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JCARME

ISSN: 2228-7922

Journal of Computational and Applied Research in Mechanical Engineering
Vol. 8, No. 1, pp. 75-84
jcarme.sru.ac.ir

Effect of variable thermal conductivity and the inclined magnetic field on MHD plane poiseuille flow in a Porous channel with non-uniform plate temperature

Muhim Chutia*

Department of Mathematics, Mariani College, Jorhat, Assam, 785634, India

Article info:

Received: 11/06/2016
Accepted: 07/11/2017
Online: 10/04/2018

Keywords:
MHD poiseuille flow,
Thermal conductivity,
Inclined uniform magnetic field,
Joule heating,
Finite difference method.

Abstract

The aim of this paper is to investigate the effect of the variable thermal conductivity and the inclined uniform magnetic field on the plane Poiseuille flow of a viscous incompressible electrically conducting fluid between two porous plates with Joule heating in the presence of a constant pressure gradient through non-uniform plate temperature. It is assumed that the fluid injection occurs at the lower plate, while fluid suction occurs at the upper plate. The governing equations of momentum and energy are transformed into coupled and nonlinear ordinary differential equations using similarity transformation and then solved numerically using finite difference technique. Numerical values for the velocity and temperature have been iterated by Gauss Seidal iteration method in Matlab programming to a suitable number so that the convergent solutions of velocity and temperature are considered to be achieved. Numerical results for the dimensionless velocity and the temperature profiles for different governing parameters such as the Hartmann number (M), angle of inclination of the magnetic field (α), suction Reynolds number (Re), Prandtl number (Pr), Eckert number (Ec), and variable thermal conductivity (ε) are discussed in detail and presented through graphs.

Nomenclature

a	Distance between two plates
B_0	Applied magnetic field
$C_{1,}$ ...	Constants
C_p	Specific heat at constant pressure
Ec	Eckert number
h	Increment along y-axis
K	Thermal conductivity
K'	Variable thermal conductivity
i	Index refers to y
M	Hartmann number
m	Number of grid points along y- direction
P	Dimensionless pressure gradient
p	Pressure gradient
Pr	Prandtl number
V	Constant suction velocity along y'-direction
x', y'	Cartesian coordinates
x, y	Dimensionless Cartesian coordinates
Greek letters	
α	Angle between velocity and applied magnetic field
ε	Thermal conductivity parameter

*Corresponding author
email address: muhimchutia@gmail.com

θ	Dimensionless fluid temperature
θ'	Fluid temperature
θ_0	Temperature of the lower plate
θ_1	Temperature of the upper plate
β	Coefficient of thermal expansion
ρ	Density of liquid
Re	Suction Reynolds number
u'	Velocity along x'-direction
u	Dimensionless velocity along x-direction
u_m	Maximum velocity
v'	Velocity along y'-direction
σ	Electrical conductivity
μ	Coefficient of viscosity
υ	Kinematic viscosity
λ	Magnetic diffusivity

1. Introduction

The study of magneto hydrodynamic (MHD) flow and heat transfer analysis in channel has been a topic of great interests by many researchers in the last few decades due to its wide range of applications in industries and engineering problems. Such applications are in solar technology, MHD power generators, MHD pumps, aerodynamics heating, electrostatic precipitation, purification of oil and fluid sprays and droplets, etc. Cooling process can be controlled effectively by theory of variable thermal conductivity for which the high quality product may be produced.

