

Computation of convective heat transfer coefficient for finite inclined and isothermal plate

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Nomenclature

B_0 - magnetic flux density, Wb /m²; C_p - specific heat constant pressure, J /kg °C; f - Reduced stream function defined by Eq. 9; Ec - Eckert number; g - gravitational acceleration, m/s²; Gr_x - Grashof number, $Gr_x = \frac{g\beta\Delta T x^3}{\nu^2}$;

L - plate length, m; M - dimensionless magnetic parameter;

Nu_x - local Nusselt number, $Nu_x = \frac{hx}{\lambda}$; P - Pressure, Pa;

Pr - Prandtl number, $Pr = \frac{\nu}{\alpha}$; Ra_x - Rayleigh number

$Ra_x = \frac{g\beta\Delta T x^3}{\nu\alpha}$; T - temperature, °C; U_c - characteristic velocity; u, v - direction velocity, m/s; x, y - axial, normal coordinates

greek symbols –
 α - effective thermal diffusivity, m²/s; β - coefficient of thermal expansion, °C⁻¹; δ_T - thermal boundary layer thickness, m; θ - dimensionless temperature defined in Eq. 9;

η - similarity variable; ν - kinematics viscosity, m²/s; ζ - nonsimilar parameter defined by Eq. 13; ρ - fluid density, kg/m³; σ - fluid electrical conductivity, A/V m; φ - angle inclination, °; ψ - stream function, m²/s)

superscripts –

' - differentiation with respect to η

subscripts –

∞ - conditions far away from the surface; w - Wall surface;

I,II - region I or II; x - local; d - global

1. Introduction

The study of the relatively new flow problems which involve the interaction of several phenomena has a wide range of application in the field of science and technology. For example, the presence of a magnetic field with dissipation effects in these flows is often encountered. It finds many applications in the systems of renewable energy or in food processing where plates of finite dimensions with arbitrary inclination emitted the heat flux transfer. Some works have been conducted in this area and focused on the inclined plates [1-8].

The studies of the natural convection under the influence of a magnetic field adjacent to a semi-infinite plate were investigated extensively [9-18]. More realistic plate expressed with finite dimensions has received little atten-

tion, compared with the idealized or semi-infinite plates. Great discrepancies are observed between the experimental results and the theoretical calculations based on the concept of semi-infinite boundary layers, fig.1. In the laminar range, more than 45% of error is found for inclined plates, as reported by Lewandowski and Radziemska [19].

Furthermore and without succeeding, tentative attempts are carried out to reduce the differences observed, by increasing accuracy or by defining simplified assumptions more accurately. The right way is rather to attribute these differences to the inappropriate physical model and the research of a new model becomes obvious. Based on some simplifications, quasi-analytical solution was developed in Lewandowski [20]. Gosh and Pop [21] present a new approach for the finite dimensions rotating plates taking into account the MHD natural convection.

The physical and classical model of convective heat transfer with or without magnetic field was proposed by Schmidt and Beckmann; it was obtained on a basis of experimental results of visualization of the boundary thermal layer on a vertical isothermal plate (Fig. 1, a). The same model has been also adopted for a description of the results obtained with inclined (Fig. 1, b) and horizontal (Fig. 1, c) plates. This similar model has also been based on a homogeneous boundary layer, increasing on a semi-infinite flat surface and which is similar to the forced convection in the boundary layer shape. Fig. 1 presents a graphical interpretation of this model.

For plate with finite dimensions, two boundary layers are developed naturally from the two leading edges. This really and physically flow is corroborated with experimental investigations.

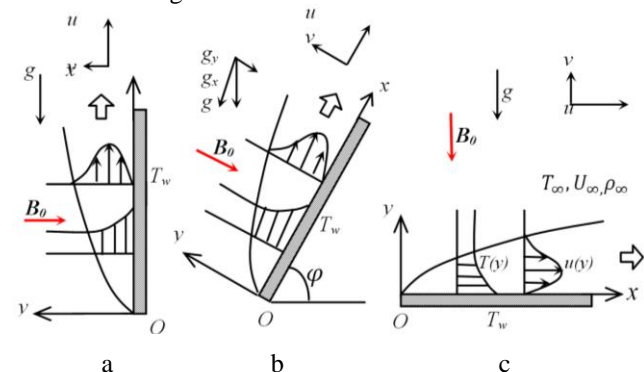


Fig. 1 Classical Model of free convection heat transfer from vertical (a), inclined (b) and horizontal (c) plate, (Schmidt and Beckmann [22])

In order to obtain a basic insight into the flows over slightly inclined plates, Kimura et al.[23] carried out flow visualizations using dye with a 50-mm-wide test plate and heating fluxes were $q = 1000\text{W/m}^2$, and the Rayleigh number was kept constant as $Ra = 6 \times 10^7$ and the representative results are shown in Fig. 2. To make the flow visible, Uranin was utilized as a dye marker, and the dye was released slowly from the slits flush-mounted on both leading edges of the plate. The photographs were taken from the side of the test plate by varying the inclination angle from $\varphi = 0$ (horizontal) to 15° at 5° intervals.

