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International Journal for Modern Trends in Science and Technology, 9(05): 218-223, 2023
Copyright © 2023International Journal for Modern Trends in Science and Technology
ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0905035
Available online at: http://www.ijmtst.com/vol9issue05.html

Estimation of Natural Convection Heat Transfer Characteristics on Vertical Plate with Uniform Heat Flux

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To Cite this Article
M. Venkatesan, R. Prem Raj, B. Tamizharasan, B. Balaji and S.M. Meyvel. Estimation of Natural Convection Heat Transfer Characteristics on Vertical Plate with Uniform Heat Flux. International Journal for Modern Trends in Science and Technology 2023, 9(05), pp. 218-223. https://doi.org/10.46501/IJMTST0905035

Article Info
Received: 02 April 2023; Accepted: 04 May 2023; Published: 14 May 2023.

ABSTRACT

The convection mode of heat transfer that occurs as a natural phenomenon is influenced by variation in the condition of the body as well as the atmosphere. This work is carried out to study the temperature and convective heat transfer coefficient of a vertical flat surface i.e, an aluminum plate of size 1 meter of height and 0.5 meter of width, under constant heat flux values of 500 W/m2 and 1000 W/m2. The atmospheric cooling of the plate across the vertical and horizontal surfaces. The surface temperature and the flow velocity were theoretically calculated and also found through computational models for comparison. The maximum temperature of the plate was found at the top of the plate and its values are 514 K, for 1000 W/m2 and 402 K, for 500 W/m2. The results revealed that temperature is highest at the top of the plate as the transfer rate is low and the convective heat transfer coefficient at the top is lesser.

KEYWORDS:Convective heat transfer, Vertical plate, Constant heat flux, Natural convection, Computational analysis

INTRODUCTION

Natural convection mode of heat transfer from a vertical plate having constant heat flux is being investigated continuously as many natural thermal processes fall in this category like solar collectors, walls, windows, ducts, pipes and electronics packages apart from finding wide variety of applications in industries. These studies are related to improving the heat transfer rate. Convective type of heat transfer can be increased either through active or passive method[1]. Active methods involve engaging external energy sources, while the passive methods simply involve modifying the thermal properties of the working fluid or the flow geometry[2][3]. In such studies Prandtl number plays a vital role in determining various parameters.

In such an analysis report, the temperature and velocity profiles of the process are graphically illustrated for different Prandtl numbers. Moreover different parameters of flow and heat transfer are also derived only as the functions of Prandtl number [4].

In another work, transfer rate measurements were made locally for Rayleigh numbers that ranged around 1016 and water-bulk temperatures that changed from 45 – 120°F. The obtained data for laminar flow matched well with previously published empirical relation [5].

In an investigation, PIV (Particle Image Velocimetry) is applied to measure the thickness of the laminar boundary layer of nano-fluid (TiO_2/water) for natural convection heat transfer from horizontal and vertical flat plates having uniform heat flux. The report revealed two heat flux strength values of 3000 W/m^2 and 7000 W/m^2 [6].

Another study reports about glycerol flow with laminar boundary layer on stationary vertical plate, having constant heat flux. This study considers both plate-heating (i.e upward flow) and plate-cooling (i.e downward flow). The results showed that temperature variation had considerable impact on the heat transfer of the wall and also the impact was more on shear stress of the wall [7].

The slip effect of the vertical plate is also studied. This study covers both gas and liquid flows and their non – continuum effect on parameters such as temperature jump, wall slip-velocity, boundary layer thickness and wall shear stress [8].

An investigation was conducted on a vertical wall keeping temperature and heat flux constant. It was reported that for different heat-input conditions, the heat transfer coefficient varied [9]. Previous studies also provide works on the instability boundary layer's free heat convection [10]and unsteadiness of vertical plate's free heat convection [11].

MATERIALS AND METHODS HEAT TRANSFER PERFORMANCE

The procedure to be followed to calculate the performance of heat transfer from the vertical plate into the ambient air is shown below. The Nusselt number (Nu) is related to conductive and convective heat transfer, with the assumption that the air flow being laminar and the heat transfer taking place from the vertical wall surface to the air is through natural free-convection. In case of the heated vertical plate having constant heat flux the value of Nu is obtained by [9][12],

$$Nu = CRa^n \qquad (1)$$

$C = 0.59$ and $n = 0.25$ for $10^4 < Ra < 10^9$;

$C = 0.1$ and $n = 0.33$ for $10^9 > Ra < 10^{13}$

Eqn. (2) can be utilized to calculate Ra (Rayleigh number), which is related to parameters like buoyancy and thermal diffusivity of the heat transfer.

$$Ra = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} Pr \qquad (2)$$

Here, g = 9.81 (m/s^2); β refers to compressibility module (K^{-1}) ; and v refers to kinematic viscosity (m^2/s) of air; *Pr* refers to Prandtl number, ratio of momentum and thermal diffusivity; L refers to length (m), T_s and T_∞ are, respectively, the plate surface and ambient air temperature (27°C).

