International Journal for Modern Trends in Science and Technology
Volume 10, Issue 02, pages 632-639.
ISSN: 2455-3778 online
Available online at: http://www.ijmtst.com/vol10issue02.html
DOI: https://doi.org/10.46501/IJMTST1002091

Numerical Analysis of Convective Heat Transfer from a Horizontal Plate Caused by a Vertically Oriented Blade's Oscillation

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To Cite this Article
Dr. Govardhan Dasari, Numerical Analysis of Convective Heat Transfer from a Horizontal Plate Caused by a Vertically Oriented Blade's Oscillation, International Journal for Modern Trends in Science and Technology, 2024, 10(02), pages. 632-639. https://doi.org/10.46501/IJMTST1002091

Article Info
Received: 31 January 2024; Accepted: 27 February 2024; Published: 29 February 2024.

ABSTRACT

In the current work, convective heat transfer from a flat plate that is boosted by an oscillating blade was examined statistically. The blade was thought to be vertically positioned at the top of the target plate and composed of a thin, stiff plate. Commercial software ANSYS Fluent 6.3 was used for numerical analysis, and the moving mesh approach was used to represent the blade's periodic oscillation. For the laminar airflow with constant physical parameters, the conservation equations of mass, momentum, and energy were solved in two dimensions and in transient form. The plate's constant temperature was taken into account, and the specifics of the flow and thermal fields were established. Convective heat transfer from the target plate was examined in relation to a number of parameters, including the geometrical parameters and the amplitude and frequency of the blade oscillation. The findings showed that raising the blade's oscillation amplitude had an impact on a larger region of the plate. Increasing the rotational Reynolds number also improved convective heat transport across the target plate.

Keywords: Convective heat transfer; Convection enhancement; Flat plate; oscillating blade.

1. INTRODUCTION

In several engineering applications and industrial devices, temperature difference potential transfers heat between solid surfaces and nearby fluids. Convective heat transfer enhancement is preferred in the majority of applications, including heat exchangers and electronic cooling. An effort is made to promote heat transfer in a straightforward and effective way while using less energy. There are two types of augmentation techniques: passive and active. The former uses no external energy. Convective heat transfer enhancement is still an open and significant research issue in the world of heat transfer research because of the range of applications and improvement strategies. In heat transfer augmentation, passive approaches have been used in a variety of ways. In several studies, convective heat transfer has been improved by using both extended surfaces and surfaces with artificial roughness; as a result, a number of review papers have also been published [1, 2]. Another evaluation of heat transfer enhancement in passive methods with an emphasis on swirl flow devices was given by Sheikholeslami et al. [3]. In that review work, the impact of several turbulators, such as coiled and corrugated tubes, twisted tape, conical rings, and coiled wire on heat transfer augmentation was briefly covered. The impact of vortex-induced vibration on breaking the thermal boundary layer and accelerating the rate of heat transfer was examined numerically by Shi et al. [4]. In their study, the vortex-generating apparatus inside a plane duct was a cylinder with a flexible plate at the rear. Several research have employed moving a cylinder inside a two-dimensional channel as an active technique to enhance convective heat transfer from the channel walls. It is recognized that oscillatory flows result in increased mass and heat transmission. Either a solid body vibrating within a fluid or the fluid vibrating around a fixed item can produce oscillating movement. Both methods accomplish the same objective, despite the fact that fluid vibration around a fixed object uses more energy.

