International Journal of Mathematical Archive-2(6), June - 2011, Page: 853-863
IJMA Available online through www.ijma.info ISSN 2229 – 5046

UNSTEADY FREE CONVECTIVE COUETTE FLOW OF HEAT GENERATING/ABSORBING FLUID IN POROUS MEDIUM

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(Received on: 29-05-11; Accepted on: 09-06-11)

ABSTRACT

The exact solution of unsteady free convective Couette flow of a viscous incompressible heat generating/ absorbing fluid confined between two vertical parallel plates in a porous medium is performed in this paper. The flow is set up by the buoyancy force arising from the temperature gradient occurring as a result of asymmetric heating of the parallel plates as well as constant motion of one of the plates. The non-dimensional governing equations are solved in closed form by using Laplace-transform technique. Numerical results for velocity, temperature, skin-friction, and Nusselt numbers are presented graphically. The effect of different parameters like Prandtl number (Pr), Grashof number (Gr), heat generation/ absorption parameter (S) and Darcy number (Da) on the flow situations are discussed. The steady state solution of the flow field is derived separately. It is observed that the transient solutions at large time coincides with the steady-state solutions.

Keywords: *Couette flow, porous medium, free convection, exact solution, heat generation/absorption.*

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1. INTRODUCTION:

Couette flow is one of the basic flow in fluid dynamics that refers to the laminar flow of a viscous fluid in the space between two parallel plates, one of which is moving relative to the other. The flow is driven by virtue of viscous drag force acting on the fluid and the applied pressure gradient parallel to the plates. Couette flow is frequently used in physics and engineering to illustrate shear-driven fluid motion. Some important application areas of Couette motion are MHD power generators and pumps, aerodynamics heating, electrostatic precipitation, polymer technology, petroleum industry, purification of crude oil etc. This problem has been studied extensively for horizontal parallel plates by many researchers since times. The flow of a viscous, incompressible fluid past an impulsively started horizontal flat plate was first studied by Stoke's. [21]. Soundalgekar [22] considered the same problem with convection currents. Choi et. al. [10] considered the buoyancy effects on plane Couette flow heated uniformly from below with constant heat flux. Unsteady Couette flow in rotating system was considered by Das et. al. [3]. The Hall effect on unsteady Couette flow with heat transfer was presented by Attia et. al. [11] . Schlichting and Gersten [23] first presented an analysis of flow formation in Couette motion between two vertical parallel plates. This problem has got fundamental importance as it provides an exact solution and shows the variation of velocity profile with time , approaching a linear distribution asymptotically.

Free convection in channels formed by vertical plates has received attention among the researchers in last few decades due to it's widespread importance in engineering applications like cooling of electronic equipments, design of passive solar systems for energy conversion, design of heat exchangers, human comfort in buildings, ,thermal regulation processes and many more. Researchers in this field such as Singh [1], Singh et. al.[2], Jha et.al. [5], Joshi [14], Miyatake et. al. [19], Tanaka et. al. [15], Mohanty [13] , Narahari et. al. [16] discussed free convection Couette flow in vertical channels under different physical situations. Chaudhary et. al [20] and Narahari [17] has studied the effects of thermal radiation on unsteady free convection Couette flow between two vertical parallel plates, as radiative heat transfer plays an important role in processes like nuclear power plants, gas turbines, astrophysical flows and solar power technology. Buouyancy driven flows over porous materials enhances heat transfer processes. Makinde et. al. [18] considered the problem of MHD steady flow in a channel filled with porous material with slip at the boundaries. On the effectiveness of variation in the physical variables on the generalized Couette flow with heat transfer in a porous medium was studied by Hazem Ali Attia [12]. He derived the solution numerically for steady generalized Couette flow. Israel-Cookey et. al. [8] studied unsteady MHD free-convection flow past an infinite heated vertical plate in a porous medium with time dependent suction. Recently Israel-Cookey [9] has solved the same problem with periodic wall temperature.

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In all these above mentioned studies the influence of internal heat generation/absorption phenomenon has not taken into consideration. However the heat generating/absorbing fluid may have strong influence on this type of flows. There are lots of physical and industrial phenomenons which involve natural convection driven by internal heat generation/absorption. Jha [4] considered the effect of heat sink in transient free convective flow in a vertical channel. Recently Jha et. al [6] investigates the free convective flow of heat generating/absorbing fluid between vertical porous plates with periodic heating. Very recently Jha et. al.[7] studied the unsteady free convective Couette flow of heat generating/ absorbing fluid. The convective current is set up due to asymmetrical heating of the plates. They have used Laplace's transform technique to find an exact solution for velocity and temperature.

In this present paper we investigate the unsteady Couette motion of a heat generating/absorbing fluid in a porous medium. The flow is set up due to impulsive motion of one of the plates as well as asymmetric heating of the plates. The non-dimensional governing equations are solved in closed form for velocity and temperature using Laplace's transform technique. The results obtained in this way are used to find skin-friction, Nusselt number and mass flux.. The effect of different parameters on velocity, temperature, skin-friction, Nusselt number and mass flux are discussed by plotting in graphs.

