = a \times f \tag{21}$$

$$a = \frac{\text{acc.} \times \sqrt{2}}{(2\pi f)^2} \tag{22}$$

3 Results

Table 1 presents the percentages of heat transfer coefficient values for cases involving vibration, compared to those without vibration. Table 2 presents the tabulated values of the constants derived from the experimental equation. The present study aims to clarify the relationship between vibration frequency and heat flow amplitude, in addition to the angle $\theta = 0°$. Figure 4 depicts the effect of varying vibration frequencies on the above parameters, especially for a heat flux of 250 W/m^2. As shown in Fig. 5, the effect of vibration frequency is shown on the vibration speed while maintaining a heat flux of 250 W/m^2 and an inclination angle $\theta = 0°$. The study conducted here examines the effect of the Reynolds number on the overall vibrational heat transfer coefficient across different levels of thermal energy flow. This is displayed visually in Fig. 6. The present investigation seeks to examine the influence of the Rayleigh number on the total Nusselt number, for the presence or absence of angular oscillation at various angles of 0°, 30°, 45°, 60°, and 90°, located at different levels of heat flow. The investigation results are visually represented in Figs. 7, 8, 9, 10 and 11.

Table 2 The values for the experimental equation constants

f (Hz)	Q(W/m2)	*C*	*l*	*n*	*m*
2	250	1.433E-93	23.735	37.027	− 0.8125
	500	2.639	1.147	− 0.693	6.92E-02
	750	0.323	1.154	− 0.703	− 7.632E-02
	1000	11,165.57	9.350E-02	− 0.703	4.489E-02
	1500	1.847E-12	4.53	4.42	− 8.78E-02
6	250	2.2E+71	− 13.968	− 27.448	0.556
	500	4.75E-25	8.095	7.595	− 0.1711
	750	5.6E-02	1.841	− 0.369	− 0.0762
	1000	527.155	0.746	− 1.8155	5.409
	1500	1.327E-13	4.457	4.5127	− 7.9744
10	250	573.7996	− 0.000977	− 0.2709	0.000329
	500	4.799E-25	7.197	8.166	− 0.146
	750	0.447	1.587	− 0.673	− 7.235
	1000	53.23	0.891	− 1.2522	1.035
	1500	0.0338	1.187	0.7966	0.0.1559
16	250	8.65E-04	2.168	4.516	− 6.485
	500	3.127E-54	15.782	18.337	− 0.939
	750	0.4929	1.546	− 0.601	− 0.072
	1000	0.276	1.67	− 0.704	− 1.667
	1500	1.095E-11	4.044	3.75	− 0.12155

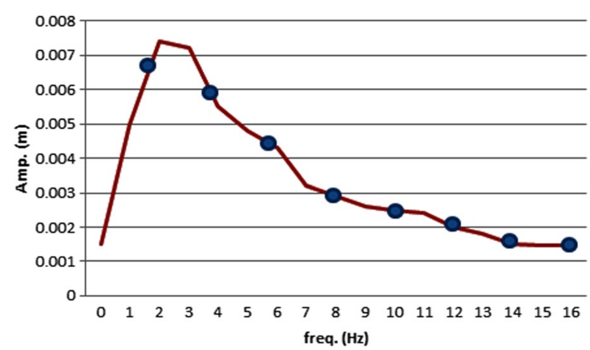

Fig. 4 The effect of the frequency of vibrations on the amplitude of a thermal Flux (250 W/m^2) and an angle ($\theta = 0°$)

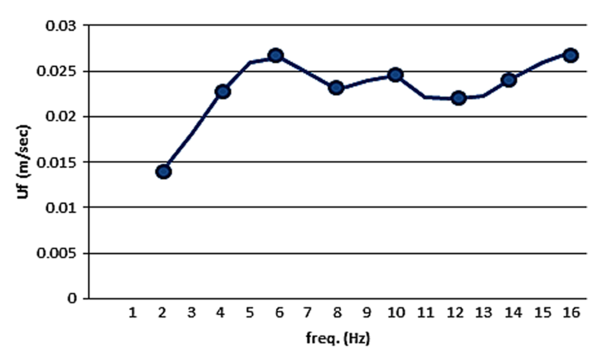

Fig. 5 Effect of the frequency of vibrations on the velocity of vibrations for a thermal flux (250 W/m^2) and angle ($\theta = 0°$)