Compact high-performance heat exchangers, piston engines, chemical reactors, pulsating burners, high-performance Stirling engines, cryogenic refrigeration, and other applications in the military and aerospace sectors all make extensive use of oscillating flows. [5–9]. Heat transfer increase in a plane duct by vortices shed from a transversely oscillating circular cylinder was quantitatively examined by Celik et al. [10]. They discovered that a transversely oscillating cylinder significantly improves convective heat transfer in the thermally developing flow area. The impact of a transversely oscillating cylinder on the heat transfer from heated blocks in a plane duct flow was investigated statistically by Fu and Tong [11] in a related work. Convective heat transfer from heated planar duct walls in the presence of a rotating oscillation cylinder was quantitatively examined by Beskok et al. [12]. The impact of a spinning and oscillating blade on the augmentation of heat transfer from the channel walls was examined numerically by Pourgholam et al. [13]. The flow and heat transmission features in a mixing tank with a helical single-blade mixer were investigated numerically by Jahangiri and Delbari [14]. They proposed a correlation between heat transmission and the development of two-phase flow inside the mixing tank. Convection heat transfer augmentation was quantitatively examined by Rahman and Tafti [15] in a system consisting of an incredibly thin plate-fin with forced oscillation when an incoming flow was present. They discovered that a single measure known as "plunge velocity" could capture the combined impact of oscillation frequency and amplitude on heat transfer augmentation. The impact of plate movement on the distribution of heat transfer over the plate impinged by an air jet was examined quantitatively by Rahimi and Soran [16]. A rectangular flat plate's vibration effect on convective heat transfer from the plate in both horizontal and inclined positions was experimentally examined by Sarhan [17]. An analysis of the impact of oscillatory motion on heat transmission from a vertical surface was conducted by Gomaa and Al Taweel [18]. The convective heat transfer from an oscillating vertical plate was experimentally examined by Akcay et al. [19]. The flapping dynamics of a piezoelectric fan and heat transfer increase from the wall in a turbulent channel flow were investigated by Chen et al. [20]. An experimental and modeling investigation was carried out by Ebrahimi et al. [22] to look into power dissipation when employing piezoelectric fans. The impact of blade geometry and shape on convective heat transfer caused by a piezoelectric vibrating fan was experimentally examined by Li et al. [23]. A number of review publications [24, 25] provide additional research on the flow structure and heat transfer enhancement caused by piezoelectric fans. Thus, the current study examines the specifics of the flow field that is created and the heat transfer enhancement from a flat plate that is brought about by an oscillating blade that is oriented vertically.

2. THE DESCRIPTION OF THE ISSUE AND THE NUMERICAL METHOD

A solid surface of 0.084 meters in length was examined horizontally in order to examine convective heat transfer from a flat plate caused by the oscillation of a vertical blade. It was supposed that the surrounding fluid was stagnant air at 100 kPa and 300 K. For the numerical analysis, a square computational domain was created, assuming a height of 0.084 meters above the solid surface. At the center of the domain, a thin, rigid blade measuring 0.038 meters in length and 1 millimeter in thickness was intended to be vertically rotated, with the lower end of the blade placed 4 millimeters from the horizontal plate. The bottom boundary condition was a flat plate with a constant temperature of 320 K and no slip velocity components. Schematic from the considered domain is shown in Fig. 1.Zero gauge pressure at the limits' outflow served as the boundary condition for the three remaining boundaries. The blade surfaces were subject to adiabatic boundary conditions with no-slip velocity components. A concentric circular segment with a radius of 0.04 meters was specified within the computational domain in order to replicate the blade's oscillation. In the numerical analysis, this subdomain which included the blade geometry was referred to as the moving (oscillating) section. In the calculations, the interface boundary condition was the circle that connected two subdomains. At the conclusion of the governing equations, specified boundary conditions were shown in equation form.