Palm et al. [1] studied on the steady free convection in porous medium. Bansal and Jain [2] studied the plane Poiseuille flow problem with unequal wall temperature of an incompressible fluid having temperature dependent viscosity. Chamkha [3] considered unsteady flow and heat transfer through a porous medium channel in the presence of a transverse magnetic field. He found closed-form solutions for steady-state problem and numerical solutions for unsteady problem using implicit finite difference method. MHD flow and heat transfer in fluid flow with variable thermal conductivity for different aspect of the problem were studied by Arunachalam and Rajappa [4], Chaim [5], Nasrin and Alim [6] and Mahanti and Gaur [7]. Uwanta and Usman [8], Gupta et al. [9]. Umavathi et al. [10] investigatedthe problem of unsteady oscillatory flow and heat transfer in a horizontal composite porous medium with viscous and Darcian dissipations. Kumar Jhankal and Kumar [11] studied the MHD plane Poiseuille flow with unequal wall temperatures of an incompressible fluid with temperature dependent viscosity. Yu et al. [12] investigated numerically MHD natural convection flow at different angles θ with respect to horizontal plane in rectangular cavities. MHD plane Poiseuille/ Couette flow with heat transfer or without heat transfer in channels with porous plates were investigated by Manyange et al.[13], Ceasar Muriuki et al. [14], Kuiry and Bahadur [15] and Joseph et al. [16]; and with non-porous plates studied by the researchers Gupta et al. [9], Idowu and Olabode [17] and Joseph et al. [18] in the presence of inclined magnetic field considering different features of the problem. Chamkha [19], Eegunjobi and Makinde [20], Attia et al. [21], Das and Jana [22] and Ganesh and Krishnambal [23] studied MHD flow with or without heat transfer through porous channel.Effects of uniform suction or injection on MHD flow in channels with porous plates were investigated by Deka and Basumatary [24], Sai and Rao [25] and Das and Jana [26] considering different aspects of the problem.

The objective of the present study is to investigate the effect of variable thermal conductivity in presence of uniform magnetic field with inclination to the channel plate on steady MHD plane Poiseuille flow through non-uniform plate temperature and with constant injection or suction and Joule heating. The governing differential equations for velocity and temperature are solved numerically by developing finite difference codes in Matlab programming.

2. Mathematical formulation

Consider steady viscous incompressible electrically conducting plane Poiseuille fluid flow bounded by two parallel porous plates separated by a distance a as shown in the Fig. 1.

The x'-axis is taken along the flow direction and the y'-axis is perpendicular to the plates. A uniform transverse magnetic field B_0 is applied normal to the plates and makes an angle α with the flow direction. Both of the plates are kept stationary and it is assumed that the lower permeable plate at $y' = 0$, where fluid injection occurs maintained at constant temperatures θ_0, while at $y' = a$, the upper permeable plate fluid suction occurs maintained at constant temperatures θ_1, where $\theta_1 > \theta_0$. The flow is driven by the constant pressure gradient $\partial p/\partial x'$.

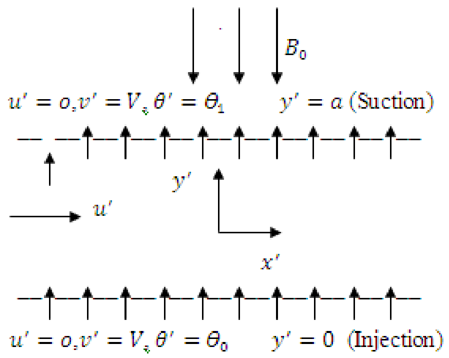

Fig. 1. Geometry of the problem.

It is assumed that the magnetic Reynolds number is very small so that the induced electric field caused by induced magnetic field is assumed negligible. The flow in the region is unidirectional, steady laminar and fully developed so all the physical variables except pressure depend on y' only. The fluid particles are injected with velocity $v' = V$ at the lower porous plate $y' = 0$ and sucked with the same velocity at the upper porous plate $y' = a$, so $\partial V/\partial y' = 0$. The governing equations of momentum and energy (Gupta et al., [9]) with Joule heating term are given by:

$$V\frac{\partial u'}{\partial y'} = -\frac{1}{\rho}\frac{\partial p}{\partial x'} + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2 \sin^2 \alpha u'}{\rho} \quad (1)$$

$$\rho C_p V\frac{\partial \theta'}{\partial y'} = \frac{\partial}{\partial y'}\left(K'\frac{\partial \theta'}{\partial y'}\right) + \mu\left(\frac{\partial u'}{\partial y'}\right)^2$$