The convective heat flux and its coefficient can be calculated using Eqn. (3, 4).

$$Nu = \frac{h_{conv} L}{k_{air}} \qquad (3)$$

$$q_{conv} = h_{conv}(T_s - T_\infty) \qquad (4)$$

SURFACE TEMPERATURE

If the estimated value is assumed as the local heat transfer coefficient the temperature difference between the wall and the surrounding is approximately obtained from the following relation:

From Equation (4),

$$T_s - T_\infty = \frac{h_{conv}}{q_{conv}} \qquad (5)$$

Where, q_w refers to the uniform heat flux at the plate; h_y refers to the estimated value of the local convection coefficient; T_∞ refers to the ambient temperature; and T_y refers to the local surface temperature at a specified distance.

Then, the film-temperature can be calculated as

$$T_f = \frac{(T_s - T_\infty)}{2} + T_\infty \qquad (6)$$

and also, at T_f, the air properties can be evaluated.

SIMULATION MODEL

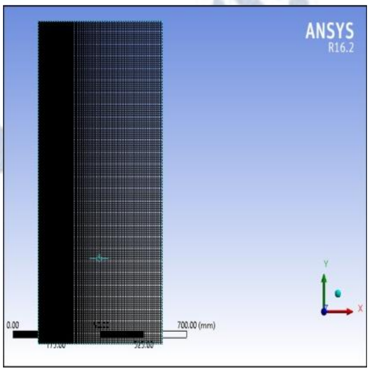


Fig. 1 Simulation model of vertical plate

To find the numerical solutions for the computational analysis (CA) work was done through FLUENT 6.0 software. For developing the model for the boundary layer of vertical plate of rectangular geometry with natural convectional mode of heat transfer, the governing equations were made under the assumptions of having: 2 dimensional, incompressible, laminar and steady flow. Also, the equations were solved by applying semi-implicit and 2nd order upwind techniques. To obtain the highest accuracy, 10 to 5 was taken as absolute criterion for residual monitor. Figure 1 shows the simulation model of vertical plate.

The dimensions of the experimental plate are 1 m of height and 0.5 m of width. The material of the plate was assumed as Aluminum, insulated on its back side and having an emissivity value of 0.05. The constant heat fluxes on the plate surface were taken as 500 $W/m^2$and 1000 W/m^2 for the study.

The assumptions for governing equations were:

The flow is 2D, incompressible, steady and laminar.

There is no heat loss through radiation.

The complete surface of the plate has invariably constant heat flux.

All the fluid-solid boundaries experience equal fluid-velocity like solid boundary (similar to no-slip condition)

All the fluid-solid boundaries experience equal fluid-temperature like solid boundary wall (similar to no-jump condition)

GOVERNING EQUATIONS

A steady two-dimensional natural-convection air flow along a vertical flat surface heated uniformly is assumed in this investigation. Figure 1 provides the flow configuration in which, x is a measurement of the horizontal distance in the direction normal to y from the surface. The gravity force actually acts in the negative y-direction. The ambient temperature ($T\infty$) is assumed to be constant. Here, u and v are respectively the x- and y-components of fluid velocity. The governing equations for the conservation of mass, momentum- conservation and energy-conservation are [13] given below:

Mass conservation:

$$\frac{\partial u}{\partial x} = \frac{\partial u}{\partial y} = 0 \qquad (7)$$

Momentum conservation

x – axis

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \qquad (8)$$

y – axis

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \qquad (9)$$

$$\frac{\partial P}{\partial x} = 0 \text{ since, } u \gg v$$

$$\frac{\partial P}{\partial y} = \frac{dP}{dy} = \frac{dP\infty}{dy} = -\rho\infty g \qquad (10)$$

Equation (9) becomes,

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -g(\rho\infty - \rho) + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \qquad (11)$$

Energy conservation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \infty\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (12)$$

The boundary conditions taken for a uniformly heated vertical plate are as follows:

$$\text{at } x = 0, u = v = 0, \dot{q}w = -k\frac{\partial T}{\partial x} + \dot{q}r \qquad (13)$$

$$\text{at } x \to \infty, u = v = 0 \text{ and } T = T_\infty$$

VALIDATION

The developed model is required to be validated for its accuracy before commencing numerical investigation. The predictions obtained from the model are compared with that of the correlations' results found in the literature in the case of vertical plates. The predicted Nusselt Numbers and surface temperature values are agreed well with the correlations of the past research obtained by [9][12]. Figure 2 shows the estimated and correlation values of good relation, hence the method could be preceded.

