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Research Article

Mixed convection heat transfer from a vertical flat plate subjected to periodic oscillations

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ABSTRACT

In this study, effects on mixed convection heat transfer of oscillation parameters on a vertical flat plate surface subjected to constant heat flux are experimentally and numerically investigated. The experimental setup includes a hanger–pulley system installed above a transparent enclosure contain a moving experimental model, flywheel-motor assembly generating the oscillating movement of the experimental model, power supply, and datalogger. The experimental model comprises two copper plates with attached thermocouples and Kapton heaters placed between the plates. In the study, heat flux applied to surface of the plates (q''), the Womersley number (Wo) and dimensionless oscillation amplitude (A_o) are varied. The effects of these parameters on the heat transfer performance are analyzed. This study is numerically solved using a control-volume based Computational Fluid Dynamics solver based on experimental data. The numerical results are compared with the experimental results and open literature. Instantaneous velocity and temperature profiles on the plate are obtained to explain the heat transfer mechanism. According to the numerical and experimental results, heat transfer performance is significantly affected by oscillation parameters and heat flux applied to the plate surface. The mixed convection heat transfer increases with the increase in oscillation parameters for all tested heat fluxes. The obtained results are presented as a function of dimensionless numbers.

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INTRODUCTION

External flows on flat surfaces have an important role in heat-transfer applications. Due to the high-velocity flows in these applications, forced-convection effects have been increasingly usually investigated [1–3]. Buoyant forces are generally neglected when examining fluid flow on horizontal surfaces. However, for vertical or inclined surfaces, buoyant forces have a strong influence on the flow area and

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thus cannot be ignored. Because heat transfer on a vertical plate with constant temperature or heat flux is common in industrial applications, mass and heat transfer on these plates are also important aspects to be studied. The condition where natural and forced convection occur together is called mixed convection. In the forced case, depending on the direction of the forces, the buoyancy forces can improve or deteriorate the heat-transfer rate. Consequently, all passive or active heat-transfer applications that improve natural or forced convection can also improve mixed-convection heat transfer. Modifications such as the use of fins to increase surface area, the addition of various turbulators into the flow, electric- or magnetic-field applications, the addition of nano-sized particles to the basic fluid, the use of basic fluid under supercritical conditions, the use of vibrating fluid, or the use of continuous moving plates improve heat transfer with natural, forced, or mixed convection [4–9]. The velocity and temperature distributions on moving surfaces can affect the heat-transfer rate on the surface. Buoyancy effects within the boundary layer have been investigated by many researchers for continuously moving horizontal [10–11], oblique [12–14], and vertical surfaces [15–17].

Oscillatory flows are known to cause higher heat and mass transfer. Oscillating movement is generated either by fluid vibration around a fixed object or by vibration of a solid body in any fluid. Although the same goal is achieved in both approaches, fluid vibration around a fixed object requires more energy. Oscillating flows/surfaces are widely used in compact high-performance heat exchangers, piston engines, chemical reactors, pulsating burners, high-performance stirling engines, cryogenic refrigeration, and in various applications in the aerospace industry and military fields [18-22]. Goma and Taweel [23], analytically investigated the effect of oscillations on natural and forced convection heat transfer on vertical surfaces with constant temperature and reported that surface oscillations improved the heat transfer. Anilkumar [24], examined the flows in the opposite direction or supports the natural convection of time dependent laminar mixed convection on a continuously moving vertical plate. At the results of study, the velocity profile increased in the presence of the buoyancy force ($Ri > 0$) for low Prandtl numbers and this caused to increase the size of the buoyancy parameter. Andreozzi et al. [25], studied the effects on mixed convection of flow induced by a moving plate placed in the middle plan of a vertical channel with turbulent RNG k-ε model.

Ramesh et al. [26], presented a mathematical model for the flow and heat transfer boundary layer passing an inclined stationary/moving flat plate with the convection boundary conditions. They analyzed effects of the inclination angle of the plate, Prandtl number (Pr), local Grashof number (Gr), and Biot number (Bi) on the flow and heat transfer and reported that the temperature of the fixed flat plate was higher than that of the moving flat plate. Li et al. [27], numerically investigated the flow and heat transfer on a vertical flat plate with constant heat flux under laminar pulsating conditions and compared the results with their experimental studies; it was indicated that the pulsating parameters significantly affected the flow and heat transfer. Krishna and Jyothi [28], theoretically studied the heat and mass transfer under the influence of magnetic field of oscillating plate in porous media. As a result, effects of the reverse flow were observed in the flow area, the velocity of the flow area decreased with increase of thermal Grashof number. Also thermal boundary layer thickness decreased with increase of Pr due to the oscillation frequency.

Patil et al. [29], numerically examined mixed convection heat transfer from a heated vertical plate moving upwards in parallel to the free flow and analyzed the effects of Richardson number (Ri), Schmidt number (Sc), velocity, and buoyancy parameters. As a result, it was reported that the boundary layer thickness decreased with increasing Sc and buoyancy parameters at certain concentrations. Khan et al. [30], analytically examined natural convection heat transfer on a vertical oscillating cylinder. They obtained velocity and temperature distributions corresponding to the cosine and sine oscillations of the cylinder and reported that the temperature values decreased with increasing Pr and Nu. Sarhan et al. [31] experimentally examined the effects of sinusoidal oscillations on the thermal performance of a flat aluminum plate at horizontal and different angles. They changed the oscillation amplitude, oscillation frequency and orientation angle, and the maximum heat transfer coefficient was obtained at the horizontal position and at high frequencies. Lee et al. [32] numerically examined mixed convection heat transfer of a flat plate rotating in a square enclosure. The studies were performed for different Rayleigh number and rotational Reynolds number with constant Prandtl number (Pr = 0.71). They reported that there was a critical Rayleigh number ($Ra = 0.13 \times 10^6$) for heat transfer, and that the heat transfer improved below this value. They declared that thermal oscillation occurs when the Rayleigh number exceeds the threshold and that the thermal oscillation frequency depends on the Rayleigh number, rotor length and rotational speed of the rotor.

Oscillating flows have a complex structure; therefore, the effects on heat transfer and fluid mechanics of oscillations are not completely understood. In these applications, the results vary depending on many parameters that affect flow and heat transfer such as flow regime, fluid type, the geometry of a solid surface geometry, heat flux, fluid and wall temperature, oscillation amplitude, and frequency. Previously, studies were generally numerically or theoretically based; therefore, experimental studies are limited. Oscillation motion was mostly created by fluid vibration, and these studies were performed for very small oscillating amplitudes and frequencies. Thus, additional research is required to determine the best parameters that improve flow and heat transfer. Therefore, in this study, the effects of mixed convection heat transfer on the oscillating vertical plate were numerically and experimentally examined for a wide range of oscillation amplitudes and frequencies. The oscillation movement was obtained by the periodic movement of the vertical plate.

EXPEREMENTAL STUDY

Experimental Test-rig

The experimental schematic and setup used in this study are shown in Figure 1. A transparent enclosure, in which the experimental model periodically moves, comprises an aluminum frame system with dimensions 800 × 800 × 800 mm^3, open top and bottom, and side surfaces designed to be closed. A hanger system with four pulleys was built to allow movement of the experimental model to the upper part of the enclosure. Inside the transparent enclosure is a rail system installed in the aluminum framework to guide the vertical movement of the experimental model.

The experimental model comprised two flat copper plates with dimensions of 210 × 210 × 1.5 mm^3, thermocouples attached to both plates, and two Kapton heaters placed between the plates. At the bottom of the experimental model, there is a triangular wooden end with dimensions of 210 × 15 × 4 mm^3. The schematic of the experimental model is illustrated in Fig. 2.

