A Generic Computational Solution of a Natural Convection Flow past an Infinite Vertical Porous Plate

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Abstract

A simulation was carried out on an unsteady flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical porous plate. A generic computer program using the Galerkin finite element method is employed to solve the coupled non-linear differential equations for velocity and temperature fields. The diffusion equation, the energy equation, the momentum equations and other relevant parameters are transformed into interpretable postfix codes. Numerical calculations are carried out on the flow fields both in the presence of cooling and heating of the plate by free convection currents. The effects of the dimensionless parameters, namely, the Prandtl number, the Eckert number, the modified Grashof number, the Schmidt number and the time on the temperature and velocity distributions are discussed.

Keywords

Computer Simulation, Generic Software Tool, Finite Element Method, Laminar Fluid Flow

1. Introduction

The effect of an applied magnetic field on unsteady free convection flow along a vertical plate has been given considerable interest because of its application in the cooling of nuclear reactors or in the study of the structures of stars and planets which are greatly influenced by the thermal convection processes in their interiors. A number of authors have made important contributions in that area and in the area of fluid flows in general like [1]-[8].

Yusuf *et al.* [9] used the Modified Adomian Decomposition Method for the first time to obtain the solution to the problem of laminar fluid flow in an inclined parallel wall resulting from the movement of the lower wall while the upper wall remains stationary in a nanofluid with thermal convection, Soret and Dufour effects with radiation. Rectangular coordinates are used in their analysis. Qadri and Krishna [10] considered the flow of an incompressible viscous Maxwell fluid between two parallel plates, initially induced by a constant pressure gradient. They assumed that pressure gradient is withdrawn and the upper plate moves with a uniform velocity while the lower plate continues to be at rest. They defined their run-up flow to be the arising and used the Laplace transform technique in order to solve their initial value problem. The authors calculated the values of the velocity and the shear stresses on the two plates. Aiyesimi *et al.* [11] presented the magnetohydrodynamic flow of an unsteady convective third grade fluid in a cylindrical system. They used the homotopy perturbation method to analytically solve the non-linear governing equations. The influences of dimensionless parameters on magnetohydrodynamic flow of a convective third grade fluid in a cylindrical system were investigated. Daniel and Seini [12] investigated the effect of inclination on the heat and mass transfer characteristics of a heated plate with viscous dissipation. An incompressible ferrofluid was made to uniformly flow over a heated plate and a transverse magnetic field applied to regulate the flow. Their mathematical model included the equation of mass conservation, the momentum equation, the energy equation and the concentration equation. They made use of the fourth order Runge Kutta method in order to solve the problem.

In this paper, we are making use of a generic computer tool based on the Galerkin finite element method in order to compute the solution of an unsteady boundary layer flow of an incompressible, viscous and electrically conducting fluid past an infinite vertical porous plate.

2. Mathematical Formulation and Solution of the Problem

The geometry and the unsteady flow fields for this problem are described by Bitok [13]. After transformation, the problem considered reduces to the following non-dimensional differential equations:

$$\frac{1}{4}Sc\frac{\partial C}{\partial t} - Sc\frac{\partial C}{\partial y} = \frac{\partial^2 C}{\partial y^2} \tag{1}$$

$$\frac{1}{4}Pr\frac{\partial \theta}{\partial t} - Pr\frac{\partial \theta}{\partial y} - \frac{\partial^2 \theta}{\partial y^2} = PrEc\left(\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right) \tag{2}$$

$$\frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} - \frac{\partial^2 u}{\partial y^2} + M_2 u = M_3 w + M_2 U + \frac{1}{4}\frac{\partial U}{\partial t} + Gr\theta + GcC \tag{3}$$

$$\frac{1}{4}\frac{\partial w}{\partial t} - \frac{\partial w}{\partial y} - \frac{\partial^2 w}{\partial y^2} + M_2 w = M_3\left(U - u\right) \tag{4}$$