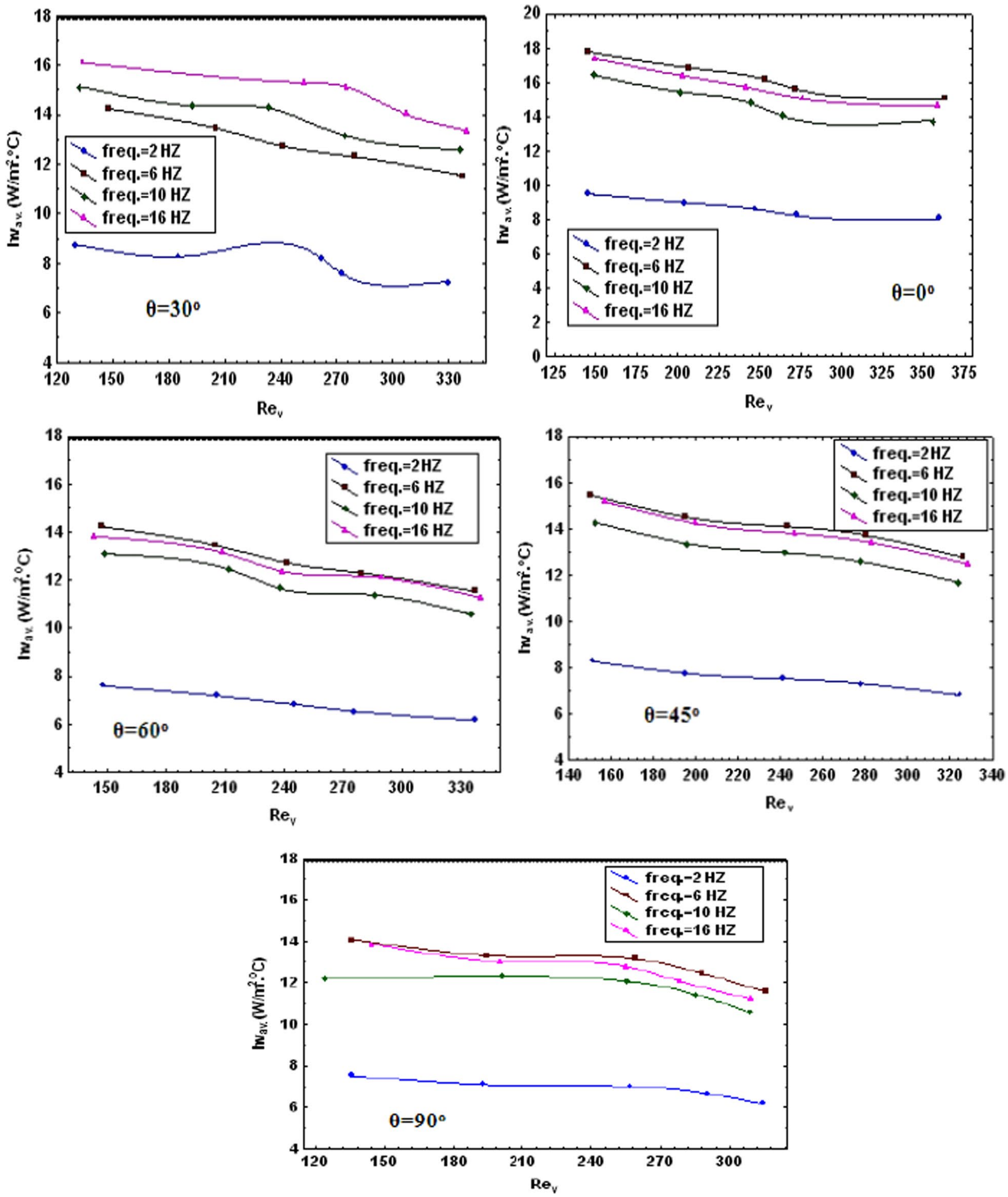

Fig. 6 The effect of the Reynolds number on the total vibrational heat transfer coefficient for different levels of heat flux