$$+\sigma B_0^2 \sin^2 \alpha u'^2 \quad (2)$$

where ρ is the density of the fluid, υ is the kinematic viscosity, σ is the electrical conductivity, μ is the coefficient of viscosity, C_p is the specific heat at constant pressure, K' is the variable thermal conductivity, α $(0 \le \alpha \le \pi)$ is the angle between velocity and magnetic field strength, u' is the axial fluid velocity, p is the pressure, and θ' is the fluid temperature.
The corresponding boundary conditions are:

$$\left.\begin{aligned} u' = 0,\ \theta' = \theta_0 \ \text{ at } y' = 0 \\ u' = 0,\ \theta' = \theta_1 \ \text{ at } y' = a \end{aligned}\right\} \quad (3)$$

Following Mahanti and Gaur [7], the thermal conductivity is considered to vary linearly with temperature and it is of the form:

$$K' = K(1 + \varepsilon\theta) \quad (4)$$

$v' = V$, constant suction velocity
Introducing dimensionless quantities as follows:

$$y = \frac{y'}{a},\ u = \frac{u'}{u_m},\ \theta = \frac{\theta' - \theta_0}{\theta_1 - \theta_0} \quad (5)$$

where $u_m = -\frac{a^2}{\mu}\frac{dp}{dx'}$, is the maximum velocity.

Since the flow is driven by a constant pressure gradient, it is sufficiently assumed that the maximum velocity ($u_m = -\frac{a^2}{\mu}\frac{dp}{dx'}$) contained in the middle of the channel in the plane Poiseuille flow with constant fluid properties (Schlichting, [27]).
Using Eq. (4) and dimensionless quantities (Eq. (5)), Eqs. (1 and 2) can be expressed as:

$$\frac{d^2u}{dy^2} - \mathrm{Re}\frac{du}{dy} - M^2 \sin^2 \alpha u + P = 0 \quad (6)$$

$$(1 + \varepsilon\theta)\frac{d^2\theta}{dy^2} + \varepsilon\left(\frac{d\theta}{dy}\right)^2 - \mathrm{Re}\,\mathrm{Pr}\frac{d\theta}{dy}$$

$$+Ec\Pr\left(\frac{du}{dy}\right)^2+Ec\Pr M^2 sin^2\alpha u^2=0 \quad (7)$$

where

$\mathrm{Re}=\frac{Va}{\nu}$, is the suction Reynolds number,

$M=B_0 a\left(\frac{\sigma}{\nu}\right)^{1/2}$, is the Hartmann number,

$\Pr=\frac{\rho C_p}{\mu}$, is the Prandtl number,

$Ec=\frac{u_m^2}{C_p\left(\theta_1-\theta_0\right)}$, is the Eckert number, and

$P=-\frac{a^2}{\mu u_m}\frac{dp}{dx'}$, is the dimensionless pressure gradient.

Normalize boundary conditions are:

$$\left.\begin{aligned} &u=0,\ \theta=0 \text{ at } y=0\\ &u=0,\ \theta=1 \text{ at } y=1\end{aligned}\right\} \quad (8)$$

3. Numerical solution

The coupled differential Eqs. (6 and 7) subjected to the boundary conditions given in Eq. (8) are solved using finite difference technique. In this method, the derivative terms, occurring in the governing differential equations, have been replaced by their finite difference approximations. Central difference approximations of second order accuracy have been used because they are more accurate than forward and backward differences. Then, an iterative scheme is used to solve the linearized system of difference equations. The linearized system of equations based on what represents in the present paper the step size by h, the finite difference equations corresponding to Eqs. (6 and 7) are given as:

$$\frac{u_{i+1}-2u_i+u_{i-1}}{h^2}-\mathrm{Re}\left(\frac{u_{i+1}-u_{i-1}}{2h}\right)$$
$$-M^2 sin^2\alpha u_i+P=0 \quad (9)$$

$$\left(1+\varepsilon\theta_i\right)\left(\frac{\theta_{i+1}-2\theta_i+\theta_{i-1}}{h^2}\right)+\varepsilon\left(\frac{\theta_{i+1}-\theta_{i-1}}{2h}\right)^2$$
$$-\mathrm{Re}\Pr\left(\frac{\theta_{i+1}-\theta_{i-1}}{2h}\right)+Ec\Pr\left(\frac{u_{i+1}-u_{i-1}}{2h}\right)^2$$
$$+Ec\Pr M^2 sin^2\alpha u_i^2=0 \quad (10)$$