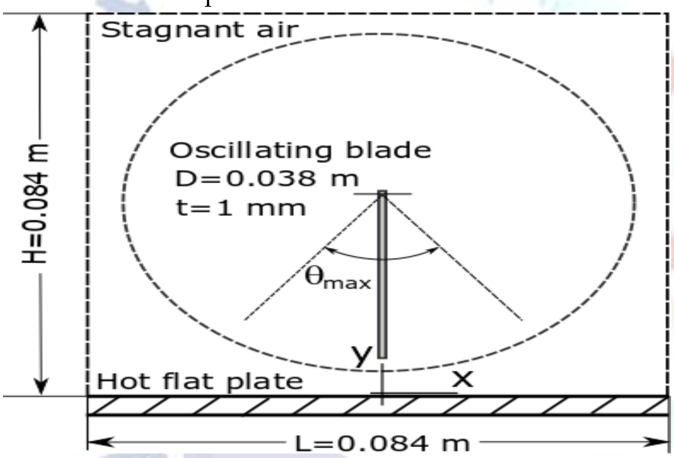


Figure 1. Schematic of the computational domain

Numerical solutions were found for the conservation equations of mass, momentum, and energy in both two-dimensional and transient forms. These equations can be expressed as follows for a fluid with constant physical characteristics and in the case of laminar flow:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

$$x=\pm\frac{L}{2}\to\frac{\partial p}{\partial x}=0,\quad T=T_\infty(for the backflow air)$$

$$y=H\to\frac{\partial p}{\partial y}=0,\quad T= \qquad y=0\to u=v=0,\quad T_w \quad (5)$$

$$at the balde surface:\ u=v=0,\quad \frac{\partial T}{1}$$

$$\frac{\partial u}{2}\quad \frac{\partial v}{2}\quad \frac{\partial T}{2}\quad \frac{\partial p}{2}$$

The commercial program ANSYS Fluent 6.3 was used for the numerical analysis. Green-Gauss cells were used to assess temperature and velocity gradients. The analysis employed a pressure-based solver with a second-order implicit formulation. Using the SIMPLE approach, pressure-velocity coupling was achieved, and the conversation equations' residuals met the convergence criterion of fewer than 10^{-3}.

$$\theta(t)=\theta_{max}\sin\left(\frac{2\pi}{\tau}t\right) \quad (6)$$

For a period with periodicity and amplitude of τ = 0.1 Sec and ^{i}max = 30°, respectively, Fig. 2 displays the blade velocity and its angular location. The graphic that is necessary for the numerical computations also displays discretized values of the angular velocity. At this sample representation, the time increment value is 0.05τ. In the transient numerical analysis, discretized angular velocity values were applied successively as the blade rotational velocity across the designated time period.

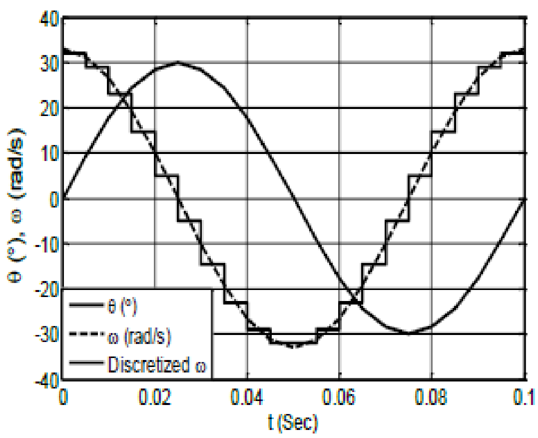


Figure 2. Variations of the angular velocity and position of the oscillating blade

3. TIME STEP SUFFICIENCY, GRID INDEPENDENCE, AND RESULT VALIDATION

An organized grid independence process was carried out in order to employ a suitable mesh size in the numerical analysis. The mesh size was raised by a factor of 1.2 in the normal direction, even though the first mesh line was 0.25 mm from the plate surface. Following a number of layers with progressively larger dimensions, the remaining portion of the domain produced mesh with a consistent size that was nearly identical to the final layer. General features of the created mesh are shown in Fig. 3, which has somewhat fewer points for simplicity's sake.