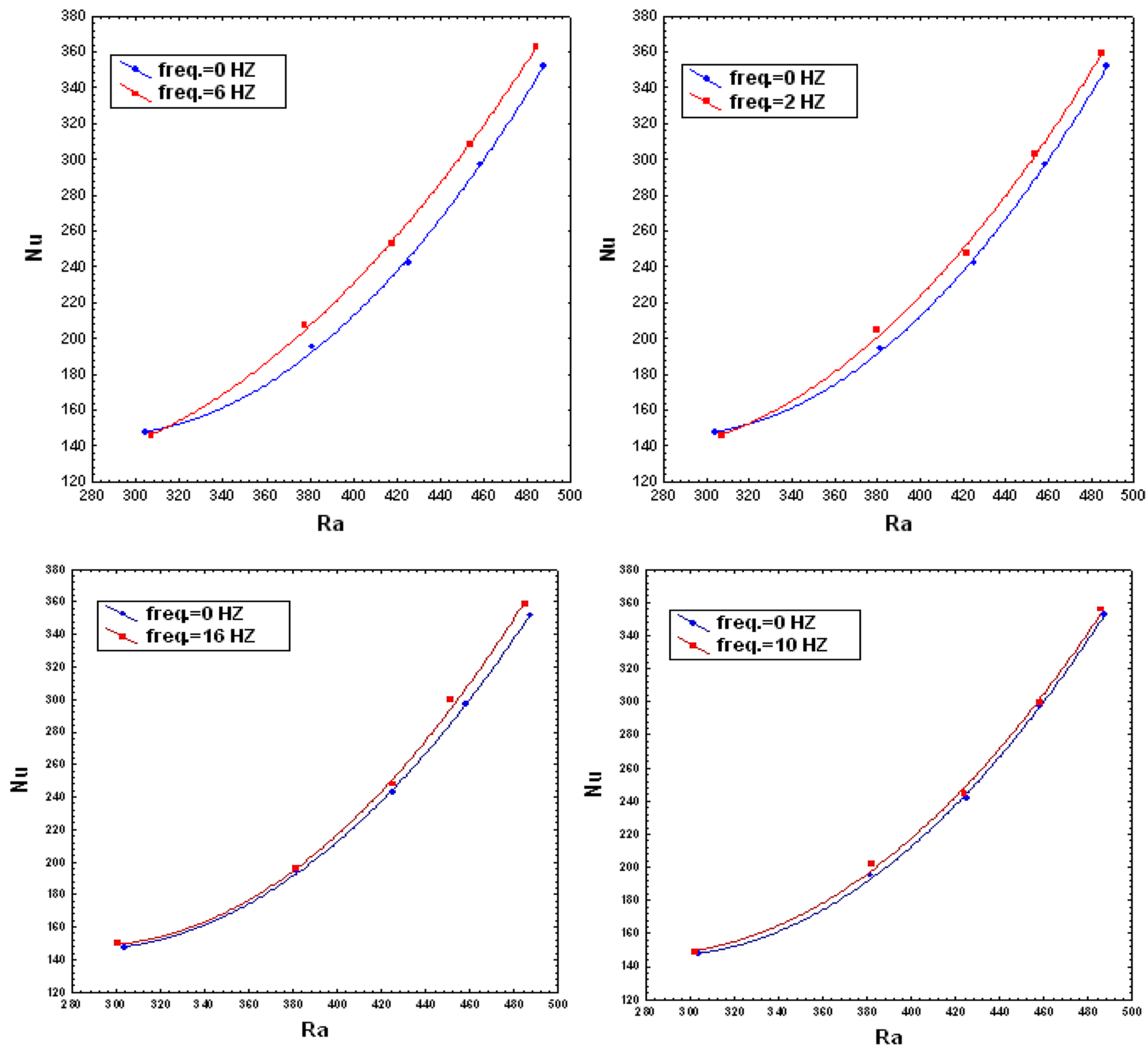

Fig. 7 The effect of the Rayleigh number on the total Nusselt number in the presence and absence of the angle vibration $\theta = 0°$and for different levels of heat flux

4 Discussion

This study presents a comprehensive analysis of outcomes and discussions derived from 225 tests conducted on a test sample with consistent dimensions ($3 \times 100 \times 300$ mm) in response to thermal currents ranging from 250 to 1500 W/m^2 and vibrations at various tilt angles (0°, 30°, 45°, 60°, and 90°). The results of this investigation are of utmost significance in understanding the impact of thermal currents and vibrations on test samples. According to the findings in Table 1, the imposition of coercive forces on a flat plate in a horizontal direction causes an elevation in the heat transfer coefficient, with the maximum value observed in the horizontal position at 13.2894%. Conversely, when the plate experiences coercive forces in a vertical direction, the heat transfer coefficient diminishes by approximately 7.6475%. These results are largely consistent with refs. [15, 19] although tubes, cylinders, or fins were used in the experiments. The results presented here show strong adherence to the previous work referred to in refs. [15, 19], although the use of different structures such as tubes, cylinders, or fins in