The boundary conditions are given as follows:

$$\begin{cases} u = 0, \quad w = 0, \quad \theta = 1 + \varepsilon e^{i\omega t}, \quad C = 1 + \varepsilon e^{i\omega t} \quad \text{at } y = 0, \\ u \to 1, \quad w \to 0, \quad \theta \to 0, \quad C \to 0 \quad \text{as } y \to \infty \end{cases} \tag{5}$$

and $U = 1 + \varepsilon e^{i\omega t}$, $M_2 = \dfrac{M^2 \lambda^2}{1 + m^2 \lambda^2}$, $M_3 = \dfrac{M^2 m \lambda^3}{1 + m^2 \lambda^2}$, $\lambda = \cos(\alpha)$

where

- u and w are the components of the dimensionless velocity;
- θ is the dimensionless temperature;
- C is the dimensionless species concentration;
- Gr is the Grashof number;
- Gc is the modified Grashof number;
- Pr is the Prandtl number;
- Ec is the Eckert number;
- Sc is the Schmidt number;
- M is the magnetic parameter;
- m is the Hall parameter;
- α is the angle of the uniform magnetic field with the y-axis.

The system of Equations (1)-(4) with boundary conditions (5) has been solved numerically by a generic computer program based on the finite element method in steps 1 - 3. In all mathematical formulations, ϕ_i denotes the test function and Ω is the region of the flow. For each element of the mesh,

$$\begin{cases} \phi_1^{(i)}(y) = \dfrac{(y_{i+1} - y)}{(y_{i+1} - y_i)} \\ \phi_2^{(i)}(y) = \dfrac{(y - y_i)}{(y_{i+1} - y_i)} \end{cases} \tag{6}$$

where $i = 1, 2, 3, \cdots, N$ and y_i and y_{i+1} are respectively the lower and upper coordinates of the element i.

Step 1: Diffusion Equation Finite Element Solution

We solve Equation (1) with the help of boundary conditions (5). Constructing the quasi-variational equivalent of Equation (1), we obtain:

$$0 = \int_\Omega \phi_i \left\{ \frac{1}{4} Sc \frac{\partial C}{\partial t} - Sc \frac{\partial C}{\partial y} - \frac{\partial^2 C}{\partial y^2} \right\} dy \tag{7}$$

Consider an N elements mesh and a two parameter (semi discrete) Galerkin approximation of the form [14]:

$$C(y,t) = \sum_{j=1}^{N} d_j^1(t) \phi_j(y) \tag{8}$$

Using Equations (6) and (8), Equation (7) reduces to:

$$\left[A^1 \right] \left\{ \frac{\partial d^1}{\partial t} \right\} + \left[B^1 \right] \{ d^1 \} = \{ P^1 \} \tag{9}$$

where

$$\begin{cases} A_{ij}^1 = \int_\Omega \dfrac{Sc}{4} \phi_i \phi_j \mathrm{d}y \\[2mm] B_{ij}^1 = \int_\Omega \left(\dfrac{\partial \phi_i}{\partial y} \cdot \dfrac{\partial \phi_j}{\partial y} - Sc\phi_i \dfrac{\partial \phi_j}{\partial y} \right) \mathrm{d}y \\[2mm] P_i^1 = 0 \end{cases} \tag{10}$$

Using the Θ-family of approximation developed by Reddy [14], Equation (9) reduces to:

$$\left[\hat{A}^1 \right] \left\{ d^1 \right\}_{n+1} = \left[\hat{B}^1 \right] \left\{ d^1 \right\}_n + \left\{ \hat{P}^1 \right\} \tag{11}$$

where

$$\begin{cases} \left[\hat{A}^1 \right] = \left[A^1 \right] + \Theta \Delta t \left[B^1 \right] \\[2mm] \left[\hat{B}^1 \right] = \left[A^1 \right] - (1-\Theta)\Delta t \left[B^1 \right] \\[2mm] \left[\hat{P}^1 \right] = \Delta t \left[\Theta \left\{ P^1 \right\}_{n+1} + (1-\Theta)\left\{ P^1 \right\}_n \right] = 0 \end{cases} \tag{12}$$

