Int. J. of Applied Mechanics and Engineering, 2022, vol.27, No.2, pp.77-86
DOI: 10.2478/ijame-2022-0020

HEAT TRANSFER IN OSCILLATING FLOW THROUGH POROUS MEDIUM WITH DISSIPATIVE HEAT

M. GURIA
Department of Mathematics, Ghatal Rabindra Satabarsiki Mahavidyalaya
Paschim Medinipur, West Bengal, INDIA
E-mail: mrinmoy9832@yahoo.com

In this paper, heat transfer in flow between two horizontal parallel porous plates through a porous medium when the upper plate oscillates in its own plane has been analyzed taking into account the effect of viscous dissipation. An increment in the Prandtl number or Reynolds number results in an increment of the temperature profile. With an increase in viscous dissipative heat the temperature distribution decreases.

Key words: injection, suction, transverse sinusoidal, transpiration cooling, viscous dissipation.

1. Introduction

The problem of Couette flow is applied in transpiration cooling. This technology is used in turbojet and rocket engines, exhaust nozzles and gas turbine blades. Gersten and Gross [1] studied a three dimensional flow and heat transfer past a porous plate by applying periodic suction. Singh [2] and Singh [3] studied a three dimensional flow and heat transfer along a porous plate. Singh *et al.* [4] studied a three dimensional free convection flow and heat transfer along a porous vertical plate. Guria and Jana [5] studied the unsteady three dimensional flow past a vertical porous plate subjected to time dependent periodic suction. The problem of transpiration cooling with the appication of transverse sinusoidal injection/suction velocity distribution was studied by Singh [6]. Sing and Sharma [7] also studied a three dimensional Couette flow in the presence of a magnetic field. Guria and Jana [8] studied a unsteady three dimensional flow and heat transfer between two horizontal plates subjected to periodic suction. Guria *et al.* [9] extended this problem by applying oscillation of the upper plate in its own plane.

Flows through porous media have many application in chemical engineering for filtration and purification processes. A viscous flow past a porous plate through a porous medium was studied by Varshney [10]. An unsteady flow past a vertical porous plate through a porous medium was studied by Raptis [11]. Raptis and Perdikis [12] studied an oscillatory flow past a vertical porous plate through a porous medium. Singh and Sharma [13] investigated a three dimensional Couette flow and heat transfer through porous media. Singh and Sharma [14] investigated a three dimensional free convection flow and heat transfer past a vertical porous plate by applying periodic permeability. Guria *et al.* [15] studied a free convection flow through a porous medium bounded by vertical porous plates. Guria *et al.* [16] also studied a three dimensional Couette flow through porous media with an upper plate in its plane. Guria *et al.* [17] studied the effect of radiation on a three dimensional flow past a vertical porous plate through a porous medium. Guria [18] also studied the radiation effect on a three dimensional flow through a vertical channel embedded in a porous medium.

The objective of this paper is to study the heat transfer taking the viscous dissipative effect into account on flow between two infinite horizontal parallel porous plates through a porous medium, when the upper plates oscillates in its own plane. The velocity distribution has already obtained by Guria *et al.* [16].

2. Basic equations

Consider an unsteady flow between two infinite parallel flat porous plates through a porous medium separared at a distance d . The upper plate oscillates in its own plane with

$$u^{\star}=U\left[1+\epsilon e^{i\omega^{\star}t^{\star}}\right] \tag{2.1}$$

where $\omega^{\star}$ is the frequency of the oscillations, $t^{\star}$ is the time and U is the free stream velocity. The $x^{\star}$ axis is taken in the direction of the flow. The upper plate is subjected to a constant suction V_0 and the lower plate to a transverse sinusoidal injection

$$v^{\star}=-V_0\left[1+\epsilon\cos\left(\frac{\pi z^{\star}}{d}\right)\right]. \tag{2.2}$$