2. MATHEMATICAL ANALYSIS:

We consider the flow of a viscous incompressible heat generating/absorbing fluid between two infinite vertical parallel plates at h distance apart from each other. The fluid is flowing in a porous medium. We consider a two dimensional co-ordinate system to analyze the flow, where x' axis is taken vertically along one of the plates and y' axis is taken normal to it. At time $t' \leq 0$, the fluid is at rest and temperature of the fluid as well as that of both the plates is kept at T_0. At time $t' > 0$, the temperature of the plate $y' = 0$ raised or fell to T_w and thereafter maintained constant, while the other plate $y' = h$ remains at same temperature T_0. Also, the plate $y' = 0$ moves in it's own plane impulsively at a uniform velocity $u' = U$, while the other plate remains at rest. Since the plates are infinite in x' directions, so the flow variables do not change in this direction, as such flow is essentially one dimensional.

Using Boussinesq's approximation and Darcy's law the vertical equation of motion in a fluid saturated porous medium becomes-

$$\frac{\partial u'}{\partial t'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g\beta\left(T' - T_0\right) - \frac{\nu}{K^*} u' \tag{1}$$

and the corresponding energy equation becomes-

$$\rho C_P \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial y'^2} - Q_0\left(T' - T_0\right) \tag{2}$$

The initial and boundary conditions are considered as follows

$$\begin{aligned} &t' \leq 0 : u' = 0, && T' = T_0, && \text{for } 0 \leq y' \leq h \\ &t' > 0 : u' = U && T' = T_w && \text{at } y' = 0, \\ &\qquad\quad u' = 0 && T' = T_0 && \text{at } y' = h \end{aligned} \tag{3}$$

On introducing the following non-dimensional quantities,

$$\begin{aligned} &y = \frac{y'}{h}, \quad t = \frac{t'\nu}{h^2}, \quad \Pr = \frac{\mu C_P}{k}, \quad \theta = \frac{T' - T_0}{T_w - T_0}, \\ &Gr = \frac{g\beta h^2\left(T_w - T_0\right)}{\nu U}, \quad S = \frac{Q_0 h^2}{k}, \quad Da = \frac{K^*}{h^2} \end{aligned} \tag{4}$$

Equations (1) and (2) take the non-dimensional form:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\theta - \frac{1}{Da} u \tag{5}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} - \frac{S}{\Pr}\theta \tag{6}$$

The non-dimensional form of the initial and boundary conditions are-

$$
\begin{aligned}
&t \le 0 : u = 0, \quad \theta = 0, \quad \text{for } 0 \le y \le 1 \\
&t > 0 : u = 1, \quad \theta = 1 \quad \text{at } y = 0, \\
&\qquad\quad u = 0, \quad \theta = 0 \quad \text{at } y = 1
\end{aligned} \tag{7}
$$

Here Pr is the Prandtl number, which is inversely proportional to the thermal diffusivity of the working fluid. S is the heat generation/absorption parameter. Positive values of S denote heat absorption while it's negative values denote heat generation. Gr is the Grashof number. The physical variables involved in equations (5) and (6) are defined in the nomenclature.

Equations (5) and (6) are solved under the conditions (7), by using Laplace's transform technique. The solutions thus obtained for velocity and temperature fields are-

Case I: $\Pr \neq 1$

Solving equations (5) and (6) under initial and boundary conditions (7), using Laplace transform technique, we have obtained the expressions for velocity and temperature as

$$
\theta = \cosh y\sqrt{S} - \coth\sqrt{S}\sinh y\sqrt{S} - \sum_{n=0}^{\infty} \frac{2n\pi \sin n\pi y}{n^2\pi^2 + S} \exp\left(-\tfrac{t}{\Pr}\left(n^2\pi^2 + S\right)\right) \tag{8}
$$

$$
\begin{aligned}
u = &\left(1 + \frac{Gr}{S - D'}\right)\left(\cosh y\sqrt{D'} - \coth\sqrt{D'}\sinh y\sqrt{D'}\right) \\
&+ \frac{Gr}{S - D'}\left\{\coth\sqrt{S}\sinh y\sqrt{S} - \cosh y\sqrt{S}\right\} - \sum_{n=0}^{\infty} \frac{2n\pi \sin n\pi y}{a_4} \exp(-t a_3) \\
&+ \frac{2Gr}{(\Pr - 1)} \sum_{n=0}^{\infty} \frac{n\pi \sin n\pi y}{a_4\left\{n^2\pi^2 + a_1\right\}} \exp(-t a_4) \\
&- \frac{2\Pr\ Gr}{(\Pr - 1)} \sum_{n=0}^{\infty} \frac{n\pi \sin n\pi y}{\left(n^2\pi^2 + S\right)\left\{n^2\pi^2 + a_1\right\}} \exp(-t a_5)
\end{aligned} \tag{9}
$$

where $D' = \dfrac{1}{Da}$, $\quad a_1 = \dfrac{\Pr D' - S}{\Pr - 1}$, $\quad a_2 = \dfrac{\Pr D' - S}{\Pr(\Pr - 1)}$