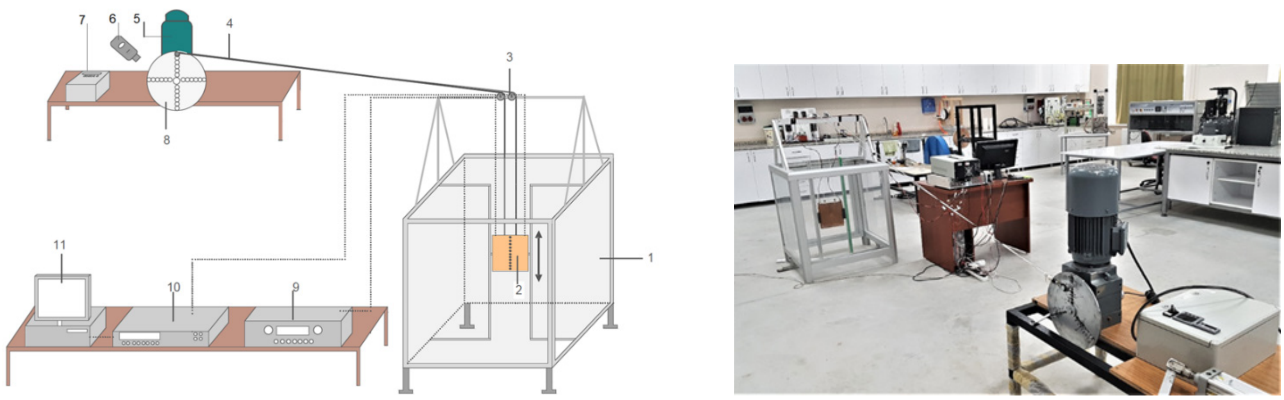
K-type thermocouples (Omega, ±0.1 °C) were attached at regular intervals along the vertical axis to measure the plate-surface temperatures (Fig. 3). There were 11 and 3 thermocouples attached to the front and rear copper plates, respectively. Two the thermocouples were used to measure the ambient temperature. The surface and ambient temperatures measured using the thermocouples were transferred to a computer via a datalogger.

In the calculations, the temperature values recorded by the 11 thermocouples attached to the front copper plate were taken into consideration. The heat transfer on the plate surface was calculated using the temperature data. A strong rope was passed through two separate holes (at the top of the experimental model) and connected to a flywheel via the pulley system. The flywheel, driven by a powerful 2.4-kW DC motor, generated the oscillating movement of the experimental model. The oscillation amplitude was adjusted through the holes of the flywheel, and the oscillation frequency was changed using a motor speed unit. The working fluid is air and the ambient thermophysical properties are used in calculations.

Experimental Study

First, the experimental model was left stable in the middle of the transparent enclosure with constant heat flux. The temperatures measured from the plate surfaces were sent to the computer. Then, the natural convection heat transfer from the vertical plate surface was calculated.

For the periodic oscillation movement, the oscillation amplitude was adjusted on the flywheel, while the experimental model was kept stable in the middle part of the enclosure. Constant heat flux was applied to the surfaces of each copper plate using a power supply. Then, the motor driving the flywheel was started, and the motor speed was adjusted to the tested frequency using the motor control unit. Thus, it was ensured that the experimental model periodically oscillated with constant heat flux as well as oscillation amplitude and frequency determined in the enclosure. The heated plate continued their periodic movement for a set period of time (2700 s), after which, the temperature readings from the thermocouples were sent to the computer from the datalogger. In this study, dimensionless numbers obtained according to the Buckingham π theorem



(a) (b)

Figure 1. (a) Experimental schema, (b) Experimental setup.

(1- Transparent volume, 2- Experimental model, 3- Pulley system, 4- Hanger system, 5- DC motor, 6- Tachometer, 7- Velocity control unit, 8-Flywheel, 9- Power supply, 10-Datalogger, 11- PC.)

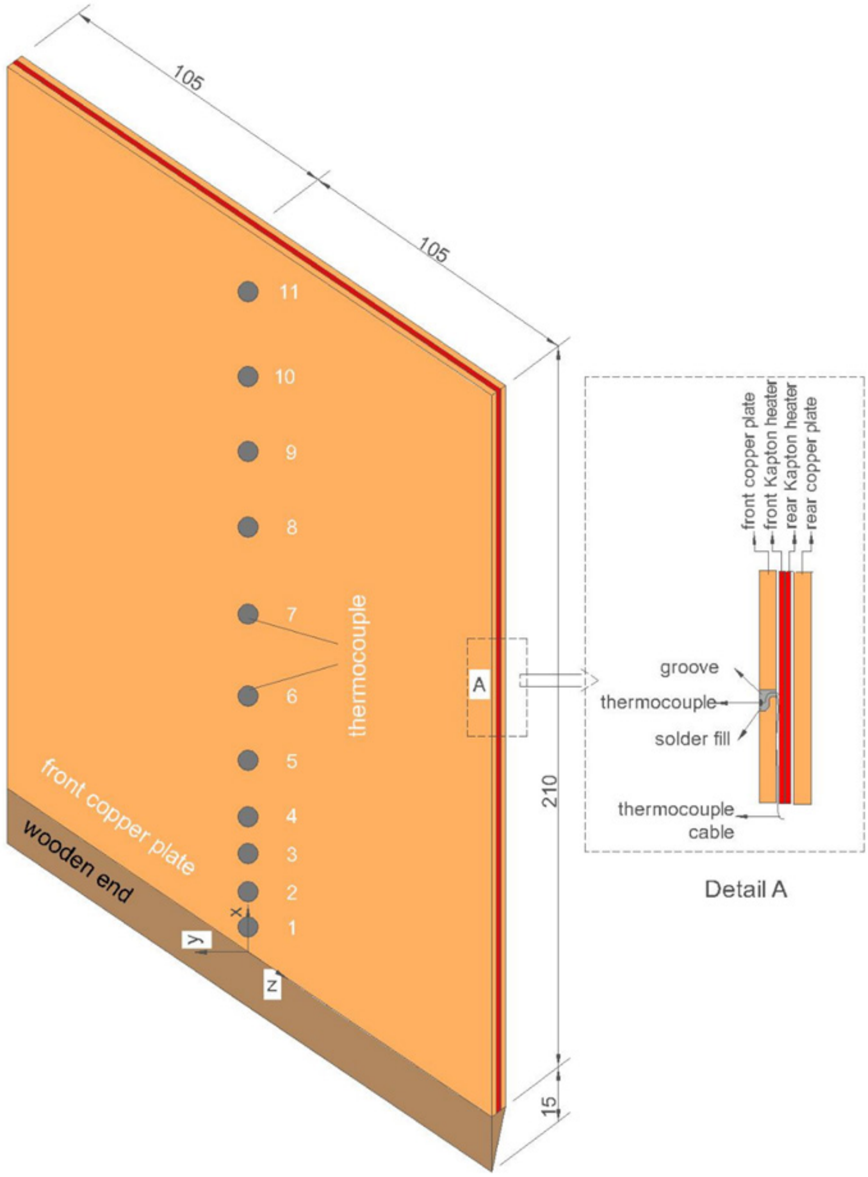


Figure 2. Experimental model.

were defined as $Nu = f(Pr, Gr, Re_\omega, A_o)$. Nu, Gr, Pr, Re_ω, A_o are Nusselt number, Prandtl number, Grashof number, Kinetic Reynolds number, dimensionless oscillation amplitude, respectively.

