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Hydro magnetic Mixed Convection Flow through Porous Medium in a Hot Vertical Channel with Span wise Co sinusoidal Temperature and Heat Radiation

B. P. Garg, K. D. Singh, N. Bansal
Research Supervisor, Punjab Technical University, Jalandhar-144002, India
Professor of Applied Mathematics, Wexlow, Lower Kaithu, Shimla-171003, India
Research Scholar, Punjab Technical University, Jalandhar-144002, India

***Abstract** An analysis of an unsteady mixed convection flow of a viscous incompressible and electrically conducting fluid in a hot vertical channel is presented. The vertical channel is filled with porous medium. The temperature of one of the channel plates is considered to be fluctuating spanwisecosinusoidally, i.e.* $T^*(y^*,z^*,t^*) = T_1 + (T_2 - T_1)\cos\left(\frac{\pi z^*}{d} - \omega^* t^*\right)$*.A magnetic field of uniform strength is applied perpendicular to the planes of the plates. The magnetic Reynolds number is assumed very small so that the induced magnetic field is neglected. It is also assumed that the conducting fluid is gray, absorbing/ emitting radiation and non-scattering. Governing equations are solved exactly for the velocity and the temperature fields. The effects of Reynolds number, Hartmann number, permeability of the porous medium, Prandtl number and frequency of oscillations are discussed with the help of figures.*

Keywords: **Mixed convection, magneto hydrodynamics, spanwisecosinusoidal, porous medium.**

I. INTRODUCTION

The phenomenon of mixed convection has been object of extensive research. Day by day the importance of this phenomenon is increasing due to its enhanced concern in science and technology about buoyancy induced motions in the atmosphere, the bodies in water and quasi solid bodies such as earth. Convective flows in porous media have applications in geothermal energy recovery, oil extraction, thermal energy storage and flow through filtering devices.Nield and Bejan[1].From technological point of view, convective flows in a porous medium have received much attention in recent time due to its wide applications in geothermal and oil reservoir engineering as well as other geophysical and astrophysical studies. A series of investigation have been made by the different scholars where the porous medium is either bounded by horizontal, vertical surface or parallel porous plates. Rudraiah and Nagraj[2] investigated natural convection through a vertical porous medium. Raptis and Perdikis[3] studied the problem of free convective flow through porous medium bounded by the vertical porous plate with constant suction when the free stream velocity oscillates in time about a constant mean value. Kim and Vafai[4] analyzed the natural convection flow through porous medium past a plate. Chauhan and Soni[5] discussed the parallel flow convection effect on Couette flow past a highly porous bed. Malashetty et al [6] analyzed the convective flow and heat transfer in an inclined composite porous medium.Raptis [7] studied the radiation and free convection through a porous medium. The heat transfer by thermal radiation is becoming of greater importance when we are concerned with space applications, higher operating temperatures and also power engineering. The radiative free convective flows are encountered in countless industrial and environment processes e.g. heating and cooling chambers, fossil fuel combustion energy processes, evaporation from large open water reservoirs, astrophysical flows, and solar power technology and space vehicle re-entry. Heat transfer due to radiation play an important role in manufacturing industries for the design of reliable equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering applications. Ayani and Fsfahani[8] discussed the effect of radiation on the natural convection induced by a line heat source. Makinde[9] studied the free convection flow with thermal radiation and mass transfer pass a moving vertical porous plate. Deka and Bhattacharya [10] obtained the exact solution of unsteady convective Couette flow of heat generating/ absorbing fluid in porous medium. Free convection magneto hydrodynamic (MHD) flow of electrically conducting fluid through porous media are very important particularly in the fields of petroleum technology for the flow of oil through porous rocks, in chemical engineering for the purification and filtration processes and in the cases like drug permeation through human skin. The principles of this subject are very useful in recovering the water for drinking and irrigation purposes. The knowledge of flows through porous medium is also useful to study the movement of natural gas and water through the oil reservoirs. A number of studied have appeared in the literature where the porous medium is either bounded between parallel plates. At the high temperature attained in some engineering devices, gas, for example, can be ionized and so becomes an electrical conductor. The ionized gas or plasma can be made to interact with the magnetic field and alter heat transfer and friction characteristic. Recently, it is of great interest to study the effect of magnetic field on the