Denoting velocity components $u^{\star},v^{\star},w^{\star}$ in the directions of the $x^{\star}-,y^{\star}-$, and $z^{\star}-$ axes respectively, the flow is governed by the following equations

$$\frac{\partial v^{\star}}{\partial y^{\star}}+\frac{\partial w^{\star}}{\partial z^{\star}}=0, \tag{2.3}$$

$$\frac{\partial u^{\star}}{\partial t^{\star}}+v^{\star}\frac{\partial u^{\star}}{\partial y^{\star}}+w^{\star}\frac{\partial u^{\star}}{\partial z^{\star}}=\nu\left(\frac{\partial^2 u^{\star}}{\partial y^{\star 2}}+\frac{\partial^2 u^{\star}}{\partial z^{\star 2}}\right)-\frac{\nu u^{*}}{K^{*}}, \tag{2.4}$$

$$\frac{\partial v^{\star}}{\partial t^{\star}}+v^{\star}\frac{\partial v^{\star}}{\partial y^{\star}}+w^{\star}\frac{\partial v^{\star}}{\partial z^{\star}}=-\frac{1}{\rho}\frac{\partial p^{\star}}{\partial y^{\star}}+\nu\left(\frac{\partial^2 v^{\star}}{\partial y^{\star 2}}+\frac{\partial^2 v^{\star}}{\partial z^{\star 2}}\right)-\frac{\nu v^{*}}{K^{*}}, \tag{2.5}$$

$$\frac{\partial w^{\star}}{\partial t^{\star}}+v^{\star}\frac{\partial w^{\star}}{\partial y^{\star}}+w^{\star}\frac{\partial w^{\star}}{\partial z^{\star}}=-\frac{1}{\rho}\frac{\partial p^{\star}}{\partial z^{\star}}+\nu\left(\frac{\partial^2 w^{\star}}{\partial y^{\star 2}}+\frac{\partial^2 w^{\star}}{\partial z^{\star 2}}\right)-\frac{\nu w^{*}}{K^{*}} \tag{2.6}$$

where ν is the kinematic coefficient of viscosity, ρ is the density, $p^{\star}$ is the fluid pressure, K^{*} is the permeability of the porous medium.

The boundary conditions of the problem are

$$\begin{aligned} &u^{\star}=0, \quad v^{\star}=-V_0\left[1+\epsilon\cos\left(\frac{\pi}{d}z^{\star}\right)\right], \quad w^{\star}=0 \quad \text{at} \quad y^{\star}=0,\\ &u^{\star}=U\left[1+\epsilon e^{i\omega^{\star}t^{\star}}\right], \quad v^{\star}=-V_0, \quad w^{\star}=0 \quad \text{at} \quad y^{\star}=d. \end{aligned} \tag{2.7}$$

Introducing the non-dimensional variables

$$y = \frac{y^\star}{d}, \quad z = \frac{z^\star}{d}, \quad t = ct^\star, \quad p = \frac{p^\star}{\rho U^2}, \quad u = \frac{u^\star}{U}, \quad v = \frac{v^\star}{U}, \quad w = \frac{w^\star}{U}. \tag{2.8}$$

Eqs (2.3)-(2.6) become

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{2.9}$$

$$\omega \frac{\partial u}{\partial t} + Re\left(v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} \right) = \left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) - \frac{u}{K}, \tag{2.10}$$

$$\omega \frac{\partial v}{\partial t} + Re\left(v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} \right) = -Re\frac{\partial p}{\partial y} + \left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) - \frac{v}{K}, \tag{2.11}$$

$$\omega \frac{\partial w}{\partial t} + Re\left(v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} \right) = -Re\frac{\partial p}{\partial z} + \left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) - \frac{w}{K} \tag{2.12}$$

where $Re = Ud/\nu$ is the Reynolds number, $S = V_0/U$ is the suction parameter and $\omega = \omega^\star d^2/\nu$ is the frequency parameter, $K = K^*/d^2$ is the permeability parameter. Using Eqs (2.8), the boundary conditions (2.7) become

$$\begin{aligned} &u = 0, \quad v = -S\left[1 + \epsilon\cos(\pi z)\right], \quad w = 0 \quad \text{at} \quad y = 0, \\ &u = \left(1 + \epsilon e^{i\omega t}\right), \quad v = -S, \quad w = 0 \quad \text{at} \quad y = 1. \end{aligned} \tag{2.13}$$