The initial value d_0^1 is obtained by the Galerkin method from a 64 elements mesh and is given by:

$$d_0^1 = [1, 0, 0, \cdots, 0]^{\mathrm{T}} \tag{13}$$

For $t > 0$,

$$\left\{ d^1 \right\}_{n+1} = \left[\left(\hat{A}^1 \right) \right]^{-1} \left[\hat{B}^1 \right] \left\{ d^1 \right\}_n + \left[\left(\hat{A}^1 \right) \right]^{-1} \left\{ \hat{P}^1 \right\} \tag{14}$$

Step 2: Energy Equation Finite Element Solution

We solve Equation (2) with the help of boundary conditions (5). Constructing the quasi-variational equivalent of Equation (2), we obtain:

$$0 = \int_\Omega \phi_i \left\{ \frac{1}{4} Pr \frac{\partial \theta}{\partial t} - Pr \frac{\partial \theta}{\partial y} - \frac{\partial^2 \theta}{\partial y^2} - PrEc \left(\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial y} \right)^2 \right) \right\} \mathrm{d}y \tag{15}$$

Consider an N elements mesh and a two parameter (semi discrete) Galerkin approximation of the form [14]:

$$\theta(y, t) = \sum_{j=1}^{N} d_j^2(t) \phi_j(y) \tag{16}$$

Using Equations (6) and (16), Equation (15) reduces to:

$$\left[A^2 \right] \left\{ \frac{\partial d^2}{\partial t} \right\} + [B^2]\left\{ d^2 \right\} = \left\{ P^2 \right\} \tag{17}$$

where

$$\begin{cases} A_{ij}^2 = \int_\Omega \frac{Pr}{4}\phi_i\phi_j \mathrm{d}y \\[2mm] B_{ij}^2 = \int_\Omega \left(\frac{\partial\phi_i}{\partial y}\cdot\frac{\partial\phi_j}{\partial y} - Pr\phi_i\frac{\partial\phi_j}{\partial y} \right)\mathrm{d}y \\[2mm] P_i^2 = \int_\Omega PrEc\phi_i\left(\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2 \right)\mathrm{d}y \end{cases} \tag{18}$$

Using the Θ-family of approximation developed by Reddy [14], Equation (17) reduces to:

$$\left[\hat{A}^2\right]\left\{d^2\right\}_{n+1} = \left[\hat{B}^2\right]\left\{d^2\right\}_n + \left\{\hat{P}^2\right\} \tag{19}$$

where

$$\begin{cases} \left[\hat{A}^2\right] = \left[A^2\right] + \Theta\Delta t\left[B^2\right] \\[2mm] \left[\hat{B}^2\right] = \left[A^2\right] - (1-\Theta)\Delta t\left[B^2\right] \\[2mm] \left[\hat{P}^2\right] = \Delta t\left[\Theta\left\{P^2\right\}_{n+1} + (1-\Theta)\left\{P^2\right\}_n\right] \end{cases} \tag{20}$$

The initial value d_0^2 is obtained by the Galerkin method from a 64 elements mesh and is given by:

$$d_0^2 = \left[1,0,0,\cdots,0\right]^{\mathrm{T}} \tag{21}$$

For $t > 0$,

$$\left\{d^2\right\}_{n+1} = \left[\left(\hat{A}^2\right)\right]^{-1}\left[\hat{B}^2\right]\left\{d^2\right\}_n + \left[\left(\hat{A}^2\right)\right]^{-1}\left\{\hat{P}^2\right\} \tag{22}$$