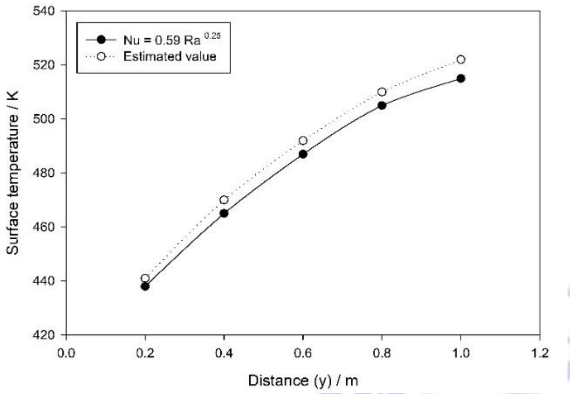


Fig. 2 Validation test

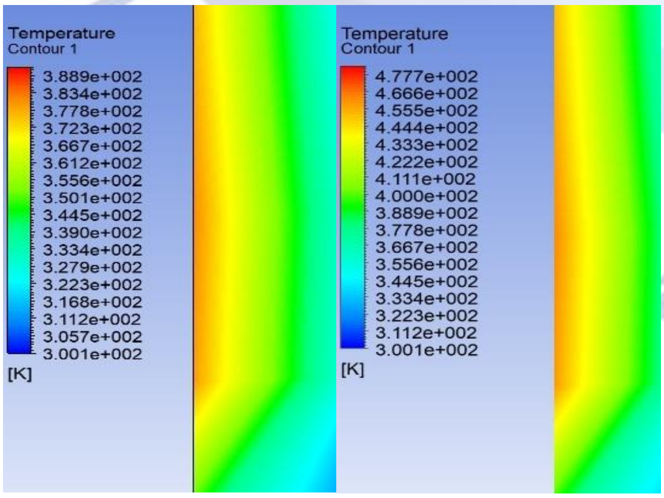
RESULTS AND DISCUSSION

As the flow of fluid is caused by the transfer of heat in natural convection mode, thermal and hydrodynamic problems are the same. Also, the fluid velocity on the surface of the plate should be zero taking no-slip condition of the boundary. Due to viscous friction of the boundary layer, the fluid velocity increases to the maximum level when moved away horizontally from the wall.

Plate temperature is highest at the top of the vertical plate while the coefficient of convective heat transfer is lesser. These values are vice versa at the bottom of the plate.

TEMPERATURE PROFILE

The simulated temperature profile of vertical plate for the constant heat flux of 500 W/m² and 1000 W/m² are shown in figure 3.

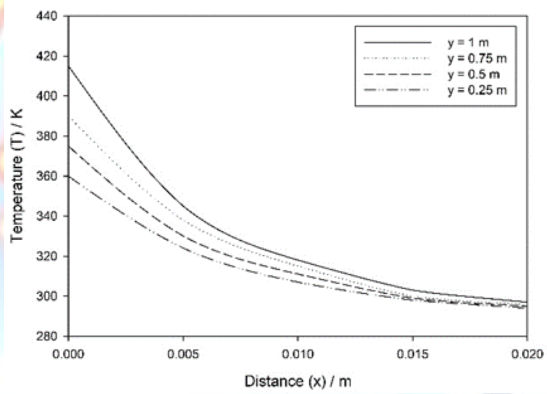


(a) (b)

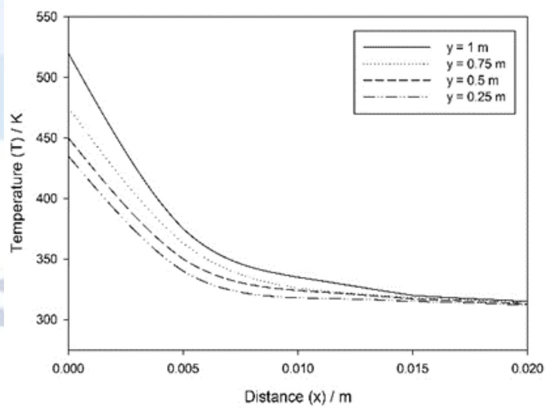
Fig. 3 Simulated temperature profile of vertical plate for constant heat flux of (a) 500 W/m² (b) 1000 W/m²