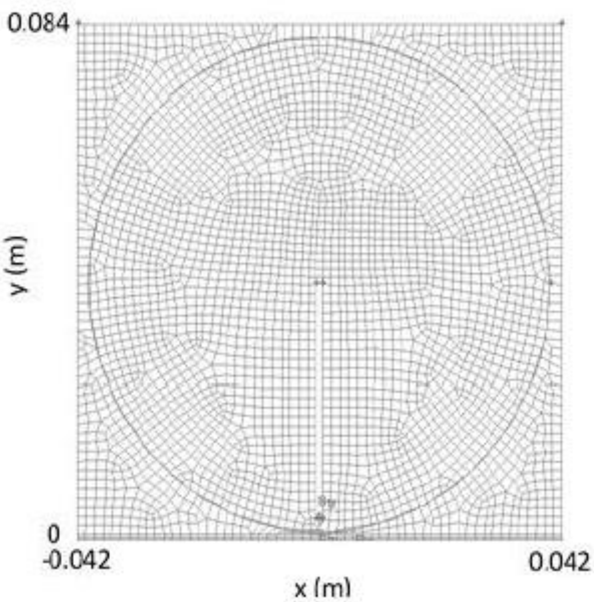


Figure 3. Schematic of generated grid with a fewer grid points

The findings indicate that a mesh size of 1.5 mm for the domain's interior portion should result in a lower average heat transfer coefficient. For the majority of the domain, it slightly increases when the mesh size is set to 1 mm. For the main portion of the computational domain, however, extremely close values are achieved when the mesh sizes of 0.5 mm and 0.25 mm are used. In contrast, the quantity of grid points Thus, in the primary study, a boundary layer mesh measuring 0.25 mm in the area around the plate and 0.5 mm in the inner part of the domain were chosen. It should be noted that further reducing the boundary layer mesh size did not significantly alter the results.

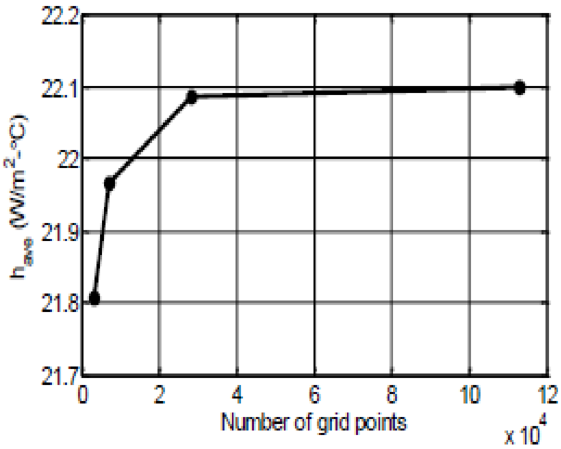


Figure 4. Average convective heat transfer coefficient over the plate for different grids, $\theta_{max} = \pi/6$, $Re_D = 6240$, $d/D = 0.105$

Discrete angular velocity data were used in the analysis, as shown in Fig. 2, and were determined by the chosen time period. Several numbers, including 0.1τ, 0.05τ, 0.025τ, and 0.0125τ, were subjected to numerical analysis in order to determine an appropriate size for the time step. As seen in Fig. 5, the fluctuation of the convective heat transfer coefficient across the plate was calculated for every time step size. This graphic shows that the chosen time step size a substantial impact on the outcomes. A significantly different distribution of heat transmission over the plate is predicted by the greatest time step size, 0.1τ.

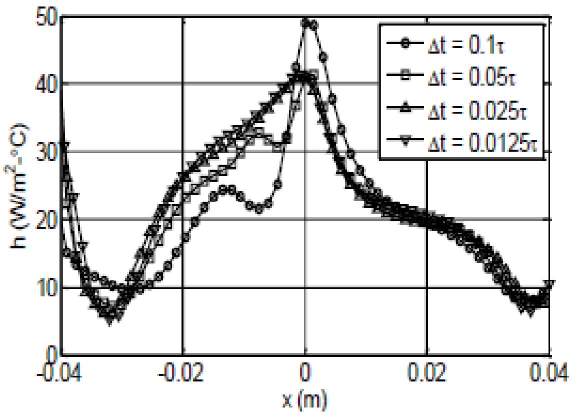


Figure 5. Convective heat transfer coefficient distributions using different time steps, $\theta_{max} = \pi/6$, $Re_D = 6240$, $d/D = 0.105$, $\tau = 0.1$ Sec.