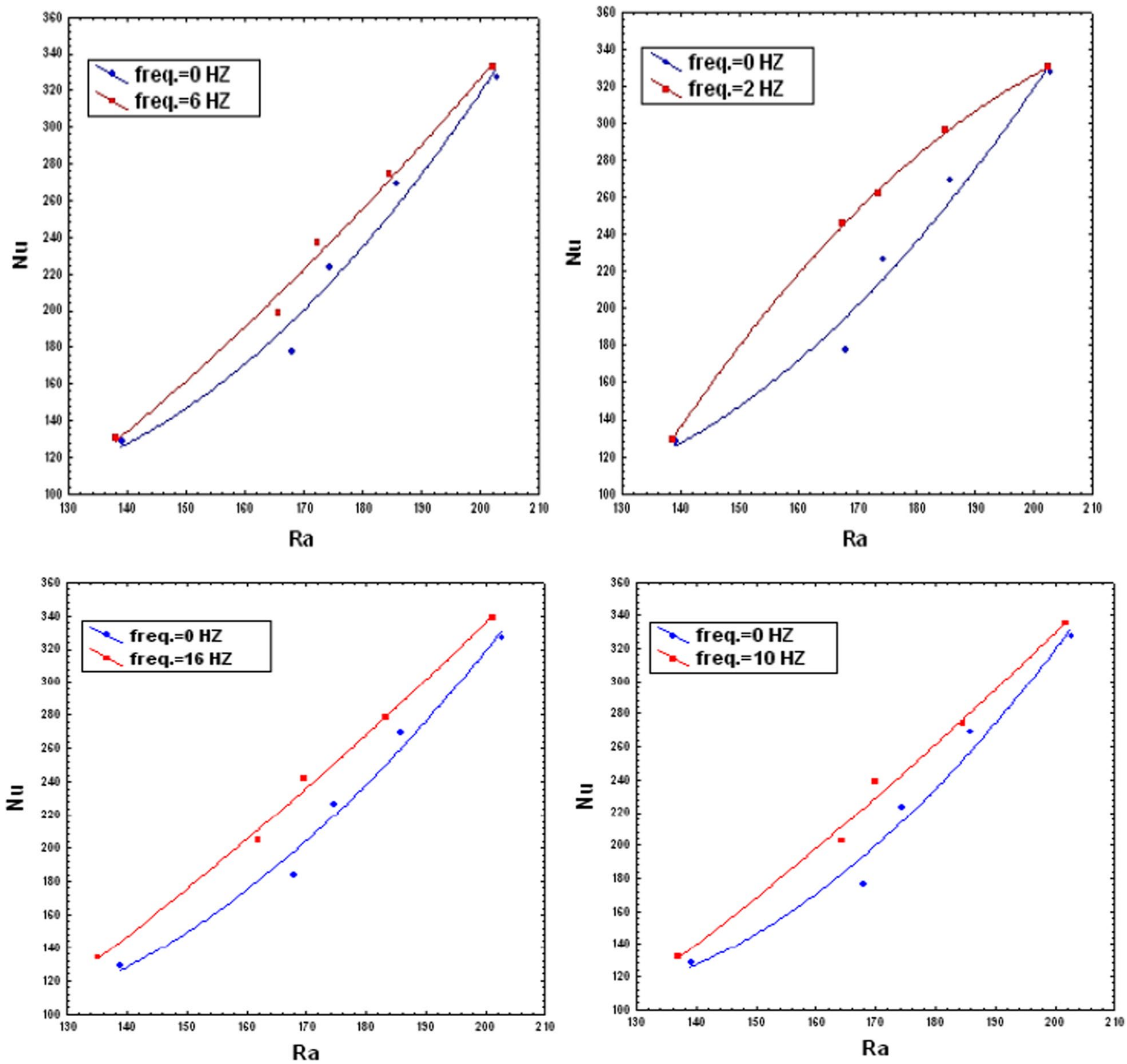

Fig. 8 The effect of the Rayleigh number on the total Nusselt number in the presence and absence of the angle vibration $\theta = 30°$and for different levels of heat flux

the experiments carried out. This study presents the development of an experimental equation that establishes a reciprocal relationship between the total Nusselt number, Rayleigh number, Reynolds number, and the angle of inclination. The formulated relation is expressed as $\mathrm{Nu} = C\mathrm{Ra}^{l}\mathrm{Re}_{\vartheta}^{m}\theta^{n}$, where C, l, m, and n denote a set of constants. For each case, the DGA-V1 program was used to determine the values of the constants associated with the experimental equation. The experimental error rate corresponding to each research condition is within a range that extends (1–2.5%). The coefficients of the above equations are shown in Table 2. Table 2 presents a large variation in the effect of heat flux magnitude and frequency amplitude on the values of the vibration-related constants. The values of these constants depend on the level of heat flow and the frequency of the vibratory motion. These results are somewhat consistent with Ref. [12]. The results showed a degree of correlation with the mentioned reference. The current study demonstrates the effect of imposed