3. Solution

We assume the solution of the given form

$$f(y,z,t) = f_0(y) + \epsilon f_1(y,z,t) + \epsilon^2 f_2(y,z,t) + \cdots, \tag{3.1}$$

when $\epsilon = 0$, the solution is

$$v_0(y) = -S, \quad u_0(y) = \frac{\left(e^{-n_1 y} - e^{-n_2 y}\right)}{\left(e^{-n_1} - e^{-n_2}\right)} \tag{3.2}$$

where

$$n_{1,2} = \frac{1}{2}\left[SRe \pm \left\{ S^2 Re^2 + 4/K \right\}^{1/2} \right]. \tag{3.3}$$

When $\epsilon \neq 0$, the solution is

$$u_1(y,z,t)=\Big[C_9e^{-r_1y}+C_{10}e^{-r_2y}+C_1e^{-(r_1+n_1)y}+C_2e^{-(r_2+n_1)y}+C_3e^{(\pi-n_1)y}+$$
$$+C_4e^{-(\pi+n_1)y}+C_5e^{-(r_1+n_2)y}+C_6e^{-(r_2+n_2)y}+C_7e^{(\pi-n_2)y}+ \tag{3.4}$$
$$+C_8e^{-(\pi+n_2)y}\Big]\cos\pi z+\frac{\left(e^{-m_1y}-e^{-m_2y}\right)}{\left(e^{-m_1}-e^{-m_2}\right)}e^{i\omega t},$$

$$v_1(y,z)=\Big[Ae^{-r_1y}+Be^{-r_2y}+Ce^{\pi y}+De^{-\pi y}\Big]\cos(\pi z), \tag{3.5}$$

$$w_1(y,z)=\frac{1}{\pi}\Big[Ar_1e^{-r_1y}+Br_2e^{-r_2y}-C\pi e^{\pi y}+D\pi e^{-\pi y}\Big]\sin(\pi z), \tag{3.6}$$

$$p_1(y,z)=S\left[\left\{Ce^{\pi y}+De^{-\pi y}\right\}-\frac{1}{K\pi Re}\left\{Ce^{\pi y}-De^{-\pi y}\right\}\right]\cos(\pi z). \tag{3.7}$$

We omit the other constants. When $K\to\infty$ the solutions coincide with the solution of Guria *et al.* [9]. The solution also exists for the blowing at the plate.

4. Heat transfer

We consider the energy equation

$$\frac{\partial T^\star}{\partial t^\star}+v^\star\frac{\partial T^\star}{\partial y^\star}+w^\star\frac{\partial T^\star}{\partial z^\star}=\alpha\left(\frac{\partial^2T^\star}{\partial y^{\star 2}}+\frac{\partial^2T^\star}{\partial z^{\star 2}}\right)-\frac{\mu}{\rho C_p}\Phi^\star \tag{4.1}$$

where $\Phi^\star$ is the viscous dissipation function given by

$$\Phi^\star=2\left[\left(\frac{\partial v^\star}{\partial y^\star}\right)^2+\left(\frac{\partial w^\star}{\partial z^\star}\right)^2\right]+\left(\frac{\partial u^\star}{\partial y^\star}\right)^2+\left(\frac{\partial w^\star}{\partial y^\star}+v^\star\frac{\partial v^\star}{\partial z^\star}\right)^2+\left(\frac{\partial u^\star}{\partial z^\star}\right)^2 \tag{4.2}$$

where C_p is the specific heat at constant pressure, μ is the viscosity, α is the thermal conductivity of the fluid.

The temperature boundary condions are

$$T^\star=T_0 \quad \text{at} \quad y^\star=0 \quad \text{and} \quad T^\star=T_1 \quad \text{at} \quad y^\star=d. \tag{4.3}$$

Introducing

$$\theta=\frac{T^\star-T_0}{T_1-T_0}, \tag{4.4}$$

Eq.(4.1) becomes

$$Pr\omega\frac{\partial\theta}{\partial t}+RePr\left(v\frac{\partial\theta}{\partial y}+w\frac{\partial\theta}{\partial z}\right)=\left(\frac{\partial^2\theta}{\partial y^2}+\frac{\partial\theta}{\partial z^2}\right)+PrEc\Phi \quad (4.5)$$

where

$$\Phi=2\left[\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]+\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}+v\frac{\partial v}{\partial z}\right)^2+\left(\frac{\partial u}{\partial z}\right)^2. \quad (4.6)$$