Step 3: Momentum Equations Finite Element Solution

We solve Equations (3), (4) with the help of boundary conditions (5). Constructing the quasi-variational statement of Equations (3), (4), we obtain:

$$\begin{cases} 0 = \int_\Omega \phi_i\left\{ \frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} - \frac{\partial^2 u}{\partial y^2} + M_2 u - M_3 w - M_2 U - \frac{1}{4}\frac{\partial U}{\partial t} - Gr\theta - GcC \right\}\mathrm{d}y \tag{23} \\[3mm] 0 = \int_\Omega \phi_i\left\{ \frac{1}{4}\frac{\partial w}{\partial t} - \frac{\partial w}{\partial y} - \frac{\partial^2 w}{\partial y^2} + M_2 w - M_3(U - u) \right\}\mathrm{d}y \tag{24} \end{cases}$$

Consider an N elements mesh and a two parameter (semi discrete) Galerkin approximation of the form [14]:

$$\begin{cases} u(y,t) = \sum_{j=1}^N d_j^3(t)\phi_j(y) \tag{25} \\[3mm] w(y,t) = \sum_{j=1}^N d_j^4(t)\phi_j(y) \tag{26} \end{cases}$$

Using Equations (6), (25) and (26), Equations (23), (24) reduce to:

$$\left[A^3 \right]\left\{ \frac{\partial d^3}{\partial t} \right\} + \left[B^3 \right]\left\{ d^3 \right\} = \left\{ P^3 \right\} \tag{27}$$

$$\left[A^4 \right]\left\{ \frac{\partial d^4}{\partial t} \right\} + \left[B^4 \right]\left\{ d^4 \right\} = \left\{ P^4 \right\} \tag{28}$$

where

$$\begin{cases} A_{ij}^3 = \int_\Omega \frac{1}{4} \phi_i \phi_j \mathrm{d}y \\[2mm] B_{ij}^3 = \int_\Omega \left(\frac{\partial \phi_i}{\partial y} \cdot \frac{\partial \phi_j}{\partial y} - \phi_i \frac{\partial \phi_j}{\partial y} + M_2 \phi_i \phi_j \right) \mathrm{d}y \\[2mm] P_i^3 = \int_\Omega \phi_i \left(M_3 w + M_2 U + \frac{1}{4} U_t + Gr\theta + GcC \right) \mathrm{d}y \\[2mm] A_{ij}^4 = \int_\Omega \frac{1}{4} \phi_i \phi_j \mathrm{d}y \\[2mm] B_{ij}^4 = \int_\Omega \left(\frac{\partial \phi_i}{\partial y} \cdot \frac{\partial \phi_j}{\partial y} - \phi_i \frac{\partial \phi_j}{\partial y} + M_2 \phi_i \phi_j \right) \mathrm{d}y \\[2mm] P_i^4 = \int_\Omega M_3 \phi_i \left(U - u \right) \mathrm{d}y \end{cases} \tag{29}$$

Using the Θ-family of approximation developed by Reddy [14], Equations (27), (28) reduce to:

$$\left[\hat{A}^3 \right]\left\{ d^3 \right\}_{n+1} = \left[\hat{B}^3 \right]\left\{ d^3 \right\}_n + \left\{ \hat{P}^3 \right\} \tag{30}$$

$$\left[\hat{A}^4 \right]\left\{ d^4 \right\}_{n+1} = \left[\hat{B}^4 \right]\left\{ d^4 \right\}_n + \left\{ \hat{P}^4 \right\} \tag{31}$$

where

$$\begin{cases} \left[\hat{A}^3 \right] = \left[A^3 \right] + \Theta \Delta t \left[B^3 \right] \\[2mm] \left[\hat{B}^3 \right] = \left[A^3 \right] - (1-\Theta) \Delta t \left[B^3 \right] \\[2mm] \left[\hat{P}^3 \right] = \Delta t \left[\Theta \left\{ P^3 \right\}_{n+1} + (1-\Theta) \left\{ P^3 \right\}_n \right] \\[2mm] \left[\hat{A}^4 \right] = \left[A^4 \right] + \Theta \Delta t \left[B^4 \right] \\[2mm] \left[\hat{B}^4 \right] = \left[A^4 \right] - (1-\Theta) \Delta t \left[B^4 \right] \\[2mm] \left[\hat{P}^4 \right] = \Delta t \left[\Theta \left\{ P^4 \right\}_{n+1} + (1-\Theta) \left\{ P^4 \right\}_n \right] \end{cases} \tag{32}$$