To express the oscillation frequency and amplitude of experimental model, the Womersley number (Wo) and dimensionless oscillation amplitude (A_o) are used as follows:

$$Wo = L\sqrt{\frac{\omega}{\upsilon}} = \mathrm{Re}_\omega^{\ 1/2} \quad (1)$$

$$A_o = \frac{x_m}{L} \quad (2)$$

where, ω, υ, x_m, L are angular velocity (rad/s), kinematic viscosity (m^2/s), the amplitude of flywheel (m), plate length (m), respectively. The experiments are performed for three different heat fluxes (q'' = 250 W/m^2, 500 W/m^2 and 625 W/m^2), four different dimensionless amplitudes (A_o: 0.4, 0.75, 1.1, 1.4) and five different frequencies (Wo: 65, 92, 113, 131, 146). The conduction resistance of the copper plate with a thickness of 1.5 mm, which was used for the heated surface, was neglected. The Biot number ($Bi = h \times L_c/k_s$) was calculated for the copper plate and $Bi = 3.16 \times 10^{-5}$ was obtained. In the literature, if the Biot number is very low ($Bi < 0.1$), the lumped model approach can be performed [33]. The heat storage capacity of the plate is neglected because the heat flux is continuously supplied.

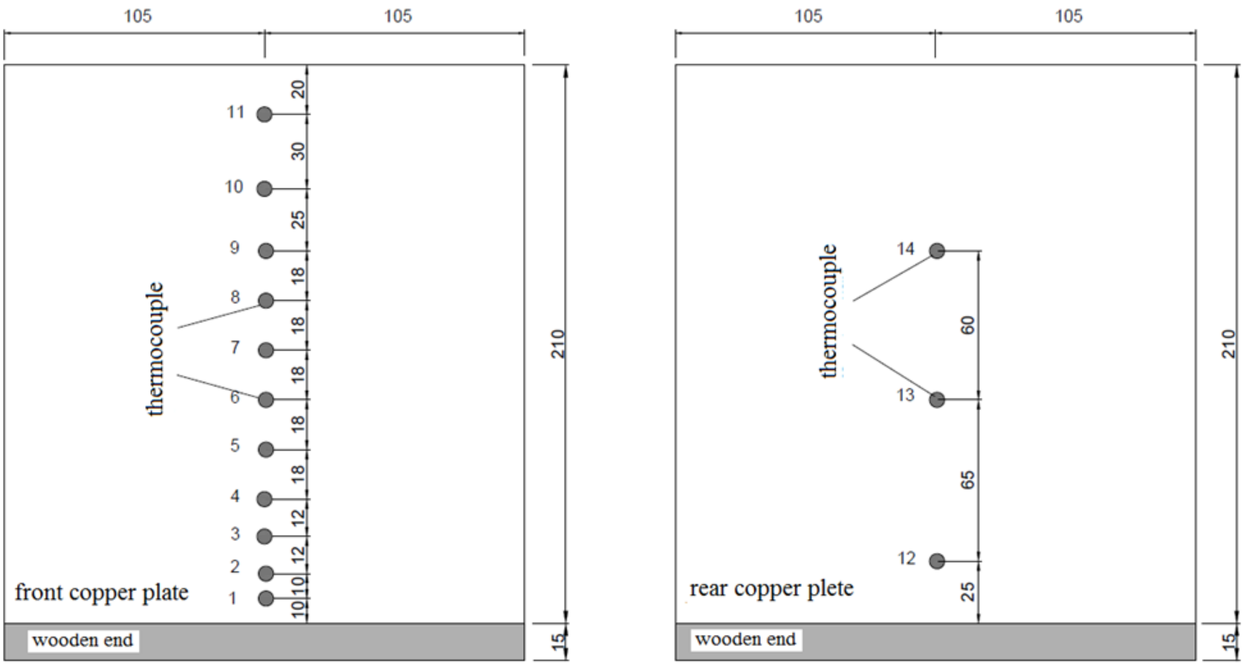


Figure 3. The thermocouple positions on the experimental model (sizes in millimeters).

This is because the incoming heat flux to the plate is equal to the heat transfer rate from the plate surface.

The instantaneous temperatures taken from each thermocouple on the vertical plates were acquired with time. Due to the periodic oscillation movement of the experimental model, periodic flow occurred on each plate, while the temperature values changed over time. These instantaneous values were used to calculate the surface temperatures. The average temperatures were determined according to the time average of the instantaneous temperatures taken from each thermocouple. Since the time intervals were equal, the average temperatures were calculated as follows:

$$T_{w,x} = \frac{1}{N\Delta t}\sum_{i=1}^{N} T_{w,i}(x,t)\Delta t \tag{3}$$

where, N is the total data number, Δt is time interval, T_w represents the instantaneous temperatures. The surface average temperature was calculated by taking the arithmetic mean of the local average temperatures (Eqn. 4).

$$\overline{T_w} = \frac{T_{w1}+T_{w2}+T_{w3}+T_{w4}+........+T_{w11}}{11} \tag{4}$$

Figure 4 shows the variation of plate surface temperatures with oscillation frequency at different oscillation amplitudes for $q'' = 500$ W/m^2. It is seen that the difference between surface temperatures increases with increasing amplitude and surface temperatures decrease with increasing frequency.

In this study, both the natural convection heat transfer on the fixed vertical plate and mixed convection heat transfer on the periodically moving vertical plate subjected to specific heat flux were calculated. The heat transfer was calculated using the Nusselt number as follows;

$$Nu(x,t) = \frac{h(x,t)L}{k_f} \tag{5}$$

The heat transfer was calculated using spatio-temporally averaged Nusselt number derived as;

$$Nu_w = \frac{1}{\tau L}\int_0^L\int_0^\tau Nu(x,t)dtdx \tag{6}$$

where τ denotes the cycle time of oscillating flow, L (m) is plate length.

The average Nusselt number was defined as;

$$Nu_w = \frac{q''L}{k_f(\overline{T}_w - T_\infty)} \tag{7}$$

where, h (W/m^{2}K) is heat convection coefficient, k (W/mK) isothermal conductivity coefficient of fluid, $\overline{T}_w$ is average temperature of plate surface, and T_∞ is ambient temperature. The heat flux applied to the plate surface by the Kapton heater is expressed as q''(W/m^2).

The rates of the natural convection heat transfer (Nu_s) obtained from the fixed plate surface of the mixed