After roughly four cycles of the blade oscillation, a periodic flow field was created within the domain as a result of the results and the deterioration of the original circumstances. Furthermore, when the plate's length was doubled, no discernible change in the distribution of convective heat transfer over it was found. With the exception of the fact that the left end of the plate's convective heat transfer coefficient's abrupt increase was moved to a comparable location. In essence, the backflow entering the domain from the left boundary was the immediate cause of this surge. Additionally, the number of oscillation periods needed for the starting condition's depreciation was somewhat enhanced by lengthening the plate. There was no comparable study in the published literature to assess the precision of the numerical analysis used in this investigation. As a result, a few findings from Pourgholam et al.'s study [13] were chosen for comparison. The influence of a revolving blade placed in the middle of the channel on the convective heat transfer from the walls is investigated in this study, which focuses on a laminar and constant flow between two parallel plates. According to the hydraulic diameter of the channel, the undisturbed flow's Reynolds number was 50. The narrow blade had a rotating velocity of 300 rpm and was one-sixth the hydraulic diameter of the channel.

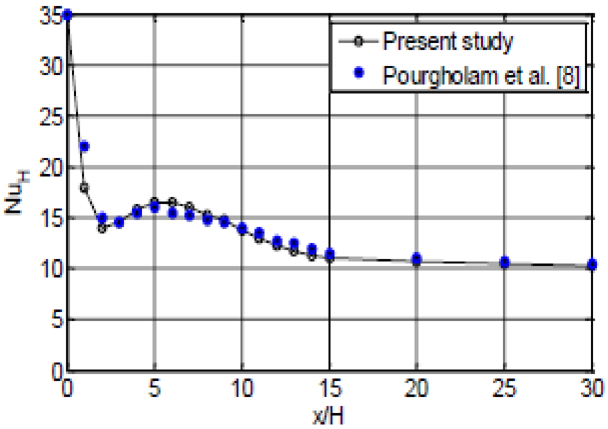


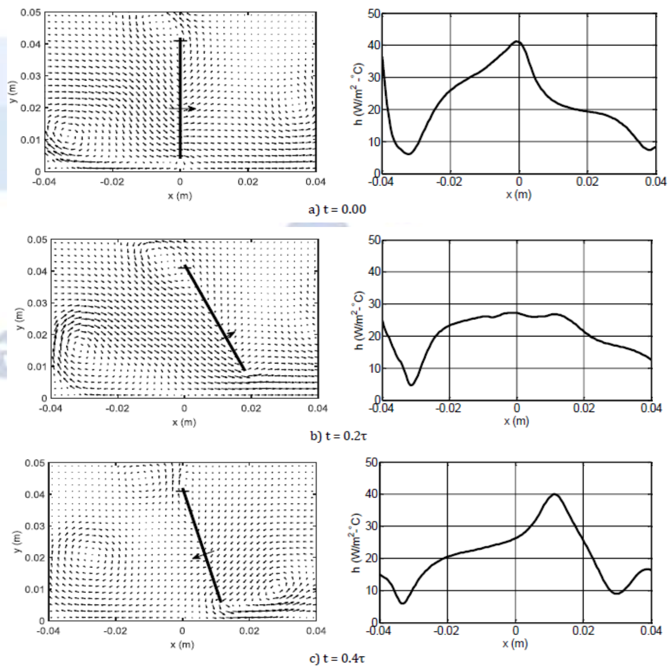
Figure 6. Comparison of the Nusselt number distributions.