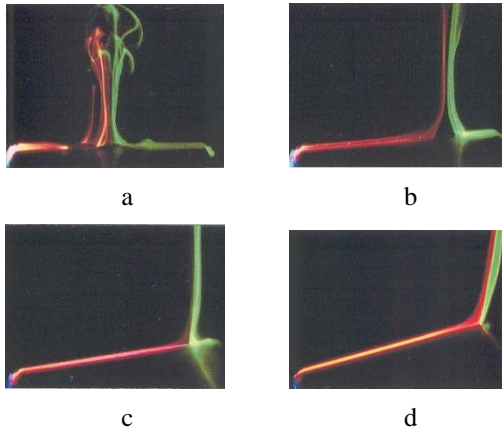


Fig. 2 Visual photographs of free convection heat transfer from an inclined isothermal finite plate: a - $\varphi = 0^\circ$; b - $\varphi = 5^\circ$; c - $\varphi = 10^\circ$; d - $\varphi = 15^\circ$ (Kimura et al. [23])

Then, the appropriate model shows two separate and distinguished regions with different fluid motions. In the suggested model (Fig. 3), the transition from one case to other proceeds together with the displacement of the separation point. Thus, the case of the inclined plate is virtually a general model concerning plate arbitrary oriented in unlimited space (Fig. 3.(b)) in which vertical (Fig. 3.(a)) and horizontal (Fig. 3.(c)) positions of plates constitute only specific cases. In the first region, the direction of fluid flow inside the boundary layer and parallel to the plate buoyancy force component converge, while in the second one these directions are opposite.

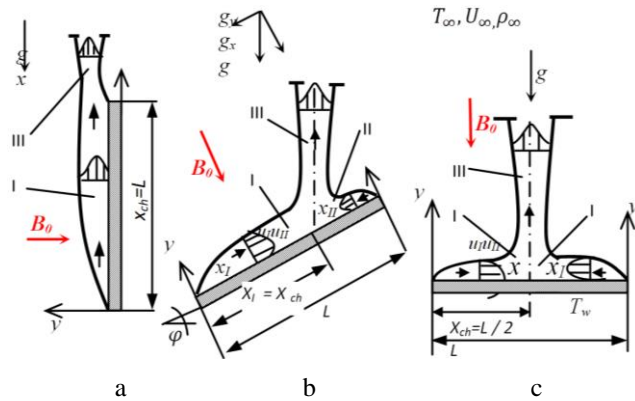


Fig. 3 Realistic model of free convection for vertical (a), inclined (b) and horizontal (c) plate

According to this pattern model, the streamlines are radial, and fluid flows toward a point at the centre of the plate where the boundary layer transforms into a

plume. The versatility of the suggested model consist of the fact that a change in surface inclination angle results in fluent changes of the participation of regions I and II in the heat exchange, whereas participation of region III remains constant. For the vertical plate, the differences between regions I and II gradually disappear. In the final effect of horizontal plates, two symmetrical boundary layers exist, growing from each edge (region I = region II) and transforming at the separation point into free stream heat convection (plume). On the other hand, in the case of vertical plate the model is identical to the hitherto applied one, because then only one boundary layer appears (region II = 0) subsequently converting into a wake and next into a plume (region III).

To our knowledge, exclusive investigation of Gosh and Pop [21], this problem rose above, has not received any attention in the literature. All works have been published and devoted to MHD free convection flows are based on the Schmidt and Beckmann model, which the semi-infinite concept is applied.

Owing to the visualization of the two boundary layers, the purpose of this paper is to highlight some numerical results for MHD natural convection over isothermal and an inclined plate of finite dimensions and taking into account the magnetic dissipation.

2. Mathematical analysis

Using the proposed general model as it is shown in (Fig. 3, b), which encompasses all angles inclination, and as discussed previously, we assume that due to the inclination of the plate, the boundary layer behavior permit to obtain two main flow (regions I and II), one frame at each leading edge.

We consider the steady, laminar, MHD free convection flow from a finite flat plate of length L , which is inclined with an angle φ from the horizontal. With x coordinate is measured from the leading of each edge of the plate and the coordinate is measured normally from the plate to the fluid, the gravitational acceleration g is acting downward and a magnetic field of uniform strength B_0 is applied in the y direction which is normal to the flow direction. Further, the fluid is assumed to be Newtonian and electrically conducting. The temperature of the surface is held uniform T_w which is higher than the ambient temperature T_∞ . The thermo-physical properties of the fluid are assumed to be constant except for the density variation that induces the buoyancy force.