The initial values d_0^3 and d_0^4 are obtained by the Galerkin method from a 64 elements mesh and are given by:

$$\begin{cases} d_0^3 = [0, 0, 0, \cdots, 1]^{\mathrm{T}} \tag{33} \end{cases}$$

$$\begin{cases} d_0^4 = [0, 0, 0, \cdots, 0]^{\mathrm{T}} \tag{34} \end{cases}$$

For $t > 0$,

$$\left\{ d^3 \right\}_{n+1} = \left[\left(\hat{A}^3 \right) \right]^{-1} \left[\hat{B}^3 \right]\left\{ d^3 \right\}_n + \left[\left(\hat{A}^3 \right) \right]^{-1} \left\{ \hat{P}^3 \right\} \tag{35}$$

$$\left\{ d^4 \right\}_{n+1} = \left[\left(\hat{A}^4 \right) \right]^{-1} \left[\hat{B}^4 \right]\left\{ d^4 \right\}_n + \left[\left(\hat{A}^4 \right) \right]^{-1} \left\{ \hat{P}^4 \right\} \tag{36}$$

The numerical values of the temperature and velocity fields have been computed from equations (14), (22), (35) and (36). All input elements such as matrix and vector elements are transformed into interpretable postfix codes.

3. Discussion of Results