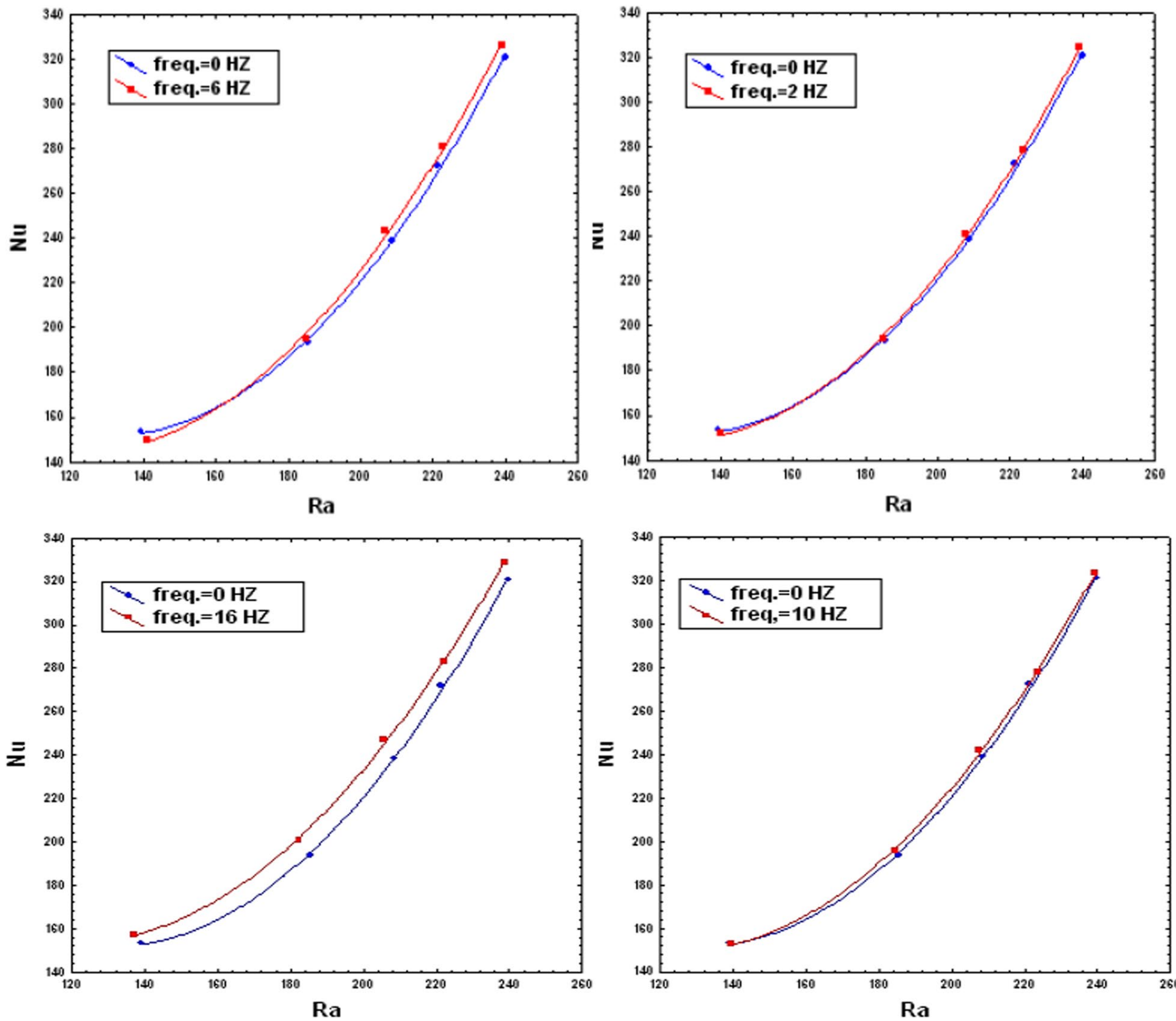

Fig. 9 The effect of the Rayleigh number on the total Nusselt number in the presence and absence of the angle vibration $\theta = 45°$ and for different levels of heat flux