With this assumption and the application of the Oberbeck-Boussinesq approximation, the governing conservation equations for laminar boundary layer free convection flow can be written as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 ; \tag{1}$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2} - \frac{1}{\rho} \frac{\partial P}{\partial x} \pm g \beta (T - T_\infty) \sin \varphi - \frac{\sigma B_0^2}{\rho} u ; \tag{2}$$

$$0 = -\frac{1}{\rho} \frac{\partial P}{\partial y} + g\beta(T - T_\infty)\cos\varphi; \quad (3)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \frac{\sigma B_0^2}{\rho c_p} u^2, \quad (4)$$

where \pm signs are for region I and region II, respectively; β is the coefficient of thermal expansion; σ is the electrical conductivity; ν is the kinematic viscosity; α is the thermal diffusivity and C_p is the specific heat capacity of the fluid, and ρ is the density of the fluid.

It must be pointed out, however, that P is the static pressure difference induced by the buoyancy force (i.e. $P = 0$ outside the boundary layer). The x -momentum and y -momentum equations, Eq. (2) and Eq. (3), can be combined with integration for finding the buoyancy induced streamwise pressure gradient from the Eq. (3) as:

$$-\frac{1}{\rho} \frac{\partial P}{\partial x} = g\beta\cos\varphi \frac{\partial}{\partial x} \int_y^\delta (T - T_\infty) dy. \quad (5)$$

This leads to use only the transformed Eq. (2):

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2} + g\beta\cos\varphi \frac{\partial}{\partial x} \int_y^\delta (T - T_\infty) dy \pm \pm g\beta(T - T_\infty)\sin\varphi - \frac{\sigma B_0^2}{\rho} u. \quad (6)$$

The boundary conditions are defined as follow:

$$\begin{aligned} \text{At } y = 0: u = 0, v = 0 \text{ and } T = T_w \\ \text{for } y \rightarrow \infty \text{ (or } y = \delta): u = 0, v = 0 \\ \text{and } T \rightarrow T_\infty. \end{aligned} \quad (7)$$

It is noted here that Eq. (6) reduced to that for a

$$f''' + 3ff'' - f'^2 \pm \xi\theta - Mf' + \frac{1}{5} \left[2\eta\theta + 2 \int_\eta^\infty \theta d\eta + 3\xi \int_\eta^\infty \frac{\partial\theta}{\partial\xi} d\eta \right] = 3\xi \left[f' \frac{\partial f'}{\partial\xi} - f'' \frac{\partial f}{\partial\xi} \right]; \quad (10)$$

$$\frac{1}{Pr} \theta'' + 3f\theta' + 5ME_c f'^2 = 3\xi \left[f' \frac{\partial\theta}{\partial\xi} - \theta' \frac{\partial f}{\partial\xi} \right] \quad (11)$$

with the boundary conditions:

$$\left. \begin{aligned} f(\xi, 0) = f'(\xi, 0) = f''(\xi, \infty) = 0; \\ \theta(\xi, 0) = 1, \theta(\xi, \infty) = 0. \end{aligned} \right\} \quad (12)$$

In the foregoing equations, the primes denote partial differentiations with respect to η , Pr is the Prandtl number, M is the magnetic parameter and E_c is the Eckert number defined respectively as:

$$Pr = \frac{\nu}{\alpha}; M = \frac{\sigma B_0 L x^2}{\rho U_c \left(\frac{Gr_x \times \cos\varphi}{5} \right)^{\frac{-1}{2}}}; E_c = \frac{5U_c^2 (Gr \cos\varphi)}{c_p (T_w - T_\infty) x^2},$$

vertical plate without the buoyancy-induced pressure gradient term when $\varphi = 90^\circ$ and to that for a horizontal plate without the buoyancy force term when $\varphi = 0^\circ$. Owing to the inclination of the plate, the boundary layer is not in the similarity form.

The system of Eq. (4), Eq. (6) and Eq. (7) will be transformed from (x, y) coordinates to the dimensionless coordinates $\xi = \xi(x), \eta(x, y)$ by introducing the following transformations used by Chen [24] for $0^\circ \leq \varphi < 90^\circ$:

$$\xi = \xi(x), \eta = \frac{y}{\xi(x)} = \frac{y}{x} \left(\frac{Gr_x \times \cos\varphi}{5} \right)^{\frac{1}{5}}, \quad (8)$$

where ξ depending only on x , is the non-similar parameter and η is a pseudo-similarity variable and Gr_x is the local