Numerical calculations have been carried out for the velocity and temperature distributions. The analysis of Bitok [13] was restricted to the behaviour of the flow fields with respect to the angle α and the Hall parameter m. We are proposing a more complete analysis and the results obtained are displayed in **Figures 1-4**. The method used is unconditionally stable and is independent of the time step Δt. The velocity profiles are examined for the cases $Gr > 0$ and $Gr < 0$. $Gr > 0$ (=+10) is used for the case when the flow is in the presence of cooling of the plate by free convection currents. $Gr < 0$ (=−10) is used for the case when the flow is in the presence of heating of the plate by free convection currents. The values of λ ($\lambda = 1$) and m ($m = 1$) are kept constant during the simulation while series of values for the other dimensionless parameters are used as shown in **Figures 1-4**.
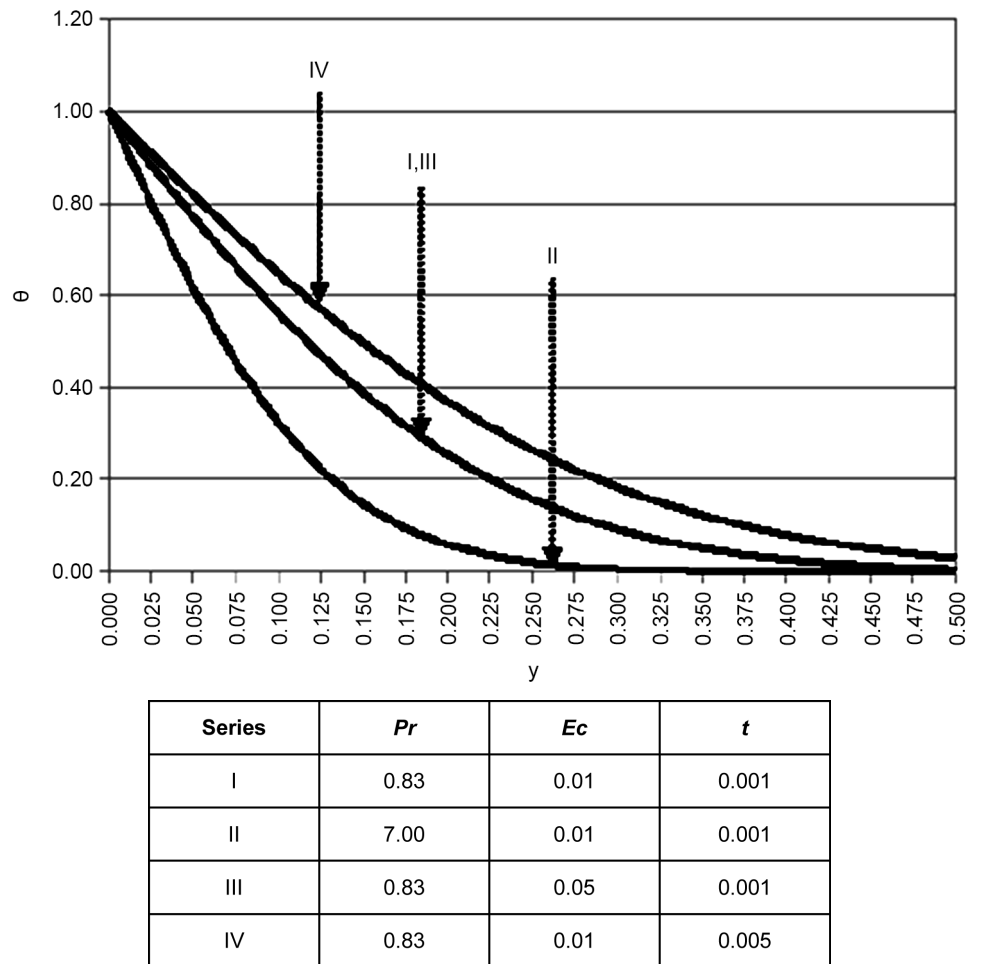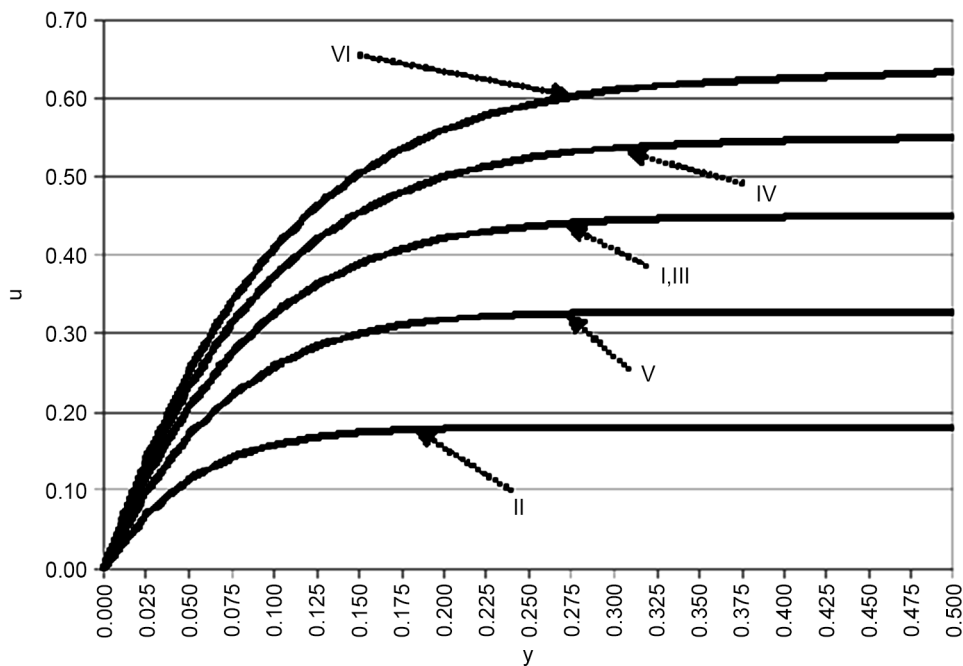

Series	Pr	Ec	t
I	0.83	0.01	0.001
II	7.00	0.01	0.001
III	0.83	0.05	0.001
IV	0.83	0.01	0.005

Figure 1. Temperature distribution for $Gr = \pm10$.