The temperature boundary conditions become

$$\theta(0)=0,\theta(1)=1. \quad (4.7)$$

We assume the soluton of the temperature equation in the form

$$\theta(y,z,t)=\theta_0(y)+\epsilon\theta_1(y,z,t)+\epsilon^2\theta_2(y,z,t)+\cdots. \quad (4.8)$$

Substituting θ in (4.5) and comparing the term free of ϵ, we get

$$\theta_0''+SRePr\theta_0'=-PrEcu_0'^2 \quad (4.9)$$

where

$$\theta_0(0)=0 \quad \text{and} \quad \theta_0(1)=1. \quad (4.10)$$

The zeroth order solution is given by

$$\theta_0(y)=d_1e^{-2n_1y}+d_2e^{-2n_2y}+d_3e^{-SRey}+d_4+d_5e^{-SRePry}, \quad (4.11)$$

where

$$K_2=\frac{-PrEc}{(e^{n_1}-e^{-n_2})^2},\quad d_1=\frac{K_2n_1^2}{2n_1(2n_1-SRePr)},\quad d_2=\frac{K_2n_2^2}{2n_2(2n_2-SRePr)},$$

$$d_2=\frac{K_2n_2^2}{2n_2(2n_2-SRePr)},\quad d_3=\frac{2K_2}{KS^2Re^2(1-Pr)},$$

$$d_4=\frac{1}{\left(1-e^{-SRePr}\right)}\Big[1-d_1\left(e^{-2n_1}-e^{-SRePr}\right)+$$
$$-d_2\left(e^{-2n_2}-e^{-SRePr}\right)-d_3\left(e^{-SRe}-e^{-SRePr}\right)\Big], \quad (4.12)$$

$$d_5=\frac{-1}{\left(1-e^{-SRePr}\right)}\Big[1-d_1\left(e^{-2n_1}-1\right)-d_2\left(e^{-2n_2}-1\right)-d_3\left(e^{-SRe}-1\right)\Big].$$

Comparing the coefficient of ϵ , we get

$$Pr\frac{\partial\theta_1}{\partial t}+RePr\left(v_1\frac{\partial\theta_0}{\partial y}+v_0\frac{\partial\theta_1}{\partial z}\right)=\left(\frac{\partial^2\theta}{\partial y^2}+\frac{\partial\theta}{\partial z^2}\right)+2PrEcu_0'u_1'. \tag{4.13}$$

Assuming

$$\theta_1(y,z,t)=\theta_{11}(y)\cos\pi z+\theta_{12}(y)e^{i\omega t} \tag{4.14}$$

and substituting Eq.(4.14) in Eq.(4.13), we get

$$\theta_{11}''+SRePr\theta_{11}'-\pi^2\theta_{11}=RePr\theta_0'v_{11}-2PrEcu_0'u_{11}', \tag{4.15}$$

$$\theta_{12}''+SRePr\theta_{12}'-i\omega Pr\theta_{12}=-2PrEcu_0'u_{12}', \tag{4.16}$$

where

$$\theta_{11}(0)=0,\quad \theta_{12}(0)=0\quad \text{and}\quad \theta_{11}(1)=0,\quad \theta_{12}(1)=0. \tag{4.17}$$

The first order solution is given by

$$\begin{aligned}\theta_1(y,z,t)=\Big[&Le^{-m_5y}+Me^{-m_6y}+A_1e^{-(r_1+SRePr)y}+A_2e^{-(r_2+SRePr)y}+\\&+A_3e^{(\pi-SRePr)y}+A_4e^{-(\pi+SRePr)y}+A_5e^{-(r_1+2n_1)y}+A_6e^{-(r_2+2n_1)y}+\\&+A_7e^{(\pi-2n_1)y}+A_8e^{-(\pi+2n_1)y}+A_9e^{-(r_1+2n_2)y}+A_{10}e^{-(r_2+2n_2)y}+\\&+A_{11}e^{(\pi-2n_2)y}+A_{12}e^{-(\pi+2n_2)y}+A_{13}e^{-(r_1+SRe)y}+A_{14}e^{-(r_2+SRe)y}+\\&+A_{15}e^{(\pi-SRe)y}+A_{16}e^{-(\pi+SRe)y}+A_{17}e^{-(r_1+n_1)y}+A_{18}e^{-(r_1+n_2)y}+\\&+A_{19}e^{-(r_2+n_1)y}+A_{20}e^{-(r_2+n_2)y}\Big]cos(\pi z)+\Big[L_1e^{-m_3y}+M_1e^{-m_4y}+\\&+B_1e^{-(m_1+n_1)y}+B_2e^{-(m_2+n_2)y}+B_3e^{-(m_2+n_1)y}+B_4e^{-(m_1+n_2)y}\Big]e^{i\omega t},\end{aligned} \tag{4.18}$$