$a_3 = \dfrac{D' - S}{\Pr - 1}$, $\quad a_4 = \left(n^2\pi^2 + D'\right)$, $\quad a_5 = \dfrac{n^2\pi^2 + S}{\Pr}$

Case II: $\Pr = 1$

If Pr =1, the expressions for temperature and velocity obtained in (8) and (9) respectively become undefined. Therefore we derived the expressions for velocity and temperature, taking Pr = 1 in equations (5) and (6) and solving them under initial and boundary conditions (7). The results thus obtained are-

$$
\theta = \cosh y\sqrt{S} - \coth\sqrt{S}\sinh y\sqrt{S} - 2\sum_{n=0}^{\infty} \frac{n\pi \sin n\pi y}{\left(n^2\pi^2 + S\right)} \exp\left\{-t\left(n^2\pi^2 + S\right)\right\} \tag{10}
$$

$$
\begin{aligned}
u = &\left(1 + \frac{Gr}{S - D'}\right)\left(\cosh y\sqrt{D'} - \coth\sqrt{D'}\sinh y\sqrt{D'}\right) - \frac{Gr}{S - D'}\left(\cosh y\sqrt{S}\right. \\
&\left. - \coth\sqrt{S}\sinh y\sqrt{S}\right) - 2\left(1 + \frac{Gr}{S - D'}\right) \sum_{n=0}^{\infty} \frac{n\pi \sin n\pi y}{a_4} e(-t a_4) \\
&+ \frac{2Gr}{S - D'} \sum_{n=0}^{\infty} \frac{n\pi \sin n\pi y}{\left(n^2\pi^2 + S\right)} \exp\left\{-t\left(n^2\pi^2 + S\right)\right\}
\end{aligned} \tag{11}
$$

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2.1 STEADY STATE SOLUTION:

At a relatively larger time, the temperature and velocity are not influenced by time. At this state, the flow becomes steady so that the time derivative of velocity and temperature can be neglected. So, putting $\frac{\partial u}{\partial t} = 0$ and $\frac{\partial \theta}{\partial t} = 0$ in equations (5) and (6) respectively, we have obtained the steady state solution as-

$$\theta^* = \frac{\sinh(1-y)\sqrt{S}}{\sinh\sqrt{S}} \quad (12)$$

$$u^* = \left(1+\frac{Gr}{S-D'}\right)\left\{\cosh y\sqrt{D'} - \coth\sqrt{D'}\sinh y\sqrt{D'}\right\} - \frac{Gr\sinh(1-y)\sqrt{S}}{(S-D')\sinh\sqrt{S}} \quad (13)$$

It can readily be observed that as t$\rightarrow \infty$, the unsteady solutions given in (8) and (9) reduce to the steady state solutions (12) and (13) obtained above.

3. SKIN-FRICTION:

Knowing the velocity field, we now obtain the skin friction (τ) on the walls of the channel. In non dimensional form skin-friction is given by

$$\tau = -\left.\frac{\partial u}{\partial y}\right|_{y=0}$$

Using the expression for velocity (u) given by (9), we derive:

on the isothermal moving plate,

$$\tau_0 = -\left.\frac{\partial u}{\partial y}\right|_{y=0}$$

$$= \sqrt{D'}\coth\sqrt{D'}\left(1+\frac{Gr}{S-D'}\right) - \frac{Gr\sqrt{S}}{(S-D')}\coth\sqrt{S} + \frac{2\Pr\ Gr}{(\Pr-1)}$$

$$\sum_{n=0}^{\infty}\frac{n^2\pi^2\exp(-ta_5)}{(n^2\pi^2+S)\{n^2\pi^2+a_1\}} + 2\sum_{n=0}^{\infty}\frac{n^2\pi^2\exp(-ta_4)}{a_4}\left\{1-\frac{Gr}{(\Pr-1)(n^2\pi^2+a_1)}\right\} \quad (14)$$

while on the cold stationary plate

$$\tau_1 = -\left.\frac{\partial u}{\partial y}\right|_{y=1}$$

$$= \left(!+\frac{Gr}{S-D'}\right)\frac{\sqrt{D'}}{\sinh\sqrt{D'}} - \frac{Gr\sqrt{S}}{(S-D')\sinh\sqrt{S}}$$

$$+2\sum_{n=0}^{\infty}\left(1-\frac{Gr}{(\Pr-1)(n^2\pi^2+a_1)}\right)\frac{n^2\pi^2\cos n\pi\exp(-ta_4)}{a_4}$$

$$+\frac{2\Pr\ Gr}{(\Pr-1)}\sum_{n=0}^{\infty}\frac{n^2\pi^2\cos n\pi\exp(-ta_5)}{(n^2\pi^2+S)(n^2\pi^2+a_1)} \quad (15)$$