From **Figure 1**, it is observed that:

1) The temperature (θ) decreases away from the plate. The decrease is greater for a Newtonian fluid than it is for a non-Newtonian fluid (θ decreases with Pr);

2) There is a rise in temperature profiles (θ) due to an increase in the time (t);

3) There is an insignificant change in the temperature profiles (θ) due to an increase in the Eckert number (Ec).

From **Figure 2**, for the case when $Gr > 0$ (in the presence of cooling of the plate by free convection currents), it is observed that:

1) The primary velocity (u) decreases due to an increase in the Prandtl number (Pr) and the Schmidt number (Sc);

2) An increase in the modified Grashof number (Gc) and the time (t) leads to a rise in the primary velocity (u);

3) There is an insignificant change in the primary velocity (u) due to an increase in the Eckert number (Ec).

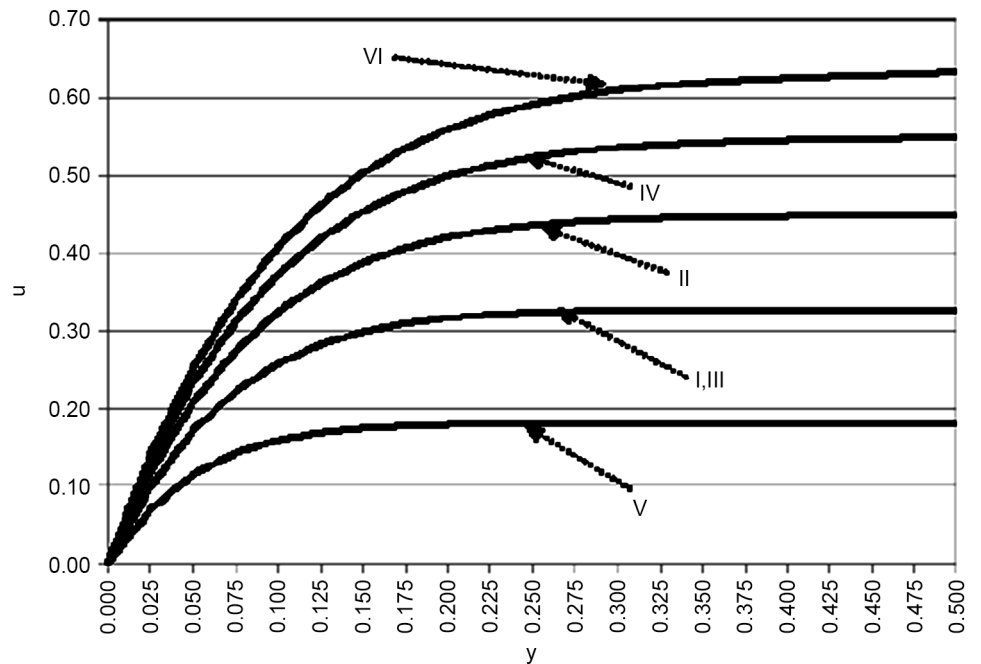| Series	Pr	Ec	Gc	Sc	t
I	0.83	0.01	2	0.60	0.001
II	7.00	0.01	2	0.60	0.001
III	0.83	0.05	2	0.60	0.001
IV	0.83	0.01	3	0.60	0.001
V	0.83	0.01	2	0.80	0.001
VI	0.83	0.01	2	0.60	0.005

Figure 2. Primary velocity distribution for $Gr = +10$.

From **Figure 3**, for the case when $Gr < 0$ (in the presence of heating of the plate by free convection currents), it is observed that:

1) The primary velocity (u) decreases due to an increase in the Schmidt number (Sc);

2) An increase in the Prandtl number (Pr), the modified Grashof number (Gc) and the time (t) leads to a rise in the primary velocity (u);

3) There is an insignificant change in the primary velocity (u) due to an increase in the Eckert number (Ec).