It is clear from the temperature profile that for any given heat flux value, the temperature of the heated plate increases vertically from the bottom. As the air-temperature is lesser at the bottom of the plate, the local temperature is also lesser at the bottom of the plate for any given heat flux value. In other words it can be said that as the distance increases from the bottom to the top of the plate, the air-temperature increases which results in increased plate temperature, but results in decreased convective heat-transfer coefficient. Due to the same reason convective heat-transfer coefficient at the bottom of the plate is lesser for any given heat flux value. The surrounding air-temperature beyond the thermal boundary of the heated plate is taken as 300 K.

The results were obtained assuming no-jump condition considering the plate to possess equal temperature at fluid-solid boundaries. The calculated temperatures from correlation are plotted in graph and are show in the figure 4.



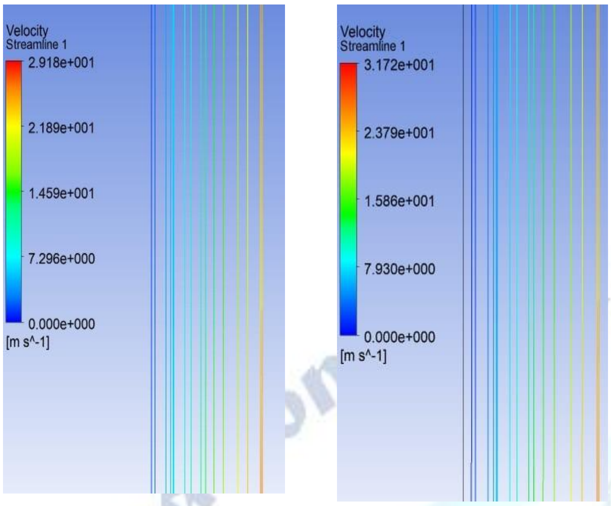
(a)



(b)

Fig. 4 Calculated temperature profile of vertical plate for constant heat flux of (a) 500 W/m² (b) 1000 W/m²

VELOCITY PROFILE



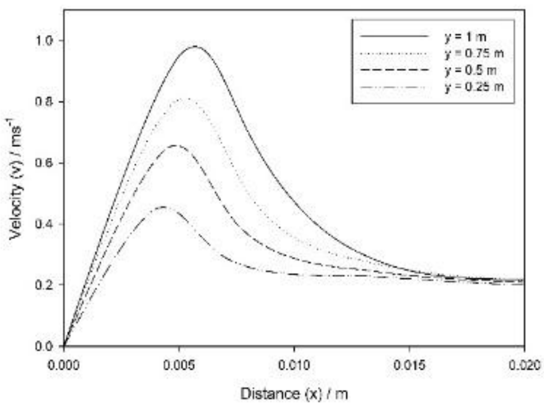
(a) (b)

Fig. 5 Simulated velocity profile of vertical plate for constant heat flux of (a) 500 W/m² (b) 1000 W/m²

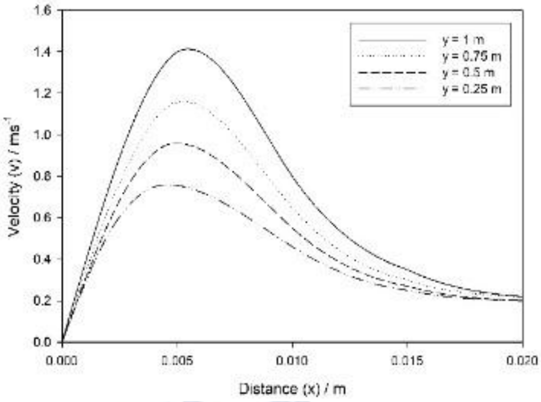
The simulated velocity profile of vertical plate for the constant heat flux of 500 W/m² and 1000 W/m² are shown in figure 5.

As discussed already, the velocity profile shows that the fluid velocity on the surface of the plate is nil (zero) due to the application of non-slip boundary condition.

However, the fluid-velocity gradually increases to the maximum value as the distance move away horizontally from the plate i.e moving away from the viscous-friction of the boundary layer. As the fluid is from the inactive zone, the air-velocity after crossing boundary layer is very minimum (0.07 & 0.1 m/s) which can be noticed at the bottom for both heat flux input values.



(a)



(b)

Fig. 6 Calculated velocity profile of vertical plate for constant heat flux of (a) 500 W/m² (b) 1000 W/m²

The calculated velocity profile for constant heat flux of 500 W/m²and 1000 W/m² are shown in figure 6.