frequencies on the vibration amplitude and vibration speed of an experimental sample placed horizontally, while subjected to a heat flow of 250 W/m^2, as shown in Fig. 4. The results show a clear relationship between vibration amplitude and frequency, where the maximum value of vibration amplitude is observed at lower frequencies, especially at 4 Hz. As the frequency increases, the amplitude of the vibration subsequently decreases. According to the data in Fig. 5, there is a positive relationship between frequency and velocity. Specifically, the velocity was observed to gradually increase with increasing frequency, culminating in an observed peak value of 0.0254 m/s at a frequency of 6 Hz. The value of velocity is manifested in the oscillations of escalation and attenuation with increasing frequency. The current study investigated the effect of the Reynolds number variation on the average total heat transfer coefficient under different inclination angles of 0°, 30°, 45°, 60°, and 90°, as well as at frequencies of 2, 6, 10, and 16 Hz and for multiple heat flow levels. These results are somewhat consistent with Ref. [15]. The results are shown in Fig. 6. The results indicate a decrease in the average value of the total heat transfer coefficient due to vibration with an increase in the

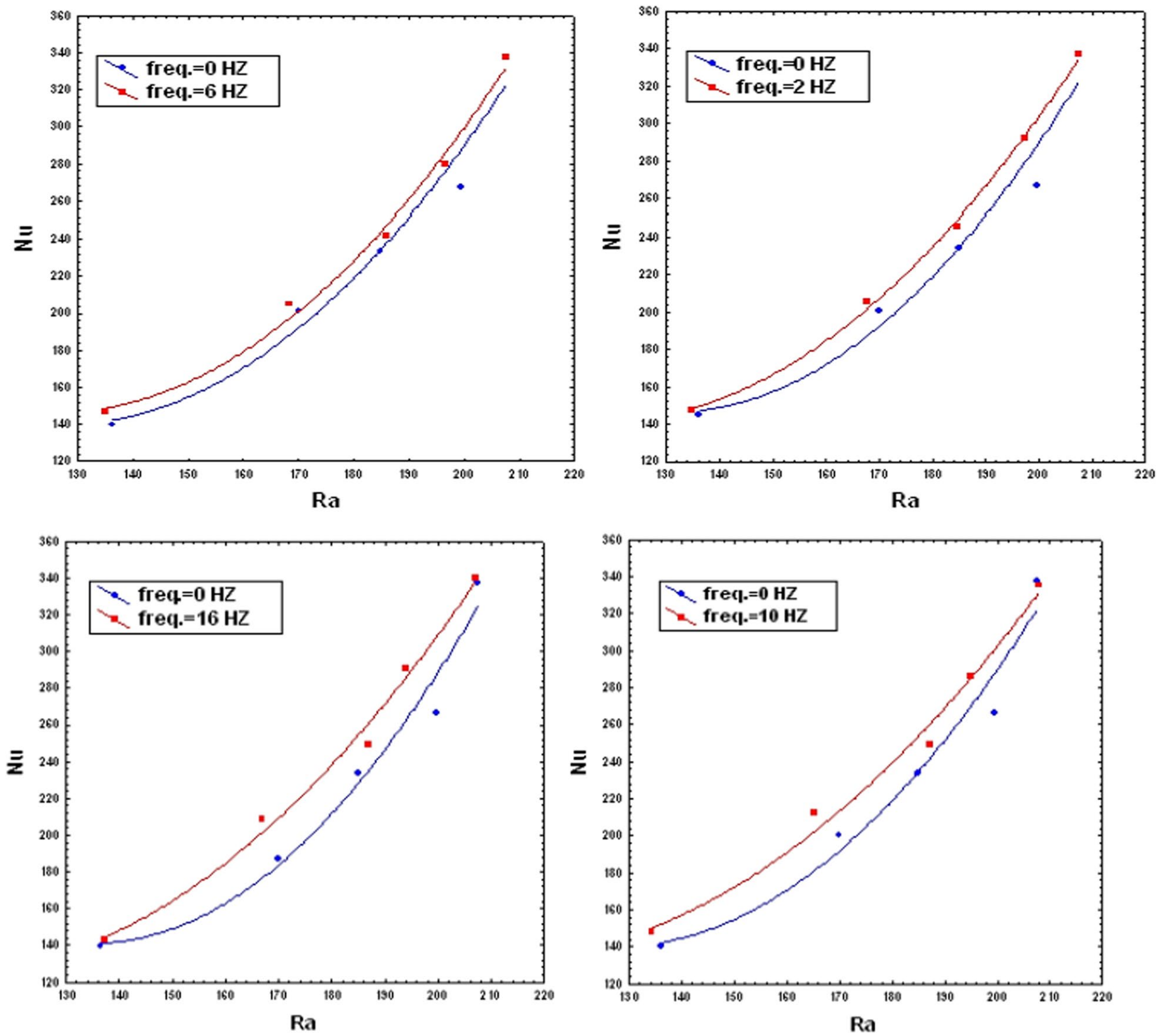

Fig. 10 The effect of the Rayleigh number on the total Nusselt number in the presence and absence of the angle vibration $\theta = 60°$ and for different levels of heat flux