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temperature distribution and heat transfer when the fluid is not only an electrical conductor but also when it is capable of emitting and absorbing thermal radiation. Alagoa et al [11] studied the radiative and free convective effects of MHD flow through a porous medium between infinite parallel plates with time-dependent suction. Jha[12] studied the effects of applied magnetic field on transient free convective flow in a vertical channel. Hassanien and Mansour [13] analyzed the unsteady MHD flow through a porous medium between two infinite parallel plates. Attia and Kotb[14]studied the MHD flow between two parallel plates with heat transfer. Hakeim[15]discussed MHD oscillatory flow on free convection radiation through porous medium with constant suction velocity.Makinde and Mhone[16] investigated the combined effect of transverse magnetic field and radiative heat transfer to unsteady flow of a conducting optically thin fluid through a channel filled with saturated porous medium and non-uniform temperature. Thereafter Israel et al [17] studied MHD oscillatory Couette flow of a radiating viscous fluid in a porous medium with periodic wall temperature. Singh [18] obtained an exact solution of an oscillatory MHD flow in a channel filled with porous medium. Singh and Garg[19] analyzed radiative heat transfer in MHD oscillatory flow through porous medium bounded by two vertical porous plates. In the above cited studies the plate temperature is considered either constant or varying with time only. But there are numerous industrial furnaces and nuclear reactor processes where the temperature at different locations of the furnace wall is different and varies with time too. In view of such situations it is proposed to study the MHD flow of a viscous, incompressible and electrically conducting fluid through porous medium filled in a vertical channel. The temperature of one of the channel plates is assumed to be varying in space and time both. A magnetic field of uniform strength is applied transversely. The magnetic Reynolds number is assumed very small so that the induced magnetic field is neglected. A closed form solution of the governing equations is obtained and the effects of various parameters on the velocity, temperature, skin-friction and the rate of heat transfer are discussed in the last section of the paper.

II. PROBLEM FORMULATION

Consider an oscillatory flow of a viscous, incompressible and electrically conducting fluid in a hot vertical channel filled with porous medium. The two parallel stationary walls of the channel are distance‘d’ apart. A Cartesian coordinate system (X^*, Y^*) is choose such that X^*-axis directed upwards lies along the centerline of the channel and Y^*-axis is perpendicular to the planes of parallel plates. A magnetic field B_0 of uniform strength is applied transversely along Y^*-axis. The magnetic Reynolds number is assumed to be small enough so that the induced magnetic field is negligible. Hall Effect, electrical and polarization effects are also neglected. All the physical quantities except pressure are independent of x^* for this fully developed laminar flow in the infinite vertical channel. The temperature of the plate at $y^* = \frac{d}{2}$ varies as spanwisecosinusoidally, i.e.

$$T^* = T_1 + (T_2 - T_1)\cos\left(\frac{\pi z^*}{d} - \omega^* t^*\right).$$

A schematic diagram of the physical problem with span wise co sinusoidal variation of plate temperature is shown in Fig. 1a. &1b.

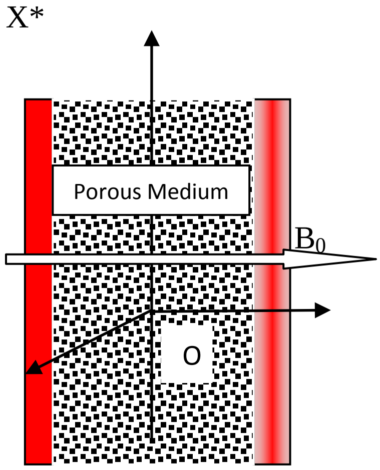

Fig.1a. Hot vertical channel.

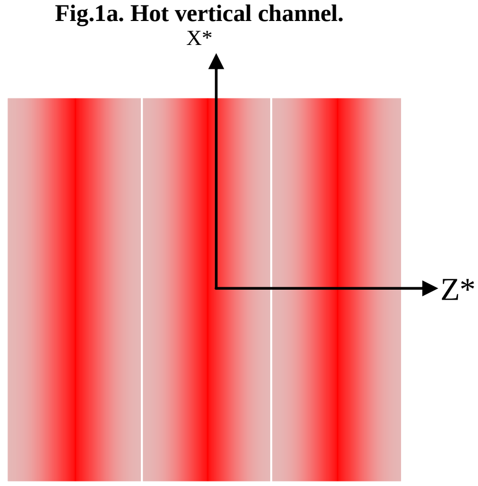

Fig. 1b.Span wise cosinusoidal plate temperature.