CONCLUSION

This investigation involves study of natural convective mode heat transfer behaviour of a vertical plate under constant heat flux values of 500 W/m² and 1000 W/m². The theoretical and computational analysis were carried out to find the variation in the surface temperature and air velocity across different locations (distances at 0.2 m intervals) of the plate. It was observed that the 'distance' from the edge of the plate and the heat flux intensity can be taken as important factors that considerably influence the temperature of the plate surface. It was found that the temperature of the plate increases vertically from the bottom. The maximum temperature of the plate was found at the top of the plate and its values are 514 K, for 1000 W/m² and 402 K, for 500 W/m². This can be attributed to the increase in air temperature at the top of the plate. Also, the convective heat transfer coefficient at the top is lesser.

Conflict of interest statement

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

REFERENCES

[1] M. Raja, R. Vijayan, P. Dineshkumar, and M. Venkatesan, "Review on nanofluids characterization, heat transfer characteristics and applications," Renewable and Sustainable Energy Reviews, vol. 64, 2016, pp. 163–173, doi: 10.1016/j.rser.2016.05.079.

[2] M. P. Rajan, E. Surendhar, C. Tamilselvan, K. Thamaraiselvan, and M. Venkatesan, "Performance analysis of flat plate solar still with different passive techniques," International Journal of Advanced Science and Engineering Research, vol. 1, no. 1, 2017.

[3] J. V. kumar M. Raja, M.Venkatesan, "Experimental studies of Al2O3/water nanofluid in a double pipe heat exchanger with serrated twisted tape insert," International Journal of Applied Engineering Research, vol. 10, no. 1, 2015, pp. 662–668.

[4] A. Mitra, "Numerical Simulation on Laminar Free-Convection Flow and Heat Transfer over a Vertical Plate with Constant Heat Flux," Journal of mechanics of continua and mathematical sciences, vol. 10, no. 2, 2016, pp. 1487–1499, doi:10.26782/jmcms.2016.01.00001

[5] C. K. L. G. C. Vliet, "An Experimental Study of Turbulent Natural Convection Boundary Layers," ASME Journal of Heat and Mass Transfer, 2016, doi:10.1007/s00348-010-0838-8.

[6] R. Parizad, S. Rashidi, and J. A. Esfahani, "Experimental investigation of nanofluid free convection over the vertical and horizontal flat plates with uniform heat flux by PIV," Advanced Powder Technology., no.1 , 2016, pp. 1–11, doi: 10.1016/j.apt.2015.12.011.

[7] A. Pantokratoras, "Laminar free-convection in glycerol with variable physical properties adjacent to a vertical plate with uniform heat flux," International Journal of Heat and Mass Transfer, vol. 46, 2003, pp. 1675–1678, doi: 10.1016/S0017-9310(02)00439-8

[8] K. Cao and J. Baker, "Slip effects on mixed convective flow and heat transfer from a vertical plate," International Journal of Heat and Mass Transfer., vol. 52, no. 15–16, 2009, pp. 3829–3841, doi: 10.1016/j.ijheatmasstransfer.2009.02.013.

[9] M. Venkatesan, M. Raja, S. Sivalaksmi, and S. Suresh, "Experimental study of heat transfer coefficients on red clay brick wall," Journal of Thermal Analysis and Calorimetry, no. 1, 2021, doi: 10.1007/s10973-021-10896-y

[10] T. Aberra, S. W. Armfield, M. Behnia, and G. D. Mcbain, "Boundary layer instability of the natural convection flow on a uniformly heated vertical plate," International Journal of Heat and Mass Transfer, vol. 55, no. 21–22, 2012, pp. 6097–6108, doi: 10.1016/j.ijheatmasstransfer.2012.06.023

[11] M. Schaub, M. Kriegel, and S. Brandt, "Experimental investigation of heat transfer by unsteady natural convection at a vertical flat plate," International Journal of Heat and Mass Transfer, vol. 136, 2019, pp. 1186–1198, doi: 10.1016/j.ijheatmasstransfer.2019.03.089

[12] M. Venkatesan M, Raja and S. S. P. Dineshkumar, "Experimental Study of Thermal Performance on Waste In - filled Building Wall Construction," International Journal of Thermophyscs, vol. 43, no. 10, 2022, pp. 1–20, doi: 10.1007/s10765-022-03082-1

[13] Cengel, Heat and Mass Transfer: Fundamentals & applications. 5th edition. Mcgrew Hill Education. Newyork. NY.,2015.