Reynolds number, regardless of the inclination angle. With an inclination angle of 0° and a frequency of 6 Hz, the maximum average value of the total heat transfer coefficient is 18 W/m^2. This characteristic relates to inclination angles of 45°, 60°, and 90° in the given context. The vibration velocity generates a secondary flow that synergistically enhances the heat transfer coefficient in conjunction with the primary flow. A visualization of this phenomenon is presented in Figs. 7, 8, 9, 10, and 11, which illustrate the effect of Rayleigh numbers on the total values of the Nusselt numbers with and without vibration for the various approved tilt angles (0°, 30°, 45°, 60°, and 90°), and on the frequencies 2, 6, 10, and 16 Hz. Generally, it has been observed that the Nusselt number rises when it is subjected to vibration across all frequencies and angles. The purpose of this procedure is to modify the direction of the mechanical vibrations imposed on the sample under study from transverse to longitudinal, which leads to the generation of a vortex movement of the airflow counteracting the main heat flow force. By this manipulation, an additional obstacle is introduced that heats the sample, thus hindering the improvement of the heat transfer coefficient. The result presented here bears some degree of

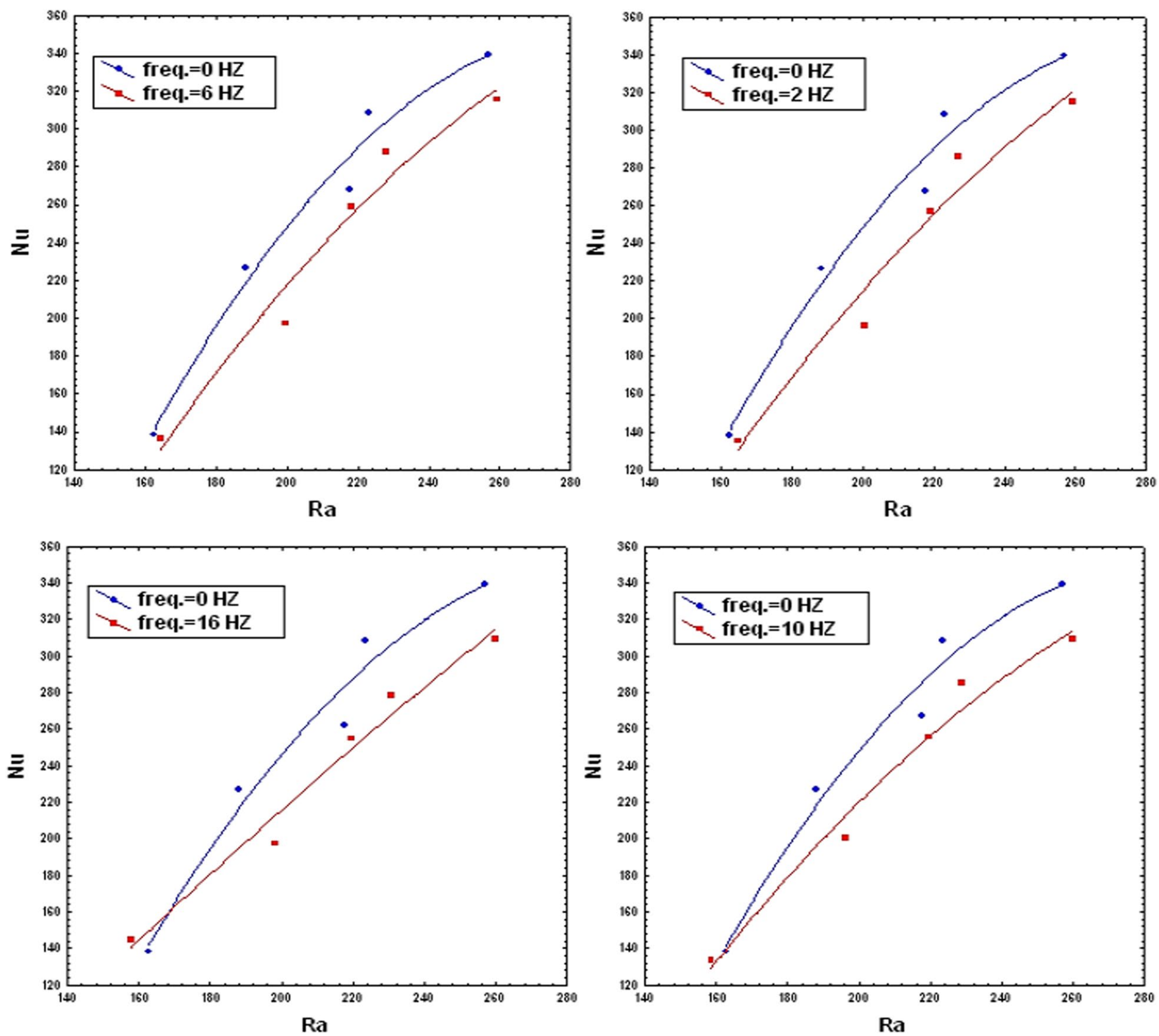

Fig. 11 The effect of the Rayleigh number on the total Nusselt number in the presence and absence of the angle vibration $\theta = 90°$ and for different levels of heat flux

similarity to the reference material; this result is somewhat consistent with Ref. [17].

5 Conclusions

When a flat plate vibrates under the influence of coercive forces, this leads to an increase in the heat transfer coefficient, and its highest value is in the horizontal position, reaching 13.2854%. When the plate vibrates vertically under the action of coercive vertical forces, the heat transfer coefficient is about 7.6475% lower than it would be in the absence of vibration, regardless of the shape of the sample used in the experiments. Small vibrational capacitances have a limited effect on the thermal boundary layer, and to improve the heat transfer coefficient, it is necessary to subject the thermal boundary layer to large vibration amplitude. As the vibrational Reynolds number increases, the total vibrational heat transfer coefficient decreases. The total Nusselt number increases with or without vibration regardless of the angle value of the plate, while the Rayleigh number increases as the angle increases. An experimental relationship was formulated showing the values of the total Nusselt number with the Rayleigh number, Reynolds number, and the angle of inclination as in the following equation:

$$\mathrm{Nu} = C\mathrm{Ra}^{l}\mathrm{Re}_{\vartheta}^{m}\theta^{n}$$

5.1 Recommendations

1. Studying the effect of vibrations resulting from pulsed waves on heat transfer on a plate and comparing it to a vibrating plate under the same conditions.
2. Studying the effect of vibrations at different frequencies and angles on forced convection heat transfer in pipes and cylinders.

Abbreviations

A	Vibration amplitude
acc.	Vibration acceleration
A_{ins}	The area of insulation
A_t	Total plate area
F	Vibration frequency
g	Ground acceleration
h	Convective coefficient
h_{av}	Total heat transfer coefficient
h_v	Vibration heat transfer coefficient.
hv_{av}	Vibration gross heat transfer coefficient
H	Heat transfer coefficient without vibration
I	Electric current
K	Coefficient of thermal conductivity of air
K_{ins}	Insulation thermal conductivity
k_p	Coefficient of thermal conductivity of aluminum
L	Plate length
Nu	Nusselt number
P	Plate circumference
Pr	Prandtl number
Q	Heat flux
Q_{con}	Free convective heat transfer
Q_{conv}	The plate by free convection
Q_{los}	Heat lost
Q_{gen}	The heat generated by the passage of an electric current
Q_{rad}	Radiant heat
R	Electric Resistance
Ra	Rayleigh number
Re_v	Vibratory Reynolds number
S_{sur}	Shape modulus
T_{air}	Ambient temperature
T_b	The base temperature
T_{bv}	The base temperature at vibration
T_f	Membrane temperature rate.
T_{Sav}	Average temperature
T_{sur}	The surface temperature of the plate
T_{tip}	Inside plate temperature
T_∞	Outside environment temperature
u_v	Vibration velocity
V	Voltages
W	Plate width
β	Thermal expansion coefficient
δ	Characteristic length
ε	Surface-emission factor

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Author contributions
MF was involved in conceptualization, investigation, resources, visualization, supervision, project administration and formal analysis; MF and AA done methodology, data duration, validation, writing—original draft preparation, writing—review and editing; AA gave software. All authors read and approved the final manuscript.

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Declarations

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