Grashof number defined as $Gr_x = \frac{g\beta\Delta T x^3}{\nu^2}$. For a similar

boundary layer, $\xi = 0$ and η reduces to a true similarity variable. One also introduces a reduced stream function $f(\xi, \eta)$ and a dimensionless temperature $\theta(\xi, \eta)$ defined as the same in Ref [24], respectively, such as:

$$\left. \begin{aligned} f(\xi, \eta) = \frac{\psi(x, y)}{5\nu(Gr_x \times \cos\varphi / 5)^{\frac{1}{5}}}, \\ \theta(\xi, \eta) = \frac{T - T_\infty}{T_w - T_\infty} \end{aligned} \right\} \quad (9)$$

where ψ is the stream function which satisfies the continuity equation and is related to the velocity components in the

usual way as $u = \frac{\partial\psi}{\partial y}$ and $v = -\frac{\partial\psi}{\partial x}$. Thus, the following

equations are obtained:

where: $U_c = \sqrt{g\beta\Delta T}$ and ξ is found to have the following expression:

$$\xi(x) = \left(\frac{Gr_x \times \cos\varphi}{5} \right)^{\frac{1}{5}} \tan\varphi. \quad (13)$$

This finding can be judiciously exploited to determine the velocity and the temperature profiles in the two regions. Eqs. (10-12) are valid for regions I and II with only difference in the signs.

As first approximation, we can delete the derivatives of ξ . Accurate solutions of the system can be checked with better approximation as prescribed in the two-level method.

$$f''' + 3ff'' - f'^2 \pm \xi\theta - Mf' + \frac{1}{5} \left[2\eta\theta + 2 \int_\eta^\infty \theta d\eta \right] = 0; \quad (14)$$

$$\frac{1}{Pr} \theta'' + 3f\theta' + 5ME_c f'^2 = 0. \quad (15)$$

3. Results and discussion

The set of Eq. (14) and Eq. (15), with the boundary conditions (12), which are valid for $0^\circ \leq \varphi < 90^\circ$, have been solved numerically, first reduced to a system of first-order differential equations which are then expressed in the finite-difference form and solved along with their boundary conditions by an iterative scheme. We can check the accuracy of the assumed missing initial condition, by comparing the calculated value of the different variables at the terminal point with the given value by the existence of the difference in improved values the missing initial conditions must be obtained.

It should be noted that the calculations are conducted for each region separately. Further, the separation point is estimated by the approximate result from the analytical procedure of Lewandowski [20] depending mainly on the angle of inclination. For any Rayleigh number, a least squares polynomial approximation is found as the

best fitting up the four degree to represent the curve $\zeta - \varphi$.

In order to gain physical insight, the velocity and temperature profiles against the dimensionless position η , for the both regions I and II, have been discussed by assigning numerical values to the parameter, encountered in the problem, i.e. numerical calculations were carried out for different values of angle inclination, Grashof number, Prandtl number, magnetic field parameter M , Eckert number E_c and their effects on flow and heat transfer characteristics are analyzed graphically.

It note that, in order to shown and analyzed the difference between the two regions I and II, these curves are plotted together at the same time in Figs. 4-12.

Figs. 4, a, b – 6, a, b depict the influence of inclination of the plate on the boundary layer of both regions I and II. Analysis of the visualization photographs gives evidence that for the horizontal surface ($\varphi = 0^\circ$), the boundary layers grow identically from opposite leading edges for that reason the Fig. 4, a, b shows confound in the velocity and temperature distribution for both region I and II.

It is seen in Fig. 5, a, b, that at increased inclination angle φ , the velocity profile in the first region grows

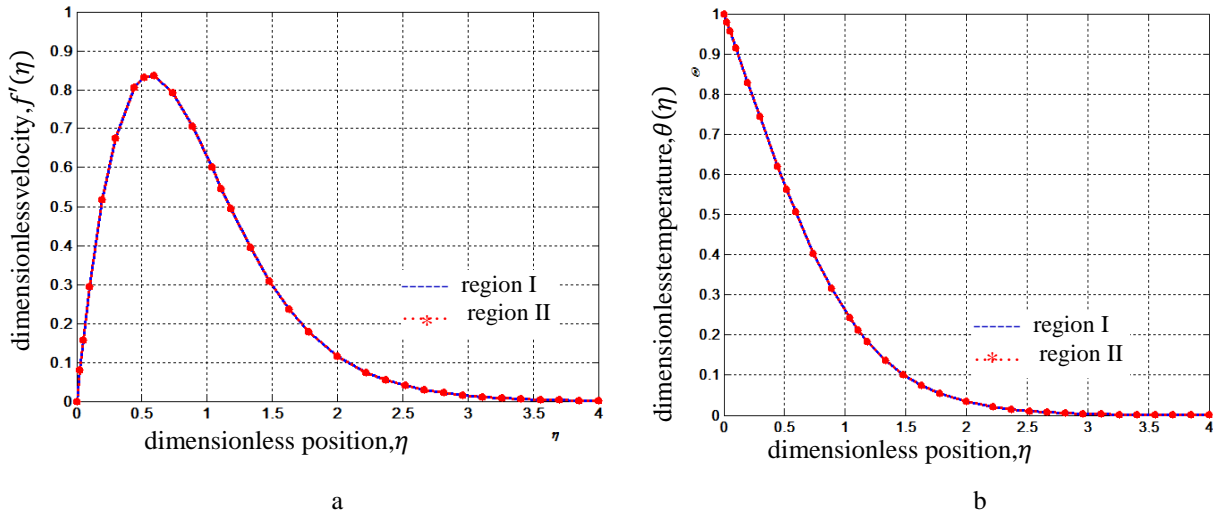


Fig. 4 Velocity a) and temperature b) distributions against η for horizontal plate ($\varphi = 0^\circ$), $Pr = 0.72$, $Gr = 0.5 \cdot 10^3$ and $M = 0$