where

$$m_{3,4}=\frac{SRePr\pm\sqrt{S^2Re^2Pr^2+4i\omega Pr}}{2},\qquad m_{5,6}=\frac{SRePr\pm\sqrt{S^2Re^2Pr^2+4\pi^2}}{2}. \tag{4.19}$$

The other constants are not given here to save space.

5. Results and discussion

Variations of θ for several values of the Eckert number Ec, Prandtl number Pr and Reynolds number Re are shown in Figs 1-3. It is found that with an increase in either Re, Pr the temperature profile θ increseases. With an increase in the viscous dissipative heat the temperature distribution decreases. It is observed that with an increase in the Prandtl number the temperature of the flow increases at all points.

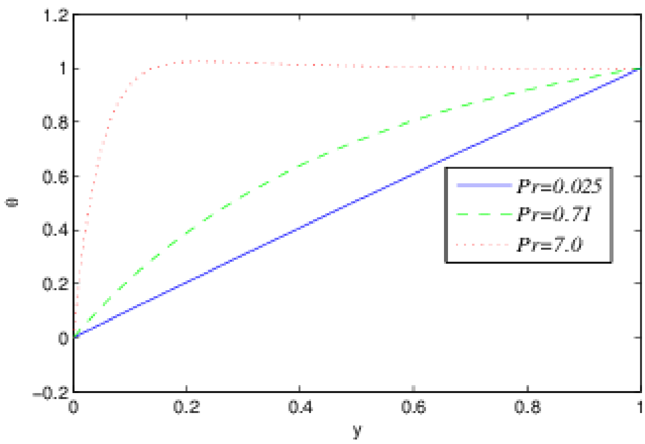

Fig.1. Variation of θ for $\omega t = 45^o$, $S = 0.5$, $K = 2$, $\omega = 5$, $Ec = 0.1$, $\epsilon = 0.25$.

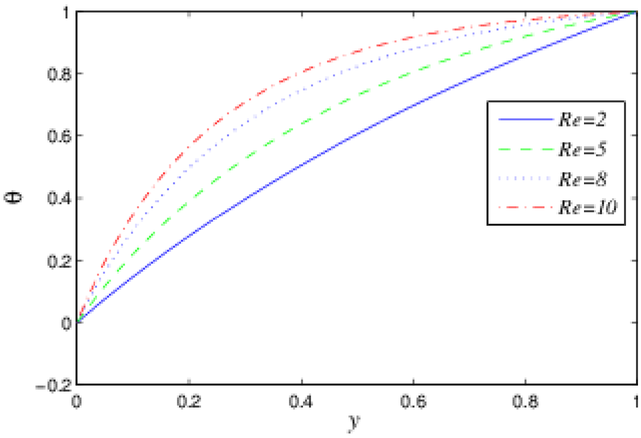

Fig.2. Variation of θ for $\omega t = 45^o$, $S = 0.5$, $K = 2$, $Ec = 0.1$, $Pr = 0.71$, $\epsilon = 0.25$.

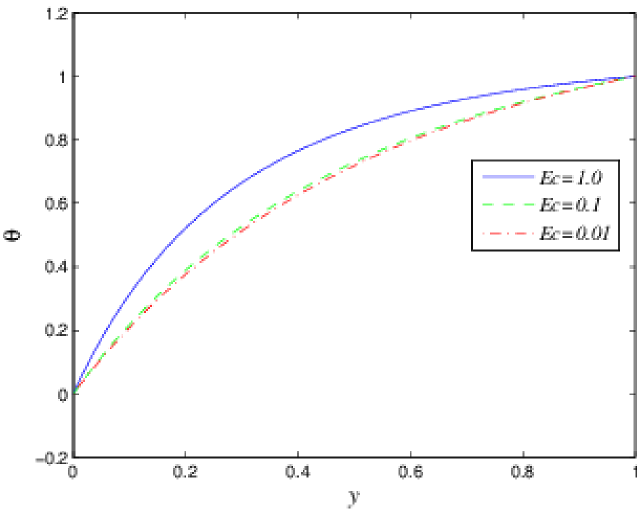

Fig.3. Variation of θ for $\omega t = 45^o, S = 0.5, K = 2, \omega = 5, Re = 5, \epsilon = 0.25$