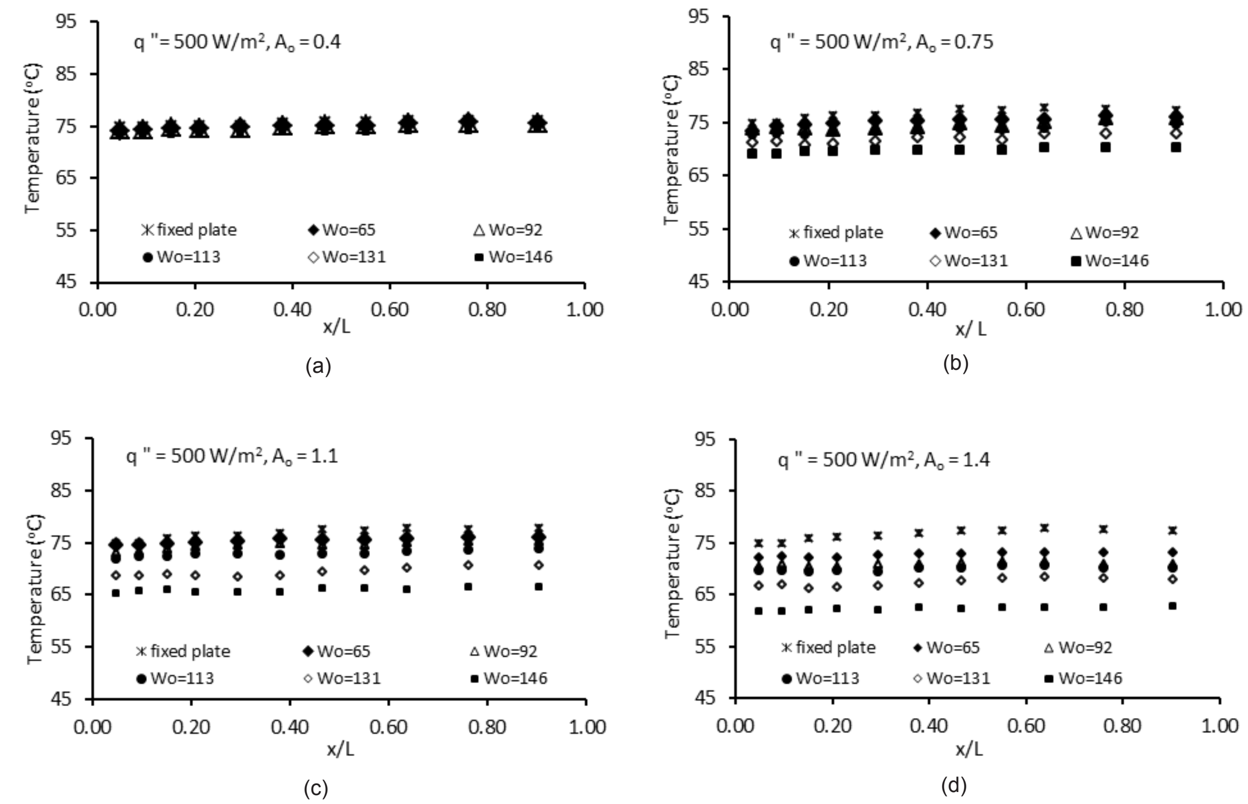


Figure 4. Variation of surface temperatures with different amplitude and frequency**,** (a) A_o = 0.4, (b) A_o = 0.75, (c) A_o = 1.1, (d) $A\mathbf{1}$ = 1.4.

convection heat transfer (Nu_w) obtained from the plate surface subjected to a periodic oscillation was defined the heat transfer performance (η), as heat transfer performance greater than 1 indicates that the mixed convection heat transfer on the oscillating plate improves according to the natural convection heat transfer on the fixed plate.

$$\eta = \frac{Nu_w}{Nu_s} \tag{8}$$

Fig. 5 shows the effects of different oscillation amplitude and frequency on the heat transfer performance for different heat fluxes. It can be observed that the heat transfer performance of moving plate increases with increasing oscillation amplitude and frequency for all heat fluxes compared to fixed plate. However, this increase was observed to be higher for low heat flux. Because of the high heat fluxes, natural convection effects are more dominant on the plate surface.The maximum heat transfer performance improvement of 45% was observed at a high amplitude (A_o = 1.4) and a high frequency (Wo = 146) for q'' = 250 W/m^2.

In this study, Holman's uncertainty-analysis method was applied to determine the measurement errors in our experiments [34-36]. The main source of the errors were the statistical uncertainties in the measurements of the heater surface temperatures (T_w, ±1 °C), free stream temperature (T_∞, ±0.25 °C), and angular velocity (ω, ±0.5 rad/s). The uncertainty of the Nusselt number for each experiment is calculated as follows:

$$w_{Nu} = \left[\left(\frac{\partial Nu}{\partial T_w} w_{T_w} \right)^2 + \left(\frac{\partial Nu}{\partial T_\infty} w_{T_\infty} \right)^2 + \left(\frac{\partial Nu}{\partial \omega} w_\omega \right)^2 \right]^{1/2} \tag{9}$$

The total uncertainty of the Nusselt number can be obtained as the arithmetic mean of the uncertainties in all tests. The total average uncertainty in the experiments was calculated to be 4.25%.

NUMERICAL STUDY

In this section, the mixed convection heat transfer on the oscillating vertical plate is examined numerically based on the experimental parameters. The simulations were performed using ANSYS Fluent 18.2 program [37]. In this CFD analysis program, the continuity, momentum, and energy equations are discretizated using the finite volumes method. The two-dimensional (*2D*) numerical solution domainwas

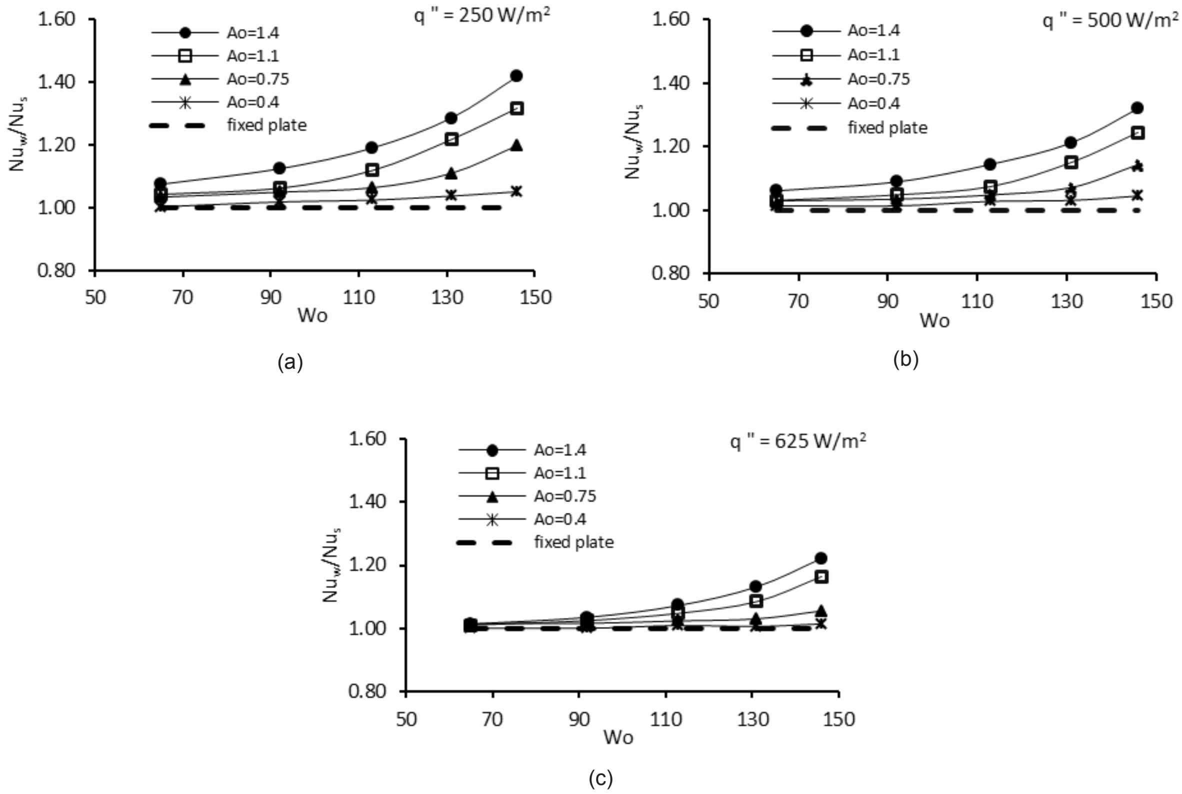


Figure 5. Variation of the heat transfer performance with oscillation parameters for different heat fluxes: (a) $q'' = 250$ W/m^2, (b) $q'' = 500$ W/m^2, (c) $q'' = 625$ W/m^2.