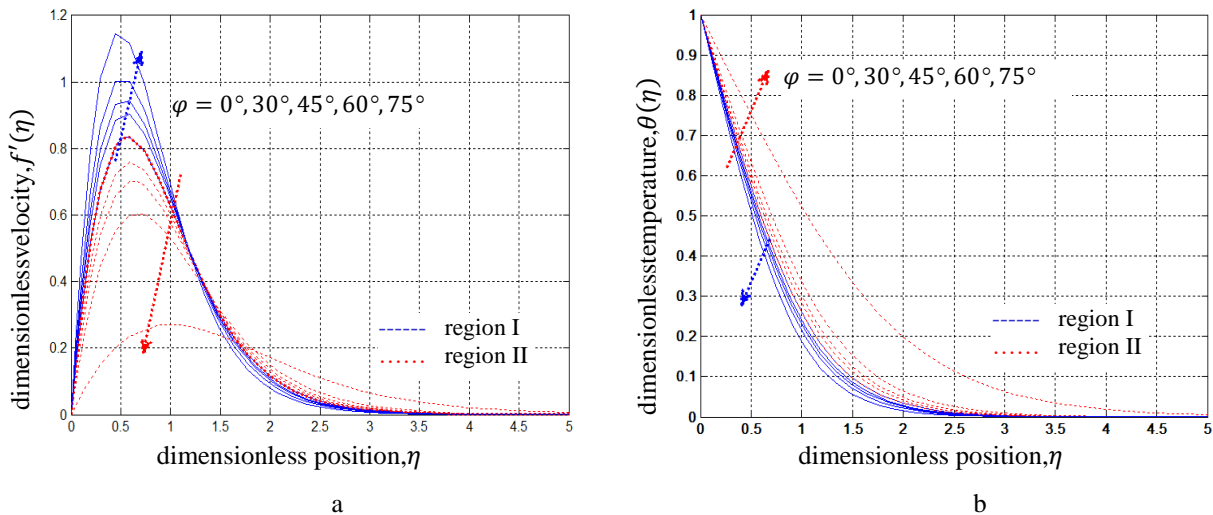
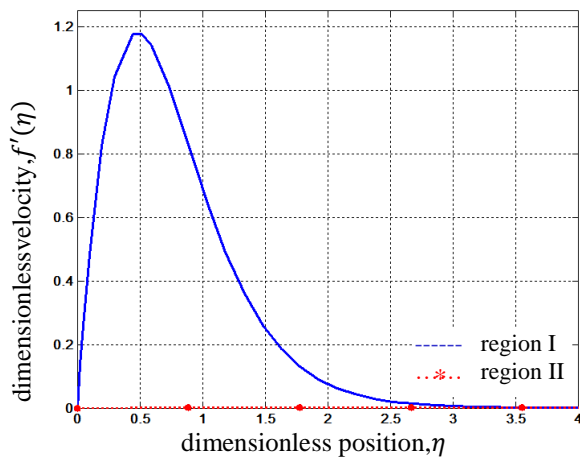


Fig. 5 Velocity a) and temperature b) distributions against η for different inclination angle values, $Pr = 0.72$, $Gr = 0.5 \cdot 10^3$ and $M = 0$

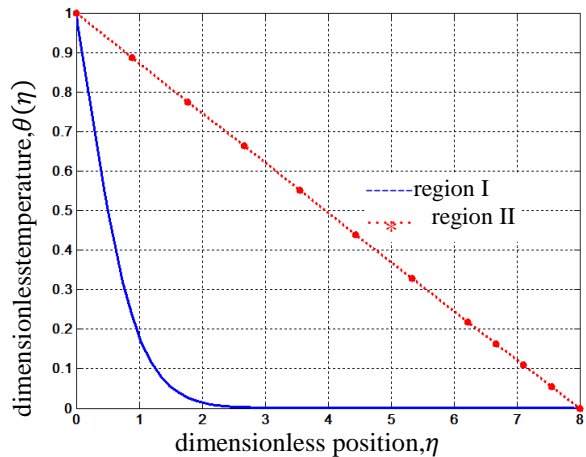
more and more than the second region, which decrease more and more until that the velocity disappear because the separation point of boundary layers, through which passes the centerline, move to one (trailing) edge and the opposite boundary layers (identical for the horizontal case) begin to differ increasingly from each other. The influence of the angle of inclination on the fluid temperature shows that the thermal boundary layer decreases in the first region and increase in the second region with the increase of the angle of inclination of the plate.