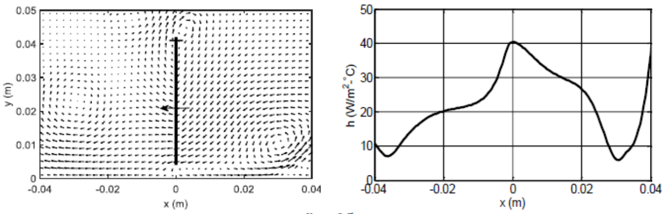
4. RESULTS AND DISCUSSION

At different points during the blade oscillation period, the distribution of convective heat transfer from the plate under the influence of the oscillating blade varies. The specifics of the flow field may also be helpful in gaining an understanding of the distribution of transient heat transfer. Thus, in this part, the flow field and convective heat transfer across the plate are examined in detail. The impact of various parameters on the average distribution of heat transmission is next examined.

4.1. Distribution of heat transfer and transient flow field

After a few oscillation cycles, as was indicated in the previous section, the effect of the beginning conditions diminishes and a periodic flow field forms inside the computational area. Figure 7 displays the velocity vectors at a very small number of domain points and at various time instants throughout a half-period of the blade oscillation. The beginning point of the period is indicated by t = 0 in this figure, which is the instant the blade crosses the upright position during its counterclockwise rotation. As a result, the flow behind the blade has a tendency to go through the space created between the target plate and the blade tip. As the blade slows down and eventually comes to a stop at the conclusion of its counterclockwise circle, the flow through this opening becomes more intense. Consistent flows form at the front and rear of the blade at a time instant of 0.4τ when it rotates in a clockwise manner. As the gap size is reduced, the opposing flow through the gap gradually gets more intense. At the final instant of 0.5τ, the blade is once more upright but rotating clockwise, and the formed flow field is inversely equal to the initial one. Fig. 7 also depicts convective heat transport from the plate at various time instants, which is consistent with the flow field indicated. According to this figure, at time instant t = 0, convection is initially higher over the central region, particularly at the blade's backside. The heat transfer distribution at the plate's left end likewise exhibits a noticeable increase. This increase is caused by the circulating flow pattern that exists there and, consequently, the flow that enters the area. As the blade rotates counterclockwise and stays out of the core zone, the convection strength over this area rapidly drops.





d) t = 0.5τ

Figure 7. Velocity vectors and convective heat transfer coefficient at some points and different time instants of a half period of oscillation, $\theta_{max} = \pi/6$, $Re_D = 6240$, $d/D = 0.105$, $\tau = 0.1$ Sec.

4.2. How various characteristics affect the distribution of convective heat transfer

A number of variables affect the distribution of convective heat transfer caused by an oscillating vertical blade. The heat transfer coefficient can be thought of as a function of a number of significant characteristics, including

$$h = f(v, k, D, d, x, \theta_{max}, \omega) \quad (8)$$

$$Nu_D = f'(Re_D, dD, xD, \theta max) \quad (9)$$

$$Nu_D = hDk, \; Re_D = D2\omega v \quad (10)$$

The convective heat transfer coefficient has distinct distributions at different times, as seen in Fig. 7. Together with the transient distribution, the average convection rate throughout an entire oscillation cycle may have practical significance and represent an increase in heat transfer from the target plate. In order to show the primary findings, the average convective heat transfer coefficient was computed. The impact of oscillation amplitude on the Nusselt number distribution is seen in Fig. 8. According to this figure, for the smallest oscillation amplitude, the Nusselt number is larger only across a small portion of the plate's center. By increasing the oscillation amplitude, the average Nusselt number rises modestly over the core region but increases dramatically on both sides of the centerline. A uniform distribution of the Nusselt number throughout a sizable core region of the plate results from further increases in the oscillation amplitude.