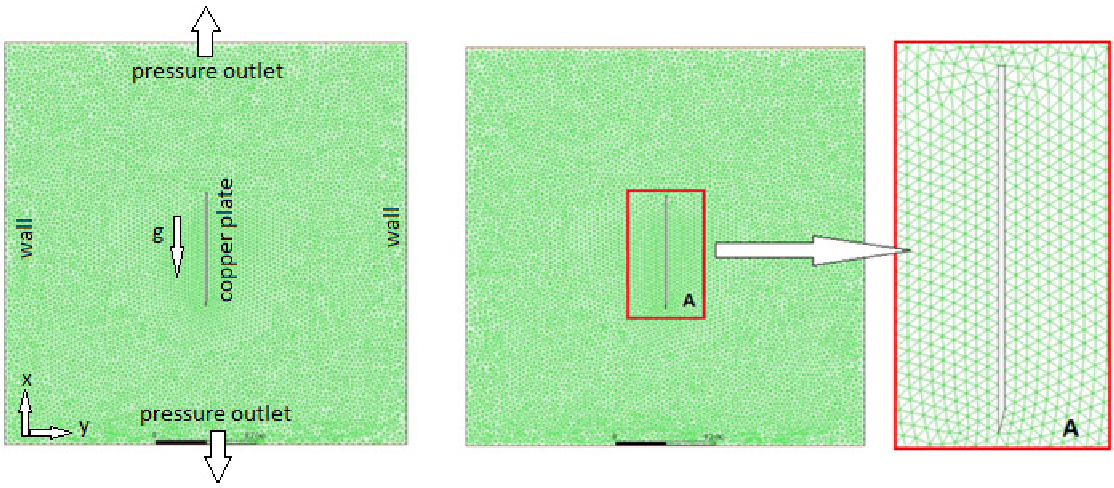


Figure 6. Numerical model mesh structure and boundary condition.

created using the Workbench program depending on the experimental geometry. The transparent enclosure for the *2D* numerical model was considered to be 800 × 800 mm^2. Inside the enclosure, a copper plate with a length of 210 mm and a thickness of 4 mm was placed vertically. Fig. 6 illustrates the mesh structure together with the boundary conditions.

The numerical solutions for different element numbers (cells) were obtained for the grid independence test, and Nusselt numbers were calculated for fixed vertical plates at $q'' = 250$ W/m^2 (Table 1). After the element number of 31625, the change in Nusselt number was determined to be < 2%, and the element numbers of 31625 were preferred for the fixed plate.

Table 1. Grid independence test

No	Element Number	Nusselt Number
1	11699	110.78
2	24518	113.25
3	31625	114.12
4	48228	114.27
5	68284	114.29

Due to the continuously renewed mesh structure, the dynamic mesh model always required an unsteady solution for the moving objects or boundaries. The pressure implicit with split operator (*PISO*) algorithm is preferred in this situation because it can provide more sensitive results. The second-order upwind schema was used for the discretization of the pressure, momentum, and energy equations. The convergence criteria were set to be 10^{-8} for the energy equations and 10^{-5} for the momentum and continuity equations. The Boussinesq approach, which defines the fluid density as a function of temperature, was chosen to include the effects of natural convection on the solutions. In this study, the time-dependent velocity profile was used to describe the periodic motion of the plate as follows [2, 30]:

$$u_w = A_0 \sin(wt) \tag{10}$$

where A_o, ω (rad/s), and t (s) denote the dimensionless amplitude, angular velocity, and time, respectively.

For the periodic motion of the experimental model in the domain, the dynamic mesh was activated in the Fluent program. Smoothing and remeshing methods were applied to the dynamic mesh model. Spring/Laplace method was used for the smoothing method. Local Cell method was used for remeshing to reconstruct the mesh structures that were skewed by moving boundaries or objects. The network structure in the deformed zones during a periodic movement of the plate was continuously renewed according to the specified parameters. In this study, the following smoothing parameter values were used: a spring constant factor of 0, a convergence tolerance of 0.001, and a number of iterations of 100. The remeshing parameter values were as follows: a maximum cell skewness of 0.3 and a size remeshing interval of 5. The mass, momentum, and energy equations according to the Boussinesq approach for the 2d, incompressible, unsteady flow on a oscillating vertical flat plate can be written as follows [33]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{11}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\left(\frac{\partial^2 u}{\partial y^2}\right) + g\beta(T - T_\infty) \tag{12}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} \tag{13}$$

A number of iterations should be performed to evaluate the solution results. In this study, the iterations for all solutions continued for 2700 s using a time step of 0.01. Then, the heat transfer was calculated using the average surface temperature. Due to the periodic motion of the plate, periodic flow occurred on the plate surface; hence, the motion period has considered in the evaluation of the solutions. One cycle was defined as $\omega t = 2\pi f t = 360°$. In this study, the instantaneous temperatures and Nusselt numbers for different oscillation parameters over a cycle were calculated.

RESULTS AND DISCUSSIONS

The experimental and numerical results obtained in this study are compared with the approach taken by Acrivos [38], results of the theoretical study conducted by Gomaa and Taweel [23], and experimental results of Prasad and Ramanathan [39] for mixed convection, at Re_ω = 4000, and Pr = 0.72 (Fig. 7). It is observed that the results of the study were in good agreement with other studies.

In Fig. 8a, the temperature distributions obtained in the experimental and numerical studies were compared for different oscillation frequencies at q'' = 250 W/m^2 and A_o = 1.4. It was found that the temperature values obtained on the surface for both studies were quite close to each other. Fig. 8b demonstrates the variation of the Nusselt number with time for different oscillation amplitudes at q'' = 250 W/m^2 and Wo = 92. At each oscillation amplitude, the Nu number changed sinusoidally and periodically. As the oscillation amplitude increases, the amplitude of the sinusoidal curve increases. As the oscillation amplitude increases, the plate oscillates at greater distance in the vertical direction. This causes the surface temperature range to be larger and thus the instantaneous Nusselt numbers obtained vary over a wide range.

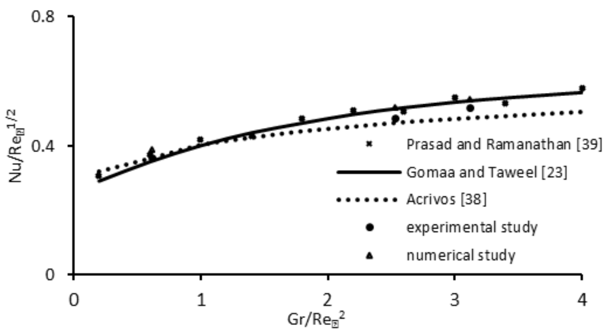
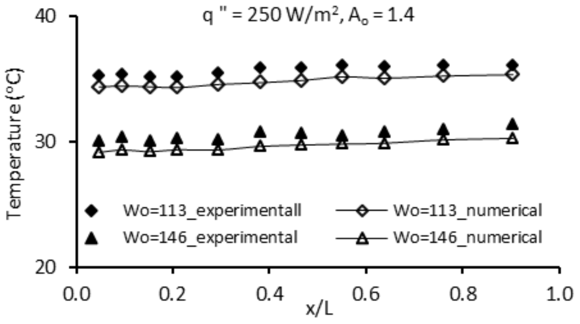
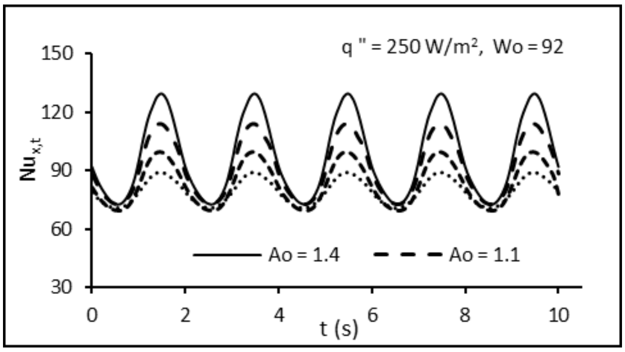


Figure 7. Comparison of the numerical and experimental results with open literature.