In figures Fig. 6, a, b for inclination near to vertical ($\varphi = 76.86^\circ$), it is clear that just the first region exists which was dominating the free convection heat transfer flow because the second region was disappear. The velocity



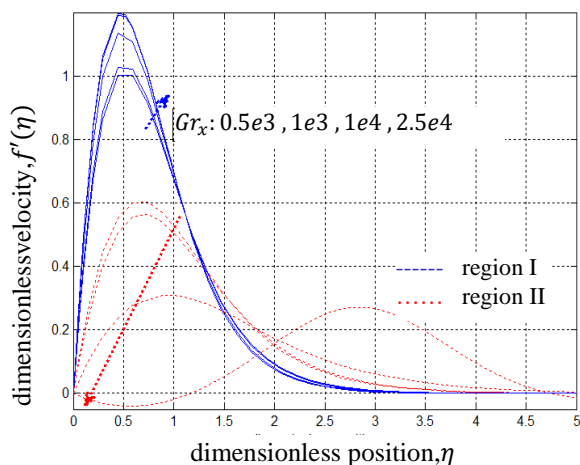
profile of the second region was banished and the temperature profile of the second region is greater than the first region, so the results can be explained the disappearance of the second boundary layer in the visualization photographs. Therefore, the results presented are satisfied asymptotically and support the validity of the suggested physical model.

Fig. 7, a, b depict that with the increasing Grashof number, velocity and temperature profiles increase in the first region and a decrease in the second region, on the other hand it appears a critical value of Grashof number which is depended from angle inclination and which reduce the second region instable, this is due to the transformation to the third region (plume).

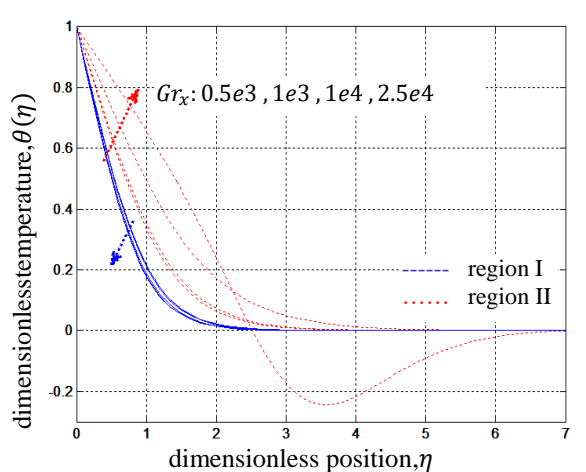


b

Fig. 6 Velocity a) and temperature b) distributions against η for angle value ($\varphi = 76.86^\circ$), $Pr = 0.72$, $Gr = 0.5 \cdot 10^3$ and $M = 0$



a



b

Fig.7 Velocity a) and temperature b) distributions against η for inclined plate ($\varphi = 60^\circ$) for different values of Grashof number, $Pr = 0.72$, $M = 0$

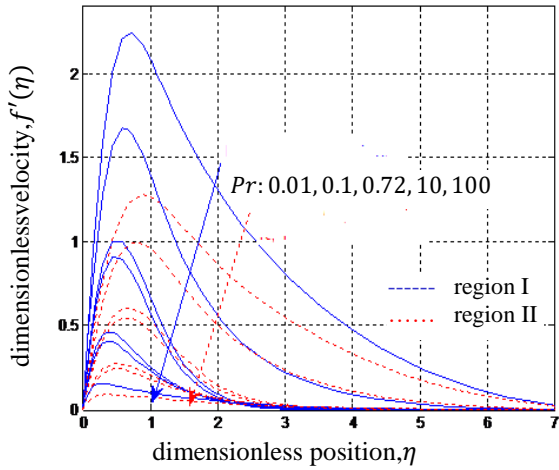
Beside to semi-analytical investigation of Lewanowski [20], which study just the case of $Pr = 1$, the present research examined for various Prandtl number, velocity and temperature profiles are plotted in Figs. 8, a, b. The velocity of air ($Pr = 0.72$) is always greater than the velocity of water ($Pr = 7$) in the same value of parameters for both regions I and II. Fig. 8, b shows that the effect of Prandtl number is very important in the temperature profiles. The thermal boundary layer thickness decreases with the increasing of the Prandtl number in the two regions, as it is known in classical studies.

From Fig. 9, a, b it is clear that magnetic field parameter M has a retarding effect on the velocity of the fluid. It is due to the fact that there exists an opposite force to the flow called Lorentz force and which results in thinning of the boundary layer thickness, and hence induces an increase in the absolute value of the velocity gradient at the surface, so the velocity profiles decreases, while the temperature profiles increases owing to the increase of magnetic field M .