The rate of heat transfer from the plate to the fluid may be calculated using the formula

$$q=-k\left(\frac{\partial T^*}{\partial y^*}\right)_{y^*=0}=-\frac{k\left(T_w-T_0\right)}{d}\left(\frac{\partial\theta}{\partial y}\right)_{y=0}. \tag{5.1}$$

In a non-dimensional form the heat transfer coefficient at the plate $y=0$ is given by

$$Nu=\frac{qd}{k\left(T_w-T_0\right)}=-\left(\frac{\partial\theta}{\partial y}\right)_{y=0}=-\theta_0'(0)-\epsilon\theta_1'(0),$$

$$Nu=-\theta_0'(0)-\epsilon\left[\theta_{11}'(0)\cos\pi z+\theta_{12}'(0)e^{i\omega t}\right],$$

$$Nu=-\theta_0'(0)-\epsilon\left[\theta_{11}'(0)\cos\pi z+H_1\cos\left(\phi_1+\omega t\right)\right]. \tag{5.2}$$

Variations of amplitude and tangent of phase shift in terms of the Nusselt number for several values of frequency parameter ω and Reynolds number Re is shown in Tab.1. It is seen that the amplitude and tangent of phase shift decreases with increase in either Re or ω. It is observed that due to high frequency of oscillations of the plate, the magnitude of the rate of heat transfer reduces. The values of $\tan\varphi_1$ show that there is a phase lead for lower frequency in the rate of heat transfer coefficient.

Table 1. The amplitude H_1 and phase shift $\tan\varphi_1$ of the Nusselt number $S=0.5$, $Pr=0.71$, $\epsilon=0.25$, $\omega t=45^o$.

Re	H_1			$\tan\phi_1$		
	$\omega=2$	$\omega=5$	$\omega=10$	$\omega=2$	$\omega=5$	$\omega=10$
1	1.76	1.28	0.59	33.01	36.21	11.08
1.5	1.46	1.42	0.64	12.58	17.62	8.19
2	0.94	1.34	0.62	5.87	9.94	5.63
2.5	0.41	1.04	0.49	2.11	5.63	3.36

6. Conclusion

The temperature distribution in a flow between two horizontal parallel porous plates through a porous medium has been obtained in the presence of viscous dissipative heat. It is found that with an increase in either Reynolds or Prandtl number the temperature profile increases but it decreases with an increase in the Eckert number. The rate of heat transfer has also been obtained in terms of the Nusselt number. It is seen that the amplitude and tangent of phase shift decreases with an increase in either the Reynolds number or frequency parameter. With an increase in the viscous dissipative heat the temperature distribution decreases. It is observed that increasing the Prandtl number increases temperature of the flow at all points. It is observed that due to a high frequency of oscillations of the plate, the magnitude of the rate of heat transfer reduces. The values of $\tan\varphi_1$ show that there is a phase lead for lower frequency in the rate of heat transfer coefficient.

Nomenclature

A_i $i=1,..20$ – constants

A,B,C,D	– constants
$C_i, i=1,\cdots 10$	– constants
C_p	– specific heat at constant pressure
$d_i, i=1,\cdots 5$	– constants
d	– channel width
Ec	– Eckert number
g	– gravitational acceleration
Gr	– Grashof number
K	– permeability parameter
K_1, K_2	– constant
$m_i, i=1,\cdots 6$	– constants
Nu	– Nusselt number at the left plate
p^*	– pressure
p	– dimensionless pressure
Pr	– Prandtl number
q	– local heat transfer at the plate
$r_i, i=1,\cdots 4$	– constants
Re	– Reynolds number
T^*	– temperature of the fluid
T_w	– plate temperature ($y^*=0$)
T_0	– plate temperature ($y^*=d$)
u^*, v^*, w^*	– velocity components in *x,y,z* axes
u,v,w	– dimensionless Velocity components in *x,y,z* axes respectively
V_0	– constant suction velocity
x^*, y^*, z^*	– Cartesian coordinates system;
x,y,z	– dimensionless Cartesian coordinate system
μ	– viscosity
β	– coefficient of thermal expansion
θ	– non-dimensional temperature
ν	– kinematic viscosity
ε	– amplitude of the suction velocity
ρ	– density of the fluid