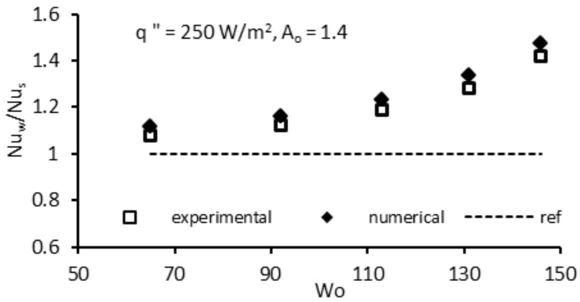


(a)

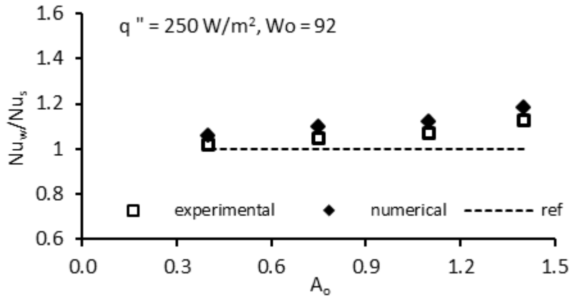


(b)

Figure 8. (a) Comparison of the plate surface temperatures for experimental and numerical studies, (b) Variation of the Nusselt number with time for different amplitudes (q'' = 250 W/m^2, *Wo* = 92).



(a)



(b)

Figure 9. Comparison of the experimental and numerical heat transfer performance.

In Fig. 9, the heat transfer performance according to the experimental results is compared to that according to the numerical solutions for different frequencies (Fig. 9a) and amplitudes (Fig. 9b). Natural convection heat transfer (Nu_s) considered as reference. Both the numerical and experimental results demonstrate that the heat transfer performance increases with the increase of the oscillation amplitude and frequency. This study demonstrates that oscillating surfaces have a significant potential in heat transfer improvement.

Figure 10 shows the variation of instantaneous and average temperatures obtained on the plate surface with different oscillation amplitudes over a cycle for q'' = 250 W/m^2 and *Wo* = 92. It can be seen from the figures that instantaneous temperatures obtained during one cycle for all oscillation amplitudes vary sinusoidally and that the amplitude of the instantaneous temperature curve decreases with decreasing oscillation amplitude. In addition, the average surface temperature of the plate decreases with increasing oscillation amplitude. This shows that oscillation amplitude has a significant effect on heat transfer and that the heat transfer improves with decreasing surface temperatures at increasing amplitudes.

In Fig. 11a, the change heat transfer performance of the oscillating plate was given for the constant amplitude (A_o= 0.75) and the heat flux (q'' = 250 W/m^2) with oscillation frequency over one cycle. It was seen that the average heat transfer performance was higher at high frequencies and the amplitude of the heat transfer performance curve increases with decreasing frequency. Increasing the oscillation frequency will increase the mixture between the hot fluid in the boundary layer and the surrounding cold fluid, and this will result in increased heat transfer as there will be a faster mixture at high speeds.

Fig. 11b shows the heat transfer performance on the plate for *Wo* = 92 and q'' = 250 W/m^2 at different the oscillation amplitude over one cycle. It is seen that the average heat transfer performance is higher at higher amplitudes, and the amplitude of the heat transfer performance curve decreases with decreasing oscillation amplitude. Since plate makes more displacement at the high oscillation amplitude, the heat transfer performance curve fluctuates at higher amplitudes. This shows that the oscillation parameters are highly effective on heat transfer enhancement.

In the numerical study, the instantaneous temperature and velocity contours of the oscillating plate were obtained

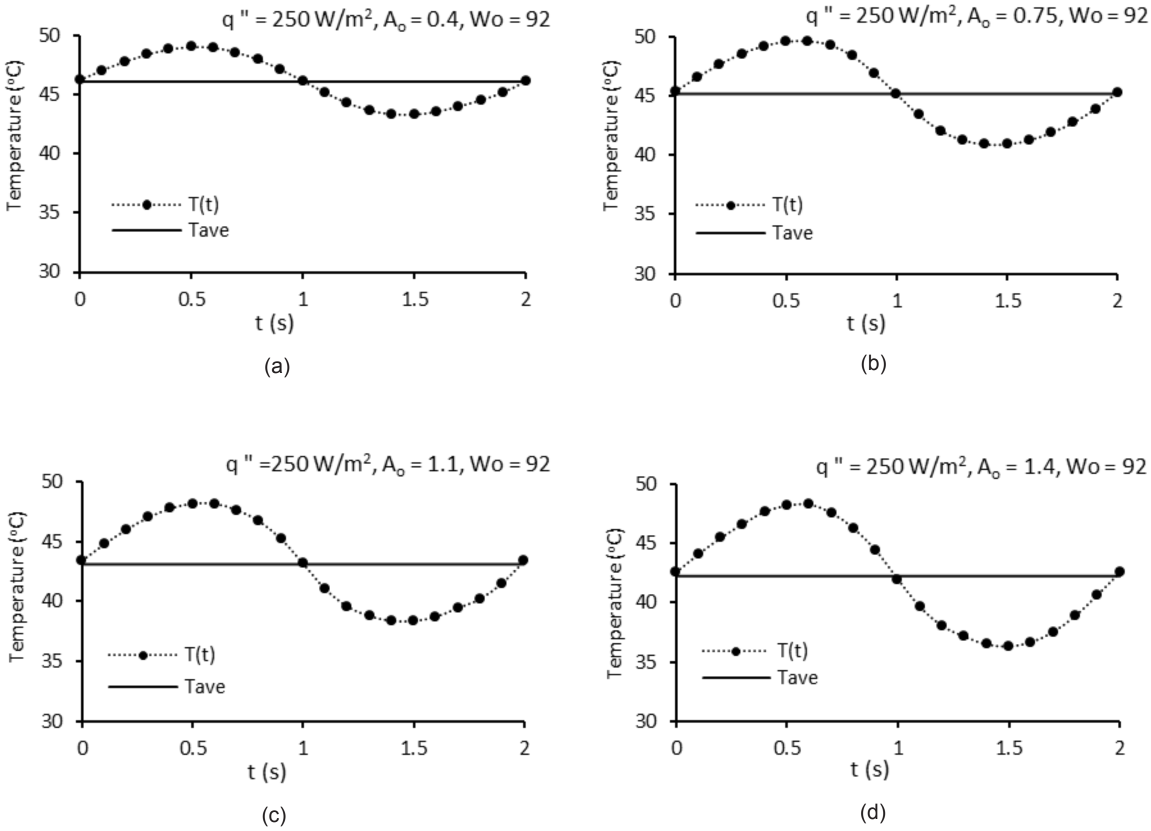


Figure 10. The variation of the instantaneous temperatures with amplitude on the plate surface during one cycle, (a) A_o = 0.4, (b) A_o = 0.75, (c) A_o = 1.1, (d) A_o = 1.4.