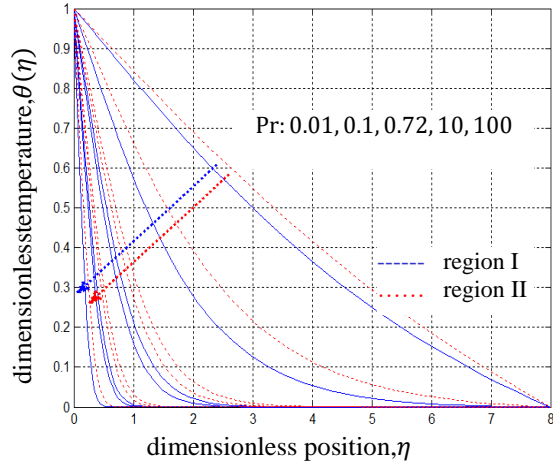
The influence of Eckert number E_c over dimensionless velocity and temperature profiles are shown in

Figs.10, a, b. It is observed that an increase in Eckert number enhances the temperature because the heat energy is stored in the fluid due to the frictional heating, hence, a

decrease of the velocity distribution in the both flow regions.

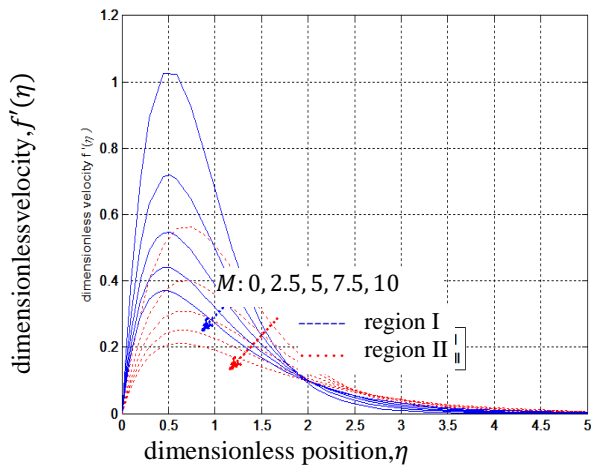


a

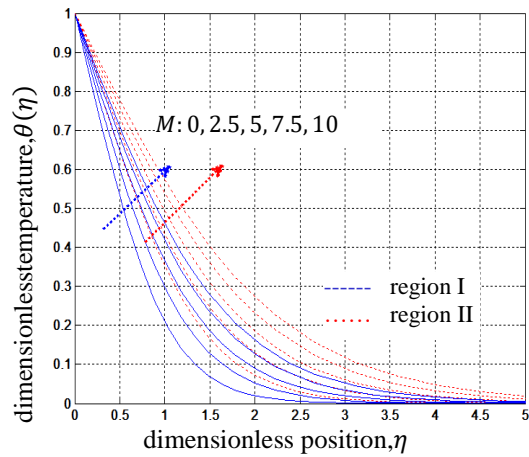


b

Fig.8 Velocity a) and temperature b) distributions against η for inclined plate ($\phi = 60^\circ$) for different values of Prandtl number, $Gr = 0.5 \cdot 10^3$, $M = 0$

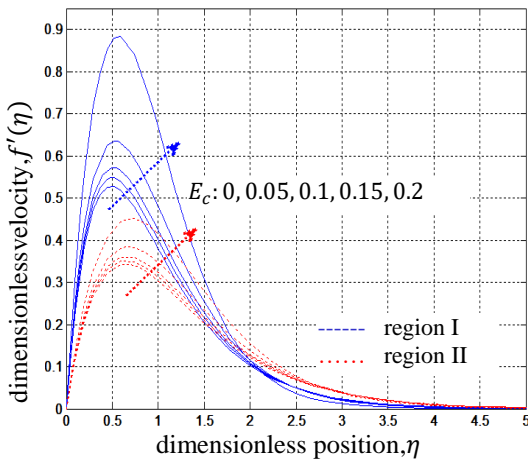


a

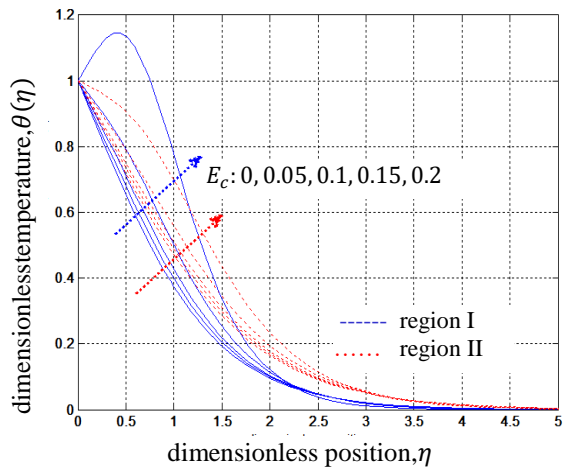


b

Fig. 9 Velocity a) and temperature b) distributions against η for inclined plate ($\phi = 60^\circ$) for different values of magnetic field parameter, $Gr = 0.5 \cdot 10^3$, $Pr = 0.72$ and $E_c = 0$.



a



b

Fig. 10 Velocity a) and temperature b) distributions against η for inclined plate ($\phi = 60^\circ$) for different values of Eckert number, $Gr = 0.5 \cdot 10^3$, $Pr = 0.72$ and $M = 5$

The relationship of the local Nusselt number Nu_x as a function of local Rayleigh number Ra_x and the global Nusselt number Nu_d with the global Rayleigh number Ra_d are depicted, respectively, in Figs. 11 and 12 for the both region I and II.