On simplification of Eq. (9 and 10) for velocity u_i and temperature θ_i can be written as:

$$u_i=C_1\left(u_{i+1}+u_{i-1}\right)-C_2\left(u_{i+1}-u_{i-1}\right)+C_3 \quad (11)$$

$$\theta_i=0.5\left(\theta_{i+1}+\theta_{i-1}\right)+C_4\left(\theta_i\theta_{i+1}-2\theta_i^2+\theta_i\theta_{i-1}\right)$$
$$-C_5\left(\theta_{i+1}-\theta_{i-1}\right)+C_6\left(\theta_{i+1}-\theta_{i-1}\right)^2$$
$$+C_7\left(u_{i+1}-u_{i-1}\right)^2+C_8u_i^2 \quad (12)$$

where

$C_1=\frac{1}{2+h^2M^2sin^2\alpha}$, $C_2=\frac{h\mathrm{Re}}{2+h^2M^2sin^2\alpha}$,

$C_3=\frac{h^2P}{2+h^2M^2sin^2\alpha}$, $C_4=0.5\varepsilon$,

$C_5=\frac{h\mathrm{Re}\Pr}{4}$, $C_6=\frac{\varepsilon}{8}$, $C_7=\frac{Ec\Pr}{8}$ and

$C_8=\frac{Ec\Pr M^2sin^2\alpha}{2}$ are constants.

Then corresponding discretized boundary conditions take the form:

$$\left.\begin{aligned} &u_i=0,\ \theta_i=0 \text{ at } i=1\\ &u_i=0,\ \theta_i=1 \text{ at } i=m+1\end{aligned}\right\} \quad (13)$$

where i stands for y and m stands for the number of grid points inside the computational domain considered.

4. Results and discussion

In this investigation, the effect of variable thermal conductivity and the inclined uniform magnetic field on steady MHD plane Poiseuille flow between two parallel porous plates through non-uniform plate temperature are discussed numerically. The computational domain is divided into 100 uniform grid points. Numerical values for the velocity (u_i) and temperature (θ_i) have been iterated by Gauss Seidal iteration method in Matlab programming (Mathews and Fink [28] Umavathi and Chamkha [30]) to a suitable number. Therefore, the convergent solutions of u_i and T_i are considered to be achieved when the maximum differences between two successive iterations are less than a tolerance, 10^{-7} (Alkhawaja and Selmi [29]). The computed results of velocity and temperature are presented in terms of graphics for relevant parameters such as Hartmann number (M), suction Reynolds number (Re), Parndtl parameter (Pr), Eckert number (Ec), dimensionless pressure gradient (P), and variable thermal conductivity (ε).

Effects of various dimensionless parameters on the velocity profiles are shown in Figs. 2–5, fixing other flow parameters constant. Usually, the velocity profiles are parabolic in geometries with zero values at the channel walls due to no slip condition and attain their maximum value in the middle portion of the channel for $Re \ll 1$. In Fig. 2, it is observed that the fluid velocity decreases with increasing Hartmann number M. This is due to fact that strength of the Lorentz force increases with increasing Hartmann number values, which acts as a retardation to the fluid flow.

Fig. 3 shows the effect of different inclination angle (α) on the velocity. It is evident that an increase in inclination angle (α), decreases the velocity of the flow field, and maximum retardation of the velocity of flow occurs at the inclination angle $\alpha = 90^0$, signifies the intensity of Lorenz force is maximum which acts against the flow direction and has a tendency to slow down the motion of fluid flow. It confirms the analytical result obtained by Gupta et al. [9].