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4. NUSSELT NUMBER:

In non-dimensional form, the coefficient of heat transfer, which is generally known as Nusselt number is given by-

$$Nu = -\left.\frac{\partial \theta}{\partial y}\right|_{y=0}$$

Using the expression for θ given by (8), we can find the rate of heat transfer at the moving hot plate as-

$$\begin{aligned} Nu_0 &= -\left.\frac{\partial \theta}{\partial y}\right|_{y=0} \\ &= \sqrt{S}\coth\sqrt{S} + \sum_{n=0}^{\infty}\frac{2n^2\pi^2\exp(-ta_5)}{n^2\pi^2+S} \end{aligned} \tag{16}$$

while on the cold stationary plate

$$\begin{aligned} Nu_1 &= -\left.\frac{\partial \theta}{\partial y}\right|_{y=1} \\ &= \frac{\sqrt{S}}{\sinh\sqrt{S}} + \sum_{n=0}^{\infty}\frac{2n^2\pi^2\cos n\pi\exp(-ta_5)}{n^2\pi^2+S} \end{aligned} \tag{17}$$

where the variables involved in (14), (15), (16) and (17) are defined earlier.

5. VOLUMETRIC FLOW RATE (MASS FLUX):

In non-dimensional form, the volumetric flow rate between the plates is obtained by using the following integral

$$Q = \int_0^1 u(y,t)dy \tag{18}$$

To know the effects of various parameters, we derive the expression of mass flux between the plates using the expression of velocity u given by (9) as :

$$\begin{aligned} Q = &\left(1+\frac{Gr}{S-D'}\right)\left(\frac{\coth\sqrt{D'}-\operatorname{cosech}\sqrt{D'}}{\sqrt{D'}}\right)+\frac{Gr}{(S-D')\sqrt{S}}\left(\operatorname{cosech}\sqrt{S}-\coth\sqrt{S}\right) \\ &-2\sum_{n=1}^{\infty}\frac{\exp(-a_4 t)}{a_4}(\cos n\pi-1)\left(1-\frac{Gr}{(\Pr-1)(n^2\pi^2+a_1)}\right) \\ &-\frac{2\Pr Gr}{(\Pr-1)}\sum_{n=1}^{\infty}\frac{(\cos n\pi-1)\exp(-ta_5)}{(n^2\pi^2+S)(n^2\pi^2+a_1)} \end{aligned} \tag{19}$$

In the steady state, the mass flux is obtained by using (13) in (18) as:

$$\begin{aligned} Q^* = &\frac{1}{\sqrt{D'}}\left(1+\frac{Gr}{S-D'}\right)\left\{\sinh\sqrt{D'}-\coth\sqrt{D'}\left(\cosh\sqrt{D'}-1\right)\right\} \\ &-\frac{Gr}{(S-D')\sqrt{S}}\left(\coth\sqrt{S}-\operatorname{cosech}\sqrt{S}\right) \end{aligned} \tag{20}$$

6. RESULTS AND DISCUSSIONS:

An unsteady free convection Couette motion of viscous incompressible fluid is considered in a vertical channel formed by two infinite vertical parallel plates filled with porous medium. The objective of the present paper is to investigate

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the influence of Prandtl number (Pr), Grashof number (Gr), Darcy number (Da) and internal heat generation/absorption (S) on the fluid velocity, temperature, skin-friction, Nusselt number and mass flux etc. The value of Prandtl number are chosen as .008, .71 and 7 so as to accommodate fluids like mercury, air and water respectively. The Grashof number for air at 20^0C is calculated as 18 and 45, when the temperature difference between the plates are taken as .2 and .5 and the other parameters as υ=0.15, h = 2.0 cm, g = 980 cms^{-2} , β = 1/293, U = 1 cms^{-1}.The internal heat generation/absorption parameter (S) is chosen arbitrarily between 0 and 6. Since the effect of heat generation is exactly opposite to that of heat absorption (Jha and Ajibade, 2009), so here we consider only the positive values of (S), that corresponds to heat absorption only and interpret the results for heat generation from it. The value of Darcy number (Da) is chosen as .5, 2 and 5.