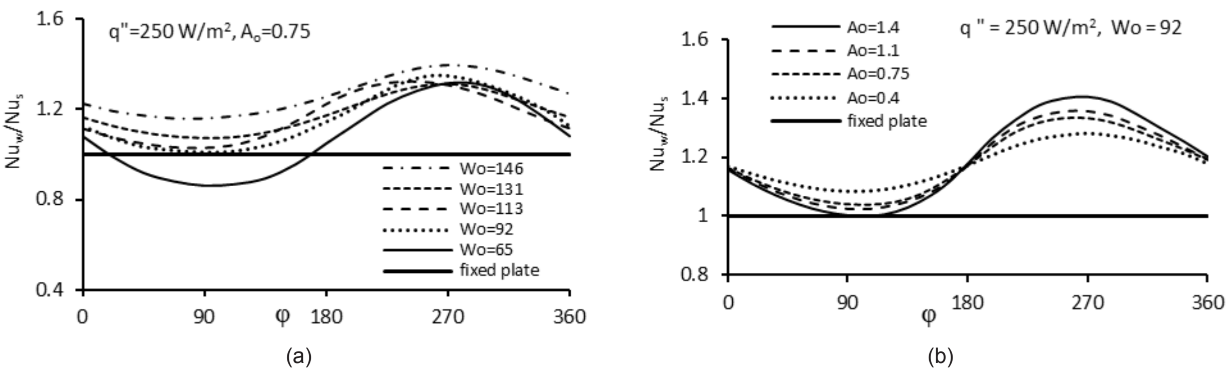
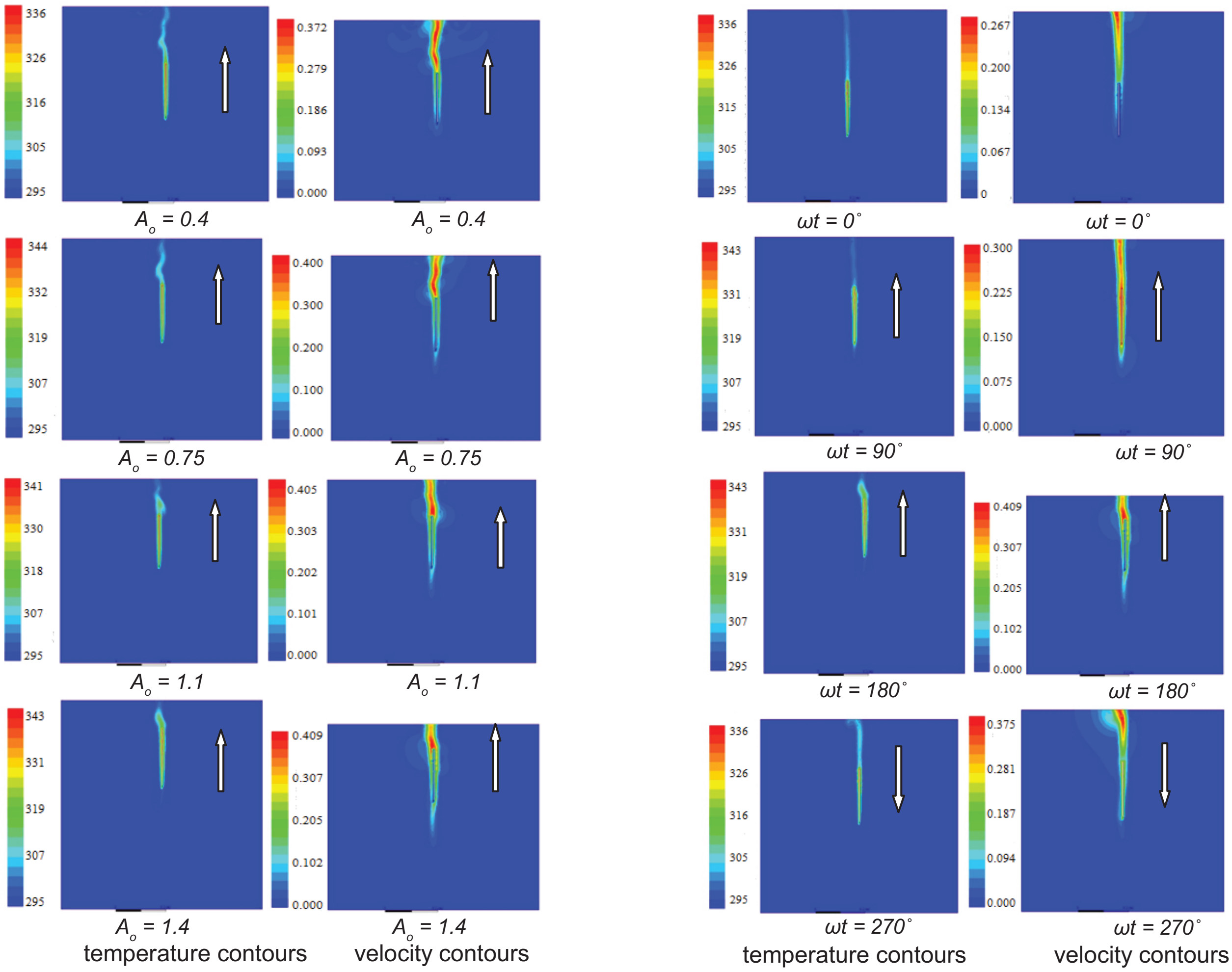


Figure 11. The variation of the heat transfer performance with oscillation parameters over a cycle (a) *Wo*, (b) A_o.

depending on different oscillation parameters. Fig. 12a shows the temperature and velocity contours of the oscillating plate at different amplitudes for q'' = 250 W/m², ωt = 180°, and *Wo* = 92. The figures demonstrate that the velocity and temperature distributions on the plate surface are highly affected by the oscillation amplitude. At lower amplitudes, the velocity profiles distributed over a larger area at the top of the plate have a narrower area as the amplitude increases. This can be explained by a more frequent regeneration of the air layer around the plate for high amplitudes.

Figure 12b shows the temperature and velocity contours during one cycle at different phase angles for q'' = 250 W/m², A_o = 1.4, and *Wo* = 92. Constant heat flux applied to the plate surface heats the surface and the heat transfer to the environment by both natural and forced convection occurs



(a) (b)

Figure 12. (a) The temperature and the velocity contours for different amplitudes (q'' = 250 W/m^2, Wo = 92, ωt = 180°), (b) the temperature and the velocity contours during a cycle (q'' = 250 W/m^2, A_o = 1.4, Wo = 92).

due to the periodic oscillation movement of the plate. The temperature and velocity gradients on the plate vary continuously over time due to the periodic oscillation movement of the plate. It can be noticed from Fig. 12 (from the temperature contours) that the heated plate is surrounded by a layer of hot air, where the heated air rises upward due to the decrease in density. The periodic oscillation movement of the plate causes the renewal of the velocity and thermal boundary layer on the plate due to its continuous deformation. This results in an increased contact of the plate surface with the layer of cold air, thereby increasing the velocity of the heat transfer on the plate surface.

Fig. 13a and 13b show the temperature and velocity contours at different Wo numbers, for q'' = 250 W/m^2, A_o = 0.75, and ωt = 270°. It can be noticed from the figures that the temperature and velocity distributions on the plate surface and flow area are significantly affected by the periodic oscillation frequency. At higher frequencies for the temperature contours, it can be observed that the hot air layer at the top of the plate is more dense. The deformation and renewal of the velocity and thermal boundary layers on the surface take place within a shorter time due to the increase in the oscillation frequency, which helps the surface of the plate to cool more quickly by providing a more frequent contact with the layer of cold air.