References

[1] Gersten K. and Gross J.F.(1974): *Flow and heat transfer along a plane wall with periodic suction.*– J. Appl. Math. Phys. (ZAMP), vol.25, pp.399-408.

[2] Singh P., Sharma V.P. and Misra U.N.(1978): *Three dimensional fluctuating flow and heat transfer along a plate with suction.*– International Journal of Heat and Mass Transfer, vol.21, No.8, pp.1117-1123.

[3] Singh K.D.(1993): *Three dimensional viscous flow and heat transfer along a porous plate.–* Z.Angew. Math. Mech., vol.73, No.1, pp.58-61.

[4] Singh P., Sharma V.P. and Misra U.N.(1978): *Three dimensional free convection and heat transfer along a porous vertical plate*.– Aplied Scientific Research, vol.34, No.1, pp.105-115.

[5] Guria M. and Jana R.N. (2005): *Hydrodynamic effect on the three dimensional flow past a vertical porous plate.–* International Journal of Mathematics and Mathematical Sciences, vol.20, pp.3359-3372.

[6] Singh K.D. (1999): *Three dimensional Couette flow with transpiration cooling.– Z. Angew.* Math. Phys., vol.50, pp.661-668.

[7] Singh K.D. and Sharma Rakesh (2001): *MHD three dimensional Couette flow with transpiration cooling.* Z.Angew. Math. Mech., vol.81, pp.715-720.

[8] Guria M. and Jana R.N.(2006): *Three dimensional fluctuating Couette flow through the porous plates with heat transfer.–* International Journal of Mathematics and Mathematical Sciences, vol.2006, Article ID 61023, pp.1-18

[9] Guria M., Jana R.N. and Pop I.(2007): *Three dimensional oscillating flow between two parallel plates with heat transfer.–* International Journal of Applied Mechanics and Engineering, vol.12, No.1, pp.19-35

[10] Varshney C.L. (1979): *Fluctuating flow of viscous fluid through a porous medium bounded by a porous plate.–* Indian J. Pure Appl. Math., vol.10, pp.1558-64.

[11] Raptis A.A.(1983): Unsteady free convective flow through porous media.– Int. J. Engng. Sci., vol.21, pp.345-348

[12] Raptis A.A. and Perdikis C.P. (1985): *Oscillatory flow through porous medium by the presence of free convective flow*.– Int. J. Engng. Sci., vol.23, pp.51-55.

[13] Singh K.D. and Sharma Rakesh (2001): *Three dimensional Couette flow through a porous medium with heat transfer.–* Indian J. Pure Appl. Math., vol.32 No.12, pp.1819-1829.

[14] Singh K.D. and Sharma Rakesh (2002): *Three dimensional free convective flow and heat transfer through a porous medium with periodic permeability.–* Indian J. Pure Appl. Math., vol.33, No.6, pp.941-949.

[15] Guria M., Jana R.N., Ghosh S.K. and Pop I. (2009): *Three dimensional free convection flow in a vertical channel filled with a porous media.–* Journal of Porous Media, vol.10, No.12, pp.985-995

[16] Guria M., Ghara N. and Jana R.N.(2013): *Three dimensional oscillating flow between two parallel plates through a porous medium.–* International Journal of Applied Mechanics and Engineering, vol.18, No.4, pp.1025-1037.

[17] Guria M., Ghara N. and Jana R.N. (2015): *Radiation effect on three dimensional flow past a vertical porous plate through porous medium.–* Journal of Physical Sciences, vol.20, pp.81-95.

[18] Guria M. (2015): *Radiation effect on three dimensional vertical channel flow through porous medium.–* International Journal of Applied Mechanics and Engineering, vol.20, No.4, pp.817-833.

Received: October 3, 2021
Revised: February 24, 2022