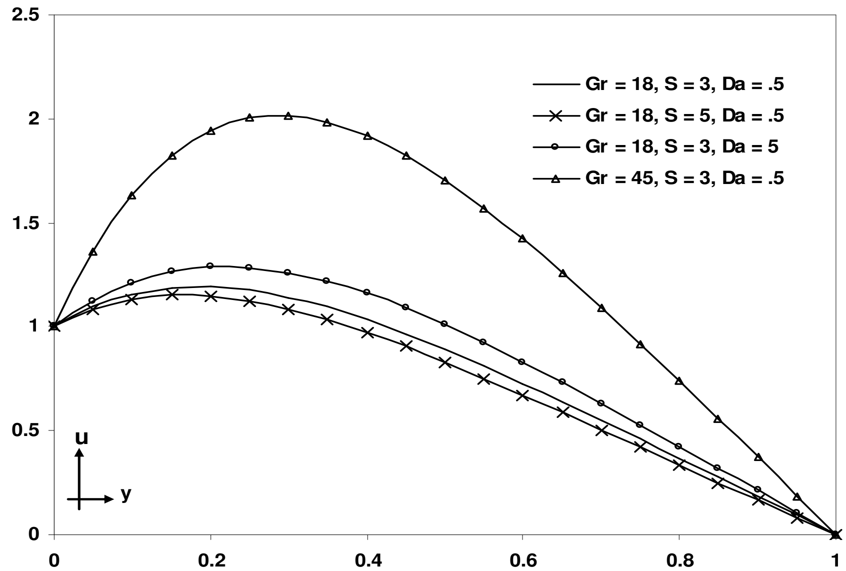

Fig 1: Velocity profiles for Pr = .71

Fig. 1 & 2 reveals the effect of various flow parameters on velocity profile. In Figures we observe that velocity near the moving plate exceeds the velocity at the plate and then decreases to zero value on the stationary plate. In Fig 1 velocity is observed to increase as Gr and Da increases and decrease as S increases. As S increases, heat absorbing capacity of the fluid increases which decreases fluid temperature and heance the fluid velocity. Increase in Gr leads to an increase in velocity, this is because, increase in Gr means more heating and less density. Again presence of porous medium produces a resisting force in the flow field. So, as Da increases resistance in the flow field decreases and as such velocity increases.

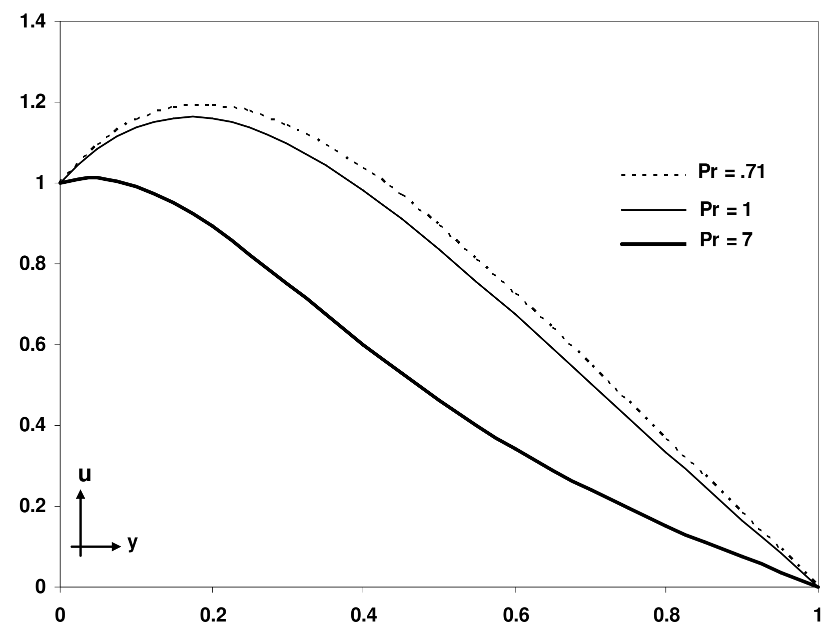

Fig 2: Effect of Pr on velocity profile (Gr = 18, S = 3, Da = .5)

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Fig 2 shows the effect of Prandtl number Pr on velocity profile. It is clear from figure that velocity decreases as Pr increases. This is due to the reason that fluid with high Prandtl number has high viscosity and hence moves slow.