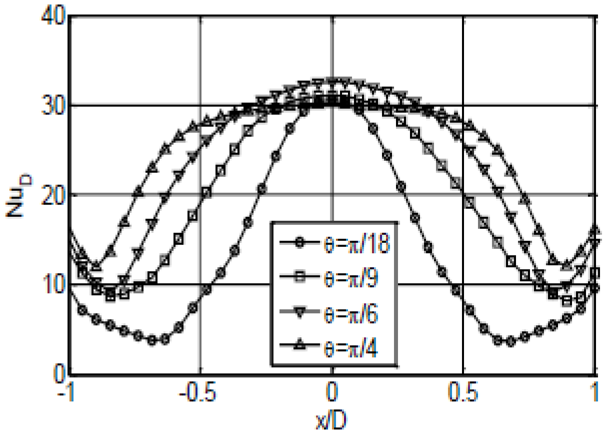


Figure 8. Average Nusselt number distribution, $d/D = 0.105$, $Re_D = 3120$

Fig. 9 illustrates how the rotating Reynolds number affects the Nusselt number distribution. As the Reynolds number is raised, this figure shows that the Nusselt number rises steadily throughout the plate, with the increase being more noticeable in the center. Eq. 10 uses the length and rotational velocity of the oscillating blade to calculate the rotational Reynolds number for air, the surrounding fluid with constant physical parameters. A larger rotational Reynolds number is the effect of increasing each of these two factors. A larger rotating Reynolds number indicates the development of a strong flow field within the domain, which raises the convective coefficient and, consequently, the distribution of the Nusselt number over the target plate.

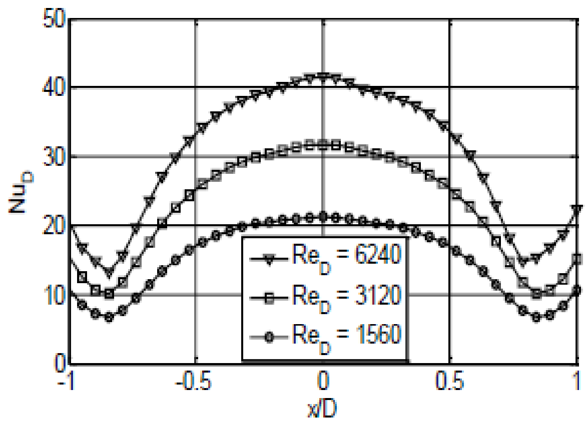


Figure 9. Average Nusselt number distribution, $d/D = 0.105$, $\theta_{max} = \pi/6$

This is because convective heat transfer is somewhat decreased in this situation due to a decrease in the flow intensity across the tip-to-plate gap. Similarly, the convective heat transfer rate increases marginally with blade length when the distance between the blade tip and the plate remains constant.

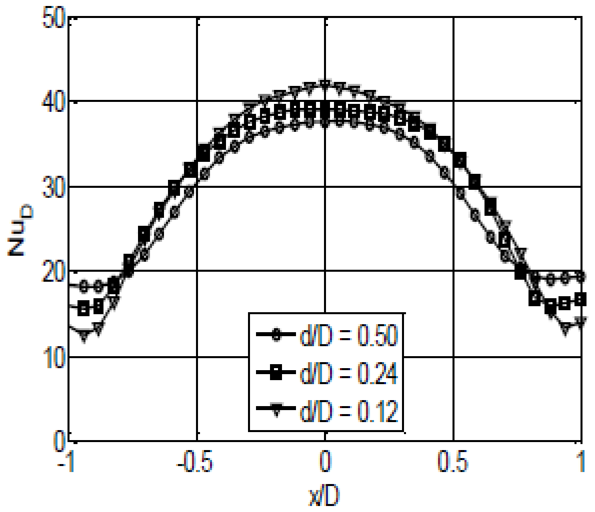


Figure 10. Average Nusselt number distribution, $Re_D = 5000$, $\theta_{max} = \pi/6$

5. CONCLUSION

Numerical research has been done on convective heat transfer from a flat plate when a vertical blade oscillates. Convective heat transfer has varying distributions over the plate at different times throughout an oscillation period, according to the data. When the oscillating blade moves in both directions from its upright position, the rate of heat transmission increases over the center of the plate. A bell-shaped distribution with its highest at the plate's center represents the average Nusselt number distribution across an entire oscillation cycle. As the oscillation's amplitude increases, the plate's surface area is impacted. In the meantime, over the center region, the convection rate stays nearly constant.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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