In Figure 14, flow vectors for velocity (a) and temperature (b) were given on the downward moving plate for q'' = 250 W/m^2, A_o = 1.4, Wo = 146, ωt = 300°. From the velocity and temperature contours, it was seen that the direction of vectors in the upper parts of the plate is upwards and their lengths are larger. At the bottom of the plate, it was seen that the length of vectors were reduced, the separation point after a certain distance occured and direction of some the vectors changed. This means that the velocity and thermal

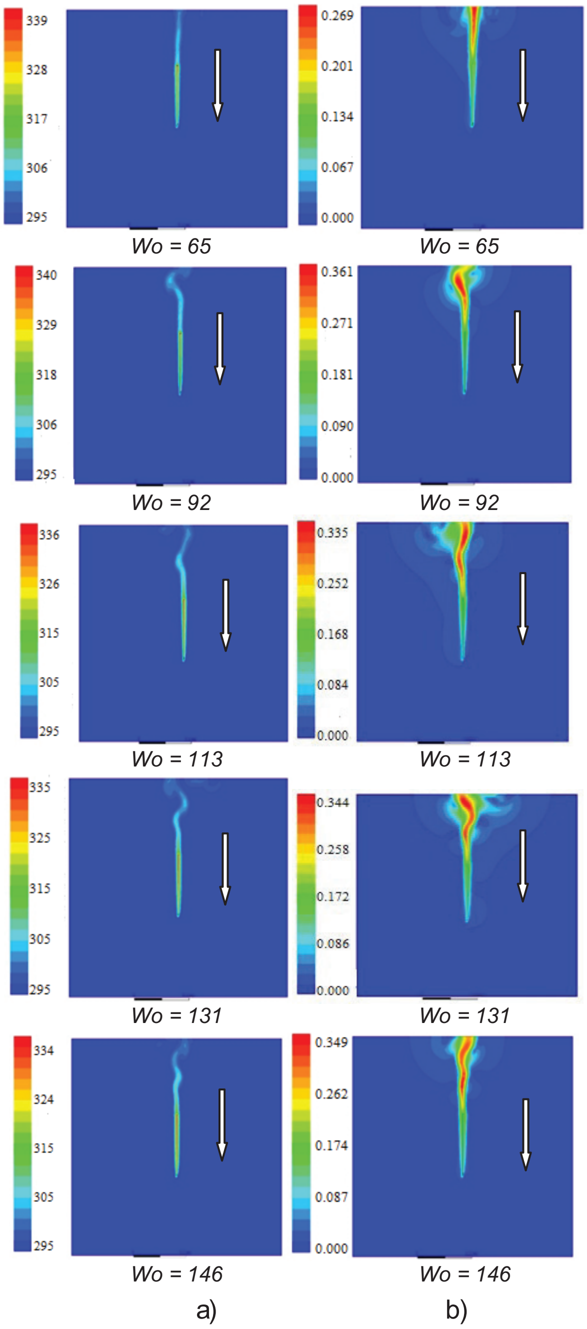


Figure 13. The temperature (a) and the velocity (b) contours for different oscillation frequencies ($q'' = 250$ W/m², $A_o = 0.75$, $\omega t = 270°$).

boundary layers were deformed and renewed continuously by the periodic cycle. Thus, in each cycle, a continuous mixture of hot and cold air was achieved, resulting in improved heat transfer.

The velocity and the temperature contours show that the oscillating vertical plate causes a significant improvement in the heat transfer compared to the fixed plate.

CONCLUSION

In this study, the effects on mixed convection heat transfer of oscillation parameterson vertical flat plate were experimentally and numerically investigated. The effects of the heat flux applied to the plate surface as well as those of oscillation amplitude and frequency on heat transfer are analyzed. The instantaneous temperatures and Nu numbers were calculated for different oscillation parameters on the plate surface. The experimental and numerical results are validated by comparing with other results reported in the open literature. The results of the study show that the heat transfer performance was affected by the heat flux applied to the plate surface as well as the amplitude and frequency of the oscillation. As the heat flux applied to the plate surface decreases, the heat transfer performance increases. Also, as the oscillation amplitude and frequency increase, the heat transfer performance increases. The maximum heat transfer performance of approximately 1.45 is achieved at a low heat flux ($q'' = 250$ W/m²) with increasing oscillation amplitude ($A_o = 1.4$) and frequency ($Wo = 146$). In the numerical study, for better understanding of flow and heat transfer mechanism, the instantaneous temperature and velocity contours are obtained based on different oscillation parameters. It is observed that the oscillating vertical plate causes a significant improvement in heat transfer as compared with the fixed plate.

NOMENCLATURE

A_o	Dimensionless oscillation amplitude [= x_m/L]
Bi	Biot number [=hL_c/k_s]
g	Gravity (m/s²)
Gr	Grashof number [= $g\beta\Delta TL^3/\upsilon^2$]
h	Heat convection coefficient (W/m²K)
k	Thermal conductivity (W/mK)
L	Plate length (m),
N	Total data number
Nu	Nusselt number [= hL/k]
Pr	Prandtl number [= $\mu C_p/k$]
q''	Heat flux (W/m²)
Re	Reynolds number [= uL/υ]
Re_w	Kinetic Reynolds number [= Wo^2]
Ri	Richardson number [= $Gr/Re^{1/2}$]
T	Ambient temperature (°C)
t	Time (s)
u	Velocity (m/s)
Wo	Womersley number [= $L/(\omega/\upsilon)^{1/2}$]
x_m	Amplitude of flywheel (m)

Greek Symbols

η	Heat transfer performance
τ	Cycle time (s)
υ	Kinematic viscosity (m2/s)
ω	Angular frequency (rad/s)

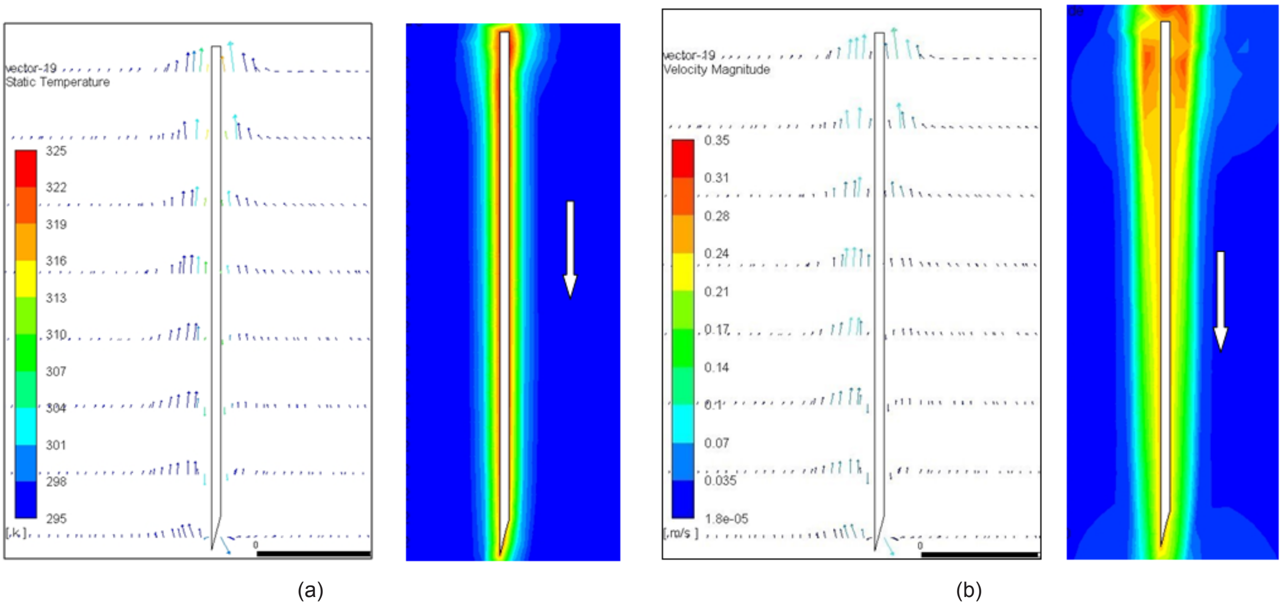


Figure 14. Flow vectors along the plate, (a) temperature, (b) velocity ($q'' = 250$ W/m^2, $A_o = 1.4$, $Wo = 92$, $\omega t = 300°$).

Subscripts

∞ Free, ambient
s Natural convection, solid
w Mixed convection, kinetic

AUTHORSHIP CONTRIBUTIONS

Design, Materials, Data Analysis, Literature search; Writing; Critical revision: Selma Akcay; Concept, Methodology, Concept; Writing - review: Unal Akdag

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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