From **Figure 4**, for both cases when $Gr > 0$ (in the presence of cooling of the plate by free convection currents) and $Gr < 0$ (in the presence of heating of the plate by free convection currents), it is observed that:

1) The secondary velocity profile (w) increases due to an increase in the time (t);

2) An increase in the Prandtl number (Pr), the Eckert number (Ec), the modified Grashof number (Gc) and the Schmidt number (Sc) leads to an insignificant change in the secondary velocity profile (w).

Series	Pr	Ec	Gc	Sc	t
I	0.83	0.01	2	0.60	0.001
II	7.00	0.01	2	0.60	0.001
III	0.83	0.05	2	0.60	0.001
IV	0.83	0.01	3	0.60	0.001
V	0.83	0.01	2	0.80	0.001
VI	0.83	0.01	2	0.60	0.005

Figure 3. Primary velocity distribution for $Gr = -10$.
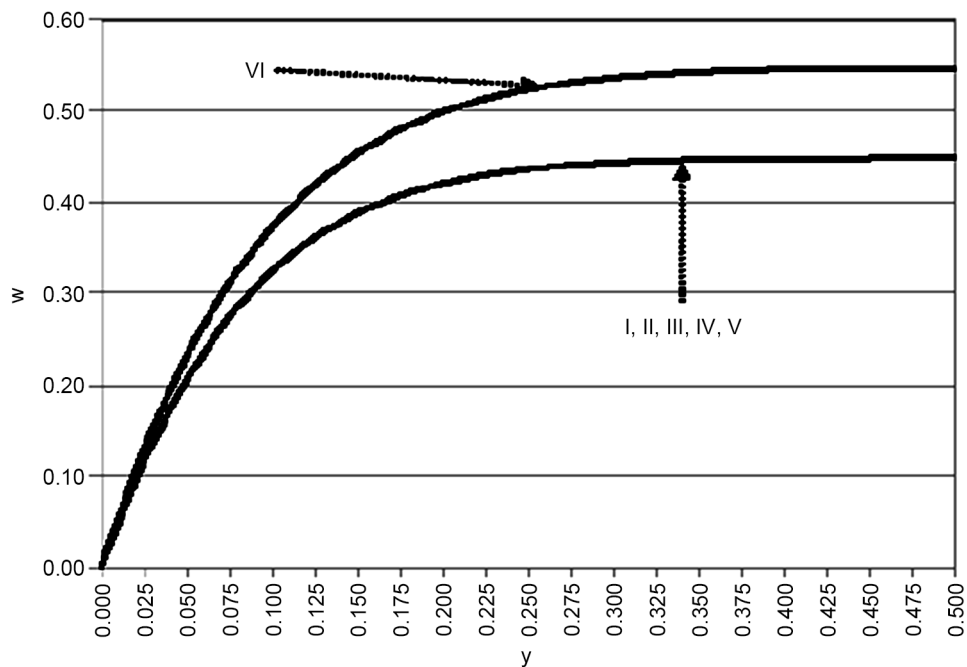
Series	Pr	Ec	Gc	Sc	t
I	0.83	0.01	2	0.60	0.001
II	7.00	0.01	2	0.60	0.001
III	0.83	0.05	2	0.60	0.001
IV	0.83	0.01	3	0.60	0.001
V	0.83	0.01	2	0.80	0.001
VI	0.83	0.01	2	0.60	0.005

Figure 4. Secondary velocity distribution for $Gr = \pm 10$.

4. Conclusion

In this work, a computer simulation was carried out on the unsteady flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical porous plate. The velocity and the temperature fields were computed using a generic software tool based on the Galerkin finite element method. The results obtained reveal that the use of interpretable codes provides a good solution to fluid flow problems.

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