From Fig. 11, the local Nusselt calculated for the two regions with the formula suggested by Lewandowski [20] and based on the quasi-analytical solution is found in divergence with the present results. In our opinion, some simplifying assumptions for the quasi-analytical solution are not reasonable. The presence of the magnetic field can be seen as a tool to regulate the velocity, but with a loss of the convective heat exchange, as shown in Fig. 12.

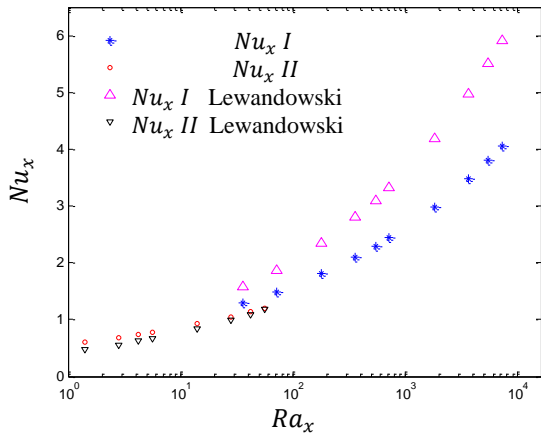


Fig. 11 Local Nusselt against local Rayleigh for inclined plate ($\varphi = 60^\circ$), $M = 0$

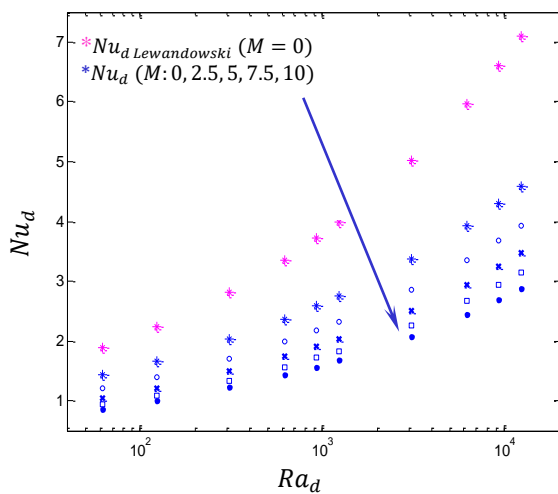


Fig. 12 Global Nusselt against global Rayleigh for inclined plate ($\varphi = 60^\circ$) for different M

4. Conclusions

The present study involved on a numerical approach on MHD natural convection boundary layer flow from a finite isothermal flat plate of arbitrary inclined surface. The governing partial differential equations were transformed into a system of ordinary differential equations using suitable similarity transformations. The resulting equations were then solved and the results obtained can be summarized as follows:

- An excellent and physically agreement was observed between our results and those obtained using technical visualization giving confidence to the suggested model.

- With an increased inclination angle φ , the maximal velocity in the first region grows while in the second region decrease more and more rapidly until the disappearance. This tendency is inverted for the temperature, but the profile remains in all cases. This behavior is valid also for the Grashof number.

- It appears a critical value of Grashof number which is depended from angle inclination which reduce the second region instable, owing the transformation to the plume.

- All the parameters, M , Ec as well as Pr have a profound effect on the velocity and temperature profiles in the both regions I and II.

- This present procedure seems to produce better estimation for local or global convective heat transfer coefficient involving plate with finite dimensions.

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COMPUTATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT FOR FINITE INCLINED AND ISOTHERMAL PLATE

S u m m a r y

In order to compute the convective heat transfer coefficient, the present study develops a new technical approach of the constitutive equations of the fluid, based on a realistic physical model of heat transfer for an inclined and an isothermal plate with finite dimensions. Two separate regions with different fluid motions are distinguished. Using suitable transformations of differential equations, the similarity ordinary differential equations were obtained and then solved by an appropriate and simple finite difference method. The analysis of numerical results for some special cases of inclination with visualization photographs is found to be in very good agreement. Numerical results for the dimensionless velocity and temperature profiles are obtained and reported graphically for various values of the parameters entering into the problem. It has observed that Lorenz forces are suitable to control the velocity. Discrepancy between the quasi-analytical formula and the present numerical results are recorded for the Nusselt number and for both the two regions.

Keywords: Inclined finite plate, physical model, MHD, natural convection, two regions, boundary layer.

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