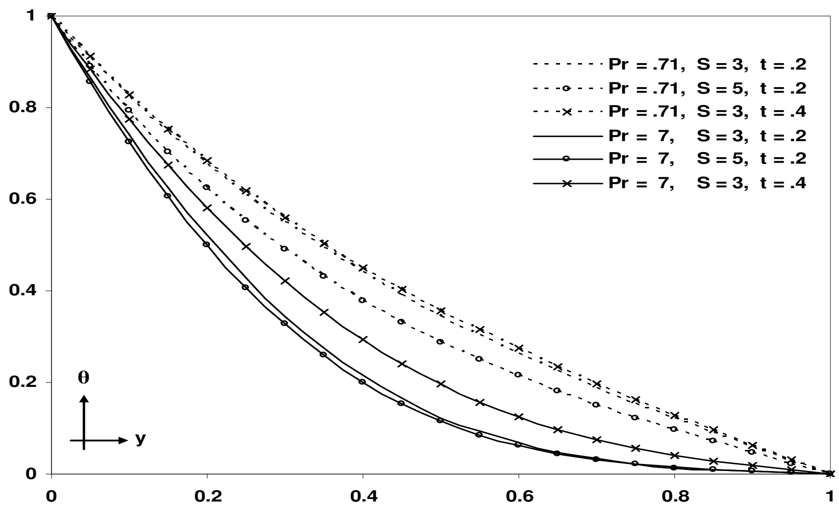

Fig 3: Temperature profile for different values of Pr, S and t

Fig 3 presents the temperature profile for different values of Pr, S and t. It is observed that temperature decreases gradually from highest value on the heated moving plate to a zero value on the cold stationary plate. Temperature increases with time. Temperature is also decreases with an increase in both Pr and S. This is because fluids with large Pr have low thermal diffusivity which causes low heat penetration resulting in reduced thermal boundary layer.

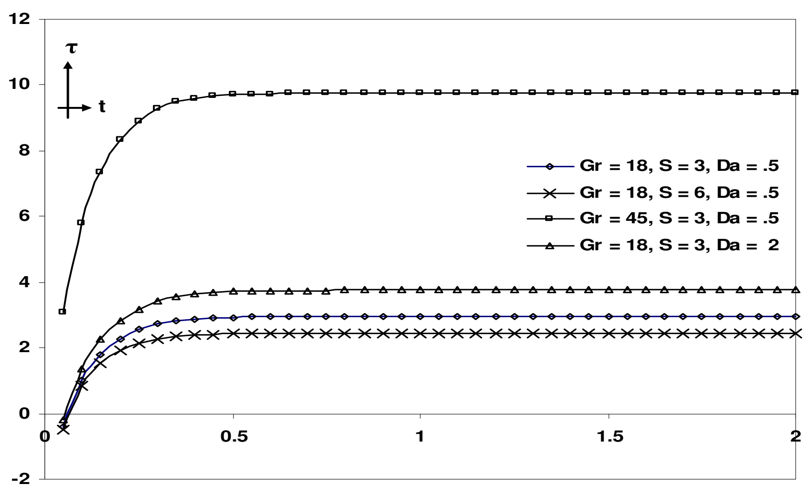

Fig 4: Skin-friction on the moving plate for Pr = .71

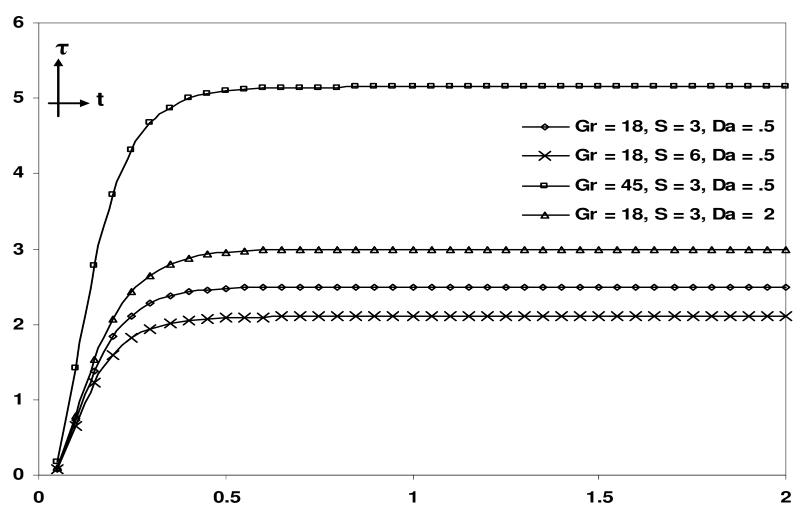

Fig 5: Skin-friction on the cold stationary plate for Pr = .71

Skin-friction on the boundary plates against time for different values of the flow parameters (Gr= 18, 45; S = 3, 6; Da = .5, 2) are presented in Figs 4 & 5 for air (Pr=.71). It is observed that skin-friction increases with time and finally reach a steady state for both the plates. Skin-friction is also observed to increase as Gr and Da increase and decrease as S increases on both the plates.

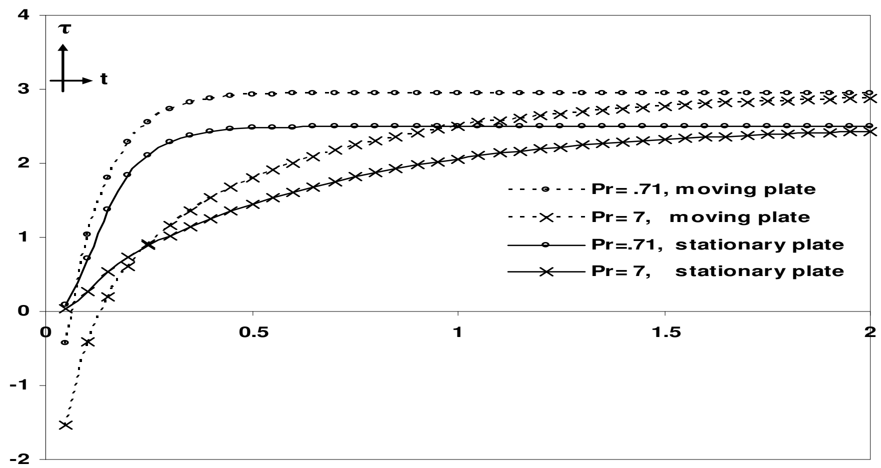

Fig 6: Effect of Pr on skin-friction for both moving as well as stationary plates.