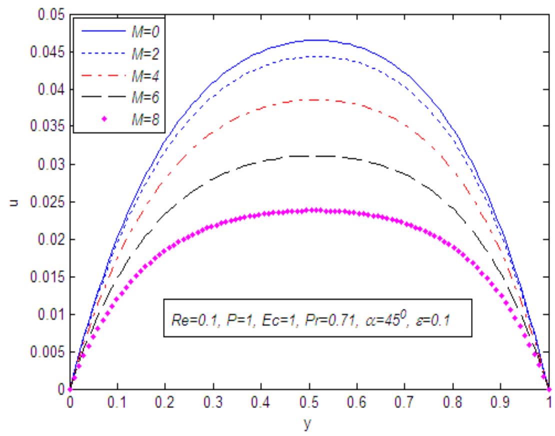

Fig. 2. Velocity profiles for different values of the Hartmann number M.

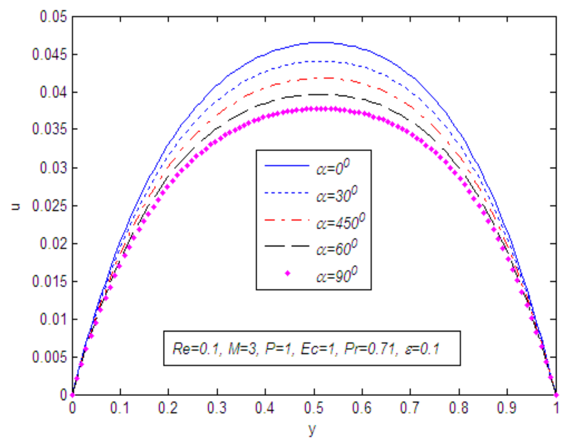

Fig. 3. Velocity profiles for different inclination angle α.

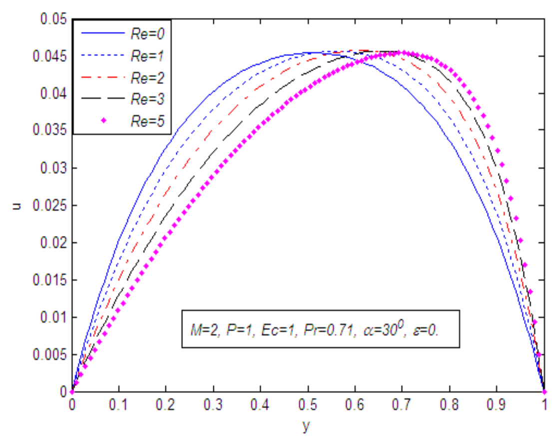

Fig. 4. Velocity profiles for different values of the suction Reynolds number Re.

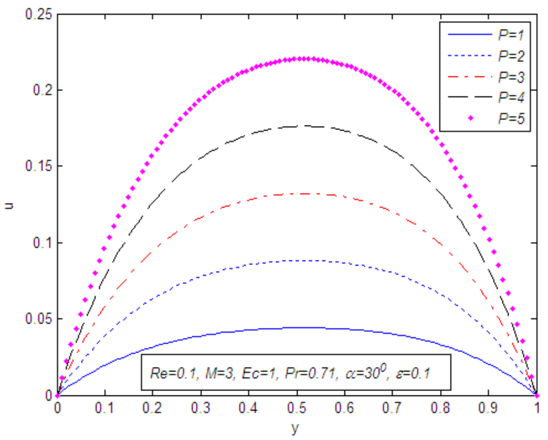

Fig. 5. Velocity profiles for different values of the dimensionless pressure gradient P.

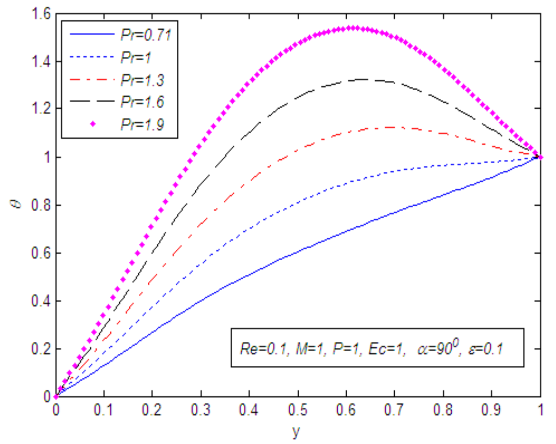

Fig. 8. Temperature field for different values of the Prandtl number Pr

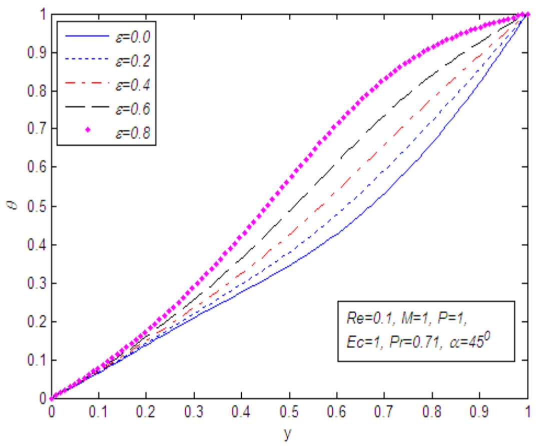

Fig. 6. Temperature field for different values of the variable thermal conductivity ε.

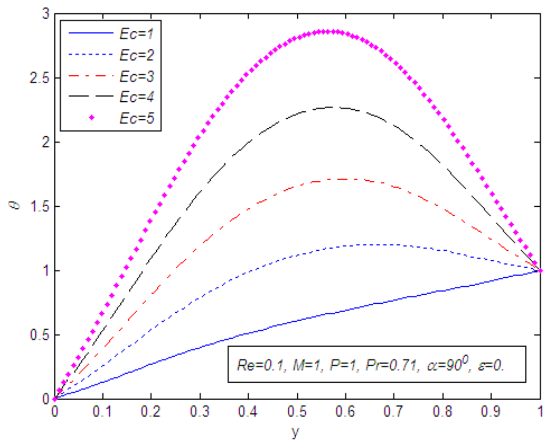

Fig. 9. Temperature field for different values of the Eckert number Ec

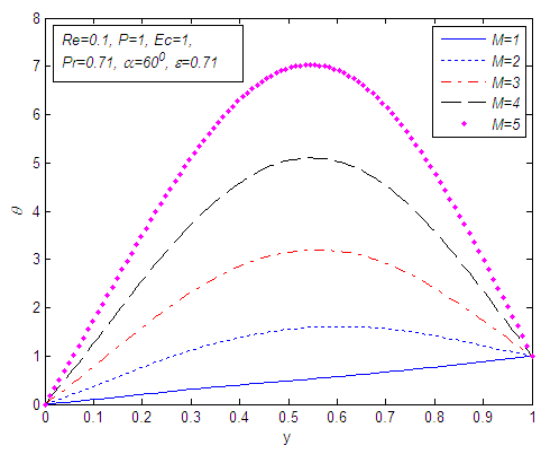

Fig. 7. Temperature field for different values of the Hartmann number M.

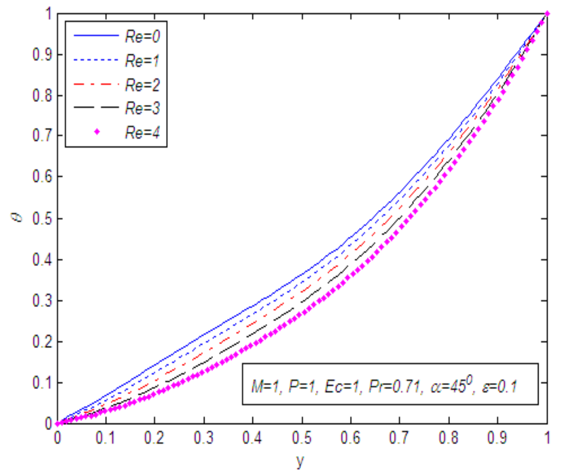

Fig. 10. Temperature field for different values of the suction Reynolds number Re