Fig 6 presents skin-friction profile for air and water on both the plates. It is observed that skin-friction is more in air (Pr=.71) than in water (Pr= 7) on both the plates. Also in case of water skin-friction does not reach a steady state (Fig 6). Noteworthy to mention here that skin-friction is higher on the moving plate as compared to the stationary plate.

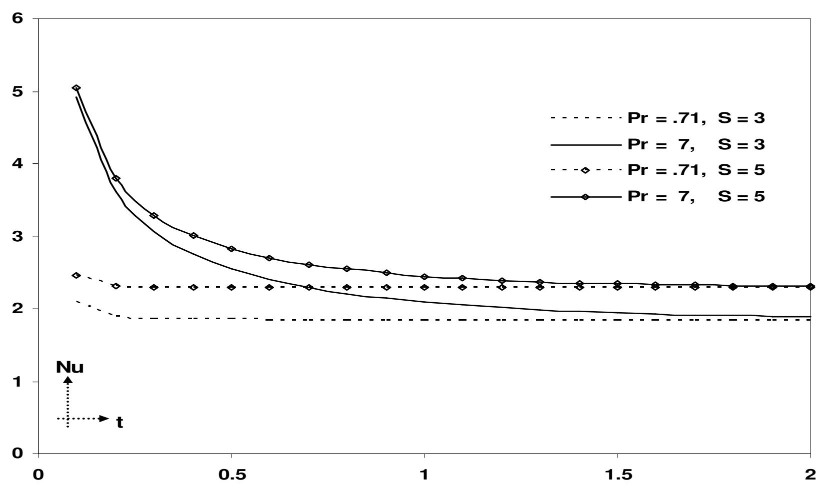

Fig 7: Rate of heat transfer on the moving plate

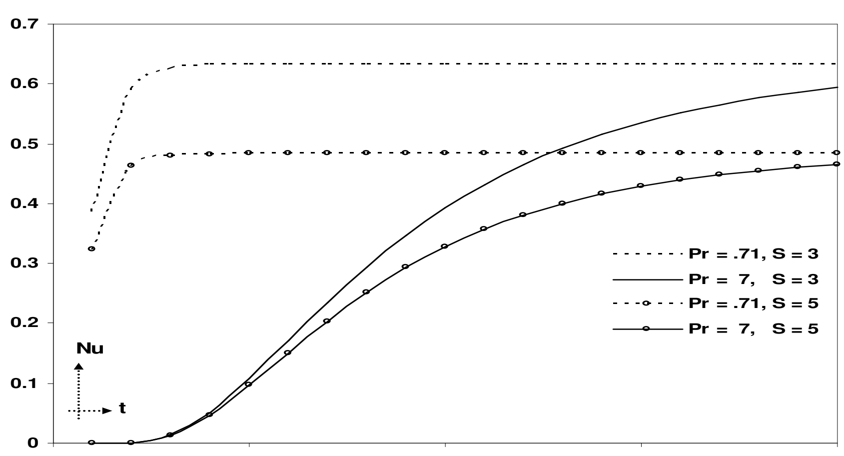

Fig 8: Rate of heat transfer on the cold stationary plate

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Fig 7 & 8 depicts rate of heat transfer on the channel plates. In figs Nusselt number (Nu) decreases with time on the moving plate while it increases with time on the stationary plate. Nusselt number is also observed to increase on the moving plate and decrease on the stationary plate as heat sink parameter S increases for both air and water. The influence of Pr on rate of heat transfer is similar to that of S, since increase in Pr results to a decrease in the temperature.