Fig. 4 presents the effect of suction Reynolds number Re on fluid velocity. It is observed that the fluid velocity is parabolic in geometry for $Re = 0$ (i.e., without injection or suction), then decreases and skews towards the upper plate as suction Reynolds number ($Re > 0$) increases due to increasing injection at the lower plate and increasing suction at the upper plate. This is good agreement with the result obtained by Eegunjobi and Makinde [20], and Das and Jana [22].

The effect of dimensionless pressure gradient P on fluid velocity is shown in Fig. 5. It is obvious from the Fig. 5 that the velocity profile increases with increasing dimensionless pressure gradient. It establishes the results of Kuiry and Bahadur [15].

The effects of various dimensionless parameters on the temperature profile are demonstrated in Figs. 6-9, fixing other flow parameters constant. The effect of variable thermal conductivity parameter (ε) on temperature field is shown in Fig. 6. It is observed that the variation of thermal conductivity affects temperature profiles. With the increase in the value of ε, the temperature of fluid increases.

Fig. 7 shows the influence of the Hartmann number (M) on the temperature field. As M increases the fluid temperature increases within the channel. The enhancement of temperature may be due to the presence of Joule heating (or Lorentz heating) in the energy equation, which serves as the additional heat source to the flow system.

The effect of Prandtl number Pr on temperature profile is depicted in Fig. 8. It is observed that fluid temperature increases for increasing values of Pr.

In Fig. 9, the effect of Eckert number Ec on temperature is depicted. It is noticed that temperature profile increases with the increasing value of Ec. This may be due to the facts that as Ec increases the viscous heating increases due to increasing convective heating at the upper plate leading to a rise in the fluid temperature.

The effect of suction Reynolds number Re on temperature profile is shown in Fig. 10. It is observed that the temperature profile decreases at all the points of fluid flow for increasing values of Reynolds number (Re), It may be attributed to the fact that injection or suction procedure absorbs the heat.

The computed results obtained in terms of graphics in this investigation are compared with earlier analytical and numerical works of authors Gupta et al. [9], Eegunjobi and Makinde [20], Kuiry and Bahadur [15], and Das and Jana [22]. It is observed that the results are in good agreement with those of earlier works.

5. Conclusions

In this paper, the effect of variable thermal conductivity and inclined uniform magnetic field on the plane Poiseuille flow of viscous incompressible electrically conducting fluid between two porous plates in the presence of a constant pressure gradient through non-uniform plate temperature with Joule heating are investigated. The non-linear differential equations for velocity and temperature are solved numerically by developing finite difference codes and using Gauss Seidal iteration scheme in Matlab software. Based on the computed results presented above in terms graphics, the following conclusions are made:

i. Fluid velocity decreases with increasing both Hartmann number (M) and inclination angle (α) values.
ii. Fluid velocity is parabolic in geometry for $Re = 0$ (i.e., without injection or suction). It decreases and skews towards the upper plate as suction Reynolds number (Re$>$ 0) increases.
iii. Fluid velocity increases with increasing dimensionless pressure gradient (P).
iv. Fluid temperature increases as variable thermal conductivity (ε), Eckert number (Ec), Prandtl number (Pr), Hartmann number (M), and inclination angle (α) increase.
v. Fluid temperature decreases with increasing suction Reynolds number (Re).

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How to cite this paper:

Muhim Chutia, "Effect of variable thermal conductivity and the inclined magnetic field on MHD plane poiseuille flow in a Porous channel with non-uniform plate temperature" Journal of Computational and Applied Research in Mechanical Engineering, Vol. 8, No. 1, pp. 75-84, (2018).

DOI: 10.22061/jcarme.2017.1620.1137

URL: http://jcarme.sru.ac.ir/?_action=showPDF&article=768