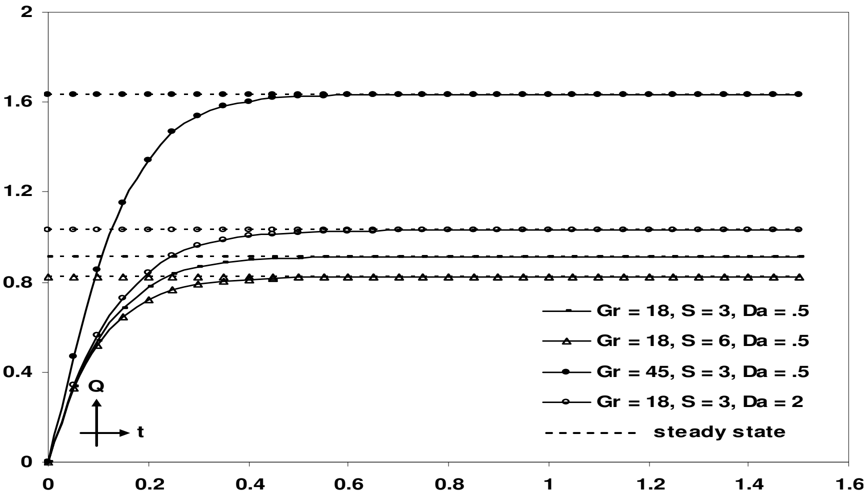

Fig 9: Mass flux for different flow parameters when Pr = .71

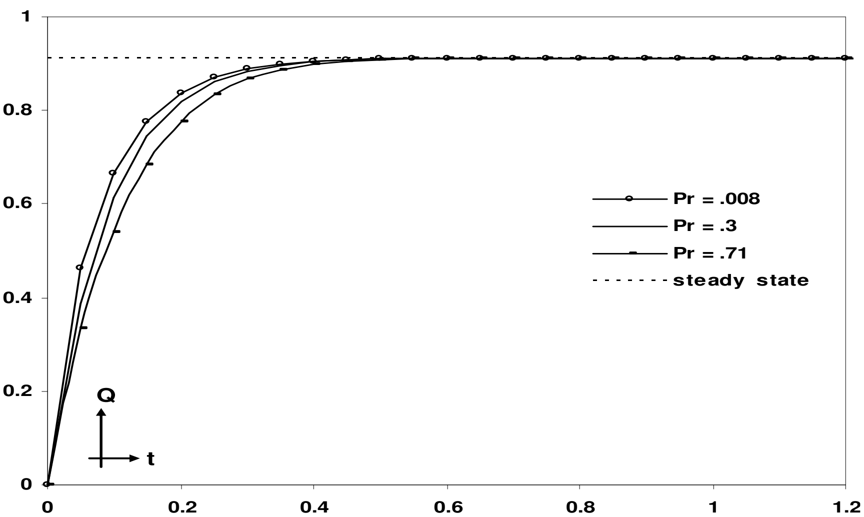

Fig 10: Mass flux for different values of Pr (Gr = 18, S = 3, Da = .5)

Fig 9 & 10 shows the mass flux within the channel against time for different values of Gr (18, 45) ; Pr (.008, .3, .71) ; S (3, 6) and Da (.5, 2) . From Fig 9 mass flux is observed to increase as Gr and Da increases and decrease as S increases. This is due to the reason that increases in Gr and Da leads to an increase in velocity and hence the mass flux, whereas increase in S leads to a decrease in velocity and so also the mass flux. Fig 10 reveals that mass flux is higher for mercury (Pr=.008) as compared to air (Pr = .71), since mercury possesses higher velocity and temperature than air. Mass flux is also observed to decrease as Pr increases until it's influence is nullified at the steady state.

7. CONCLUSIONS:

In this paper a natural convection flow of heat generating/absorbing fluid past a porous medium in a vertical channel is considered. The effects of governing parameters on the velocity, temperature, skin-friction, Nusselt number and mass flux are discussed with the help of graphs. The following conclusions have been derived:

(i) Velocity increases as Gr and Da increase and decreases as Pr and S increase.

(ii) Temperature decreases as both Pr and S increase.

(iii) Skin-friction increases with time on both the plates. Skin-friction is more in air than in water.

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(iv) Skin-friction decreases as heat absorption increases on both the plates.

(v) Rate of heat transfer decreases with time on the moving plate, whereas it increases with time on the stationary plate.

(vi) An increase in heat absorption increases the rate of heat transfer on the moving plate and decreases the rate of heat transfer on the stationary plate.

(vii) Increase in Gr and Da leads to an increase in mass flux. On the other hand increase in heat absorption decrease the mass flux.

Nomenclature:

C_p - specific heat at constant pressure
g - acceleration due to gravity
Gr - Grashof number
h - width of the channel
Pr - Prandtl number
Da - Darcy number
S - dimensionless heat source/sink parameter
$t^{/}$ - dimensional time
t - dimensionless time
T_0 - initial temperature of the fluid at ($t^{/} \leq 0$)
T_w - temperature of wall $y^{/} = 0$ at ($t^{/} > 0$)
$T^{/}$ - dimensional fluid temperature
K^* - permeability of porous medium
K - thermal conductivity
$u^{/}$ - dimensional velocity
u - dimensionless velocity
U - dimensional velocity of the moving plate
$x^{/}$ - vertical axis along the direction of flow
$y^{/}$ - co-ordinate perpendicular to the plate
y - dimensionless co-ordinate perpendicular to the plate

Greek alphabets

β - co-efficient of thermal expansion
ν - kinematic viscosity
μ - co-efficient of viscosity

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