Then taking into account the usual Boussinsq’s approximation, the forced and free convection flow is governed by the following differential equations:

Momentum equation;

$$\frac{\partial u^*}{\partial t^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \vartheta\left(\frac{\partial^2 u^*}{\partial y^{*2}} + \frac{\partial^2 u^*}{\partial z^{*2}}\right) - \frac{\vartheta}{K^*}u^* - \frac{\sigma B_0^2}{\rho}u^* + g\beta(T^* - T_1), \quad (1)$$

Energy equation;

$$\frac{\partial T^*}{\partial t^*} = \frac{k}{\rho c_p}\left(\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{\partial^2 T^*}{\partial z^{*2}}\right) - \frac{1}{\rho c_p}\frac{\partial q^*}{\partial y^*}, \quad (2)$$

Where in momentum equation (1) term on the L. H. S. is the inertial force and on the R. H. S. the terms respectively represent imposed pressure gradient, viscous force, pressure drop across the porous matrix, Lorentz force due to magnetic field B_0 and the buoyancy force due to temperature difference. In energy equation (2) term on the L. H. S. is the heat due to convection and on the R. H. S. the

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terms respectively represent conduction heat and radiation heat. The boundary conditions of the problem are

$$u^* = 0, \quad T^* = T_1 \, at \, y^* = -\frac{d}{2} \quad (3)$$

$$u^* = 0, T^* = T_1 + (T_2 - T_1)\cos\left(\frac{\pi z^*}{d} - \omega^* t^*\right) at \, y^* = \frac{d}{2}. \quad (4)$$

For the case of an optically thin gray gas the local radiant is expressed by

$$\frac{\partial q^*}{\partial y^*} = 4a^* \sigma^* (T^{*4} - T_1^4), \quad (5)$$

Where a^* is the mean absorption coefficient and σ^* is Stefan- Boltzmann constant. We assume that the temperature differences within the flow are sufficiently small such that T^{*4} may be expressed as a linear function of the temperature. This is accomplished by expanding T^{*4} in a Taylor series about T_1 and neglecting higher order terms, thus

$$T^{*4} \cong 4T_1^{*3} T^* - 3T_1^4. \quad (6)$$

Substituting (6) into (5) and simplifying, we obtain

$$\frac{\partial q^*}{\partial y^*} = 16 a^* \sigma^* T_1^3 (T^* - T_1). \quad (7)$$

Further, substitution of (7) into the energy equation (2) gives

$$\frac{\partial T^*}{\partial t^*} = \frac{k}{\rho c_p}\left(\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{\partial^2 T^*}{\partial z^{*2}}\right) - \frac{16 a^* \sigma^* T_1^3 (T^* - T_1)}{\rho c_p}. \quad (8)$$

Now introducing the following non-dimensional quantities

$$x = \frac{x^*}{d}, y = \frac{y^*}{d}, z = \frac{z^*}{d}, t = \omega^* t^*,$$

$$\omega = \frac{\omega^* d^2}{\vartheta}, u = \frac{u^*}{U}, \theta = \frac{T^* - T_1}{T_2 - T_1}, p = \frac{dp^*}{\mu U}, \quad (9)$$

in equations (1), (8), (3) and (4)we obtain governing equations and the boundary conditions in dimensionless form as

$$\omega \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + \left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - (M^2 + K^{-1})u + Gr\theta, \quad (10)$$

$$\omega Pr \frac{\partial \theta}{\partial t} = \left(\frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) - N\,\theta, \quad (11)$$

with boundary conditions

$$u = 0, \quad \theta = 0, \quad at \quad y = -\frac{1}{2}, \quad (12)$$

$$u = 0, \quad \theta = \cos(\pi z - t), \quad at \quad y = \frac{1}{2} \quad (13)$$

Where $Gr = \frac{g\beta T_0 d^2}{\vartheta U}$, is the Grashof number,

$Pr = \frac{\rho c_p U d}{k}$, is the Prandtl number,

$M = B_0 d\sqrt{\frac{\sigma}{\mu}}$, is the Hartmann number,

$K = \frac{K^*}{d^2}$, is the permeability of the porous medium,

$N = \frac{16 a^* \sigma^* T_1^3 d^2}{k}$, is the radiation parameter,

Where U is the mean flow velocity.

III. SOLUTION OF PROBLEM

In order to obtain the solution of this unsteady problem it is convenient to adopt complex variable notations for velocity, temperature and pressure. The real part of the solution will have physical significance. Thus, we write velocity, temperature and pressure as

$$\begin{cases} u(y,z,t) = u_0(y) e^{i(\pi z - t)} \\ \theta(y,z,t) = \theta_0(y) e^{i(\pi z - t)} \\ -\frac{\partial p}{\partial x} = A e^{i(\pi z - t)} \end{cases} \quad (14)$$

Where A is a constant. The boundary conditions in equations (12) and (13) can also be written in complex notations as

$$u = 0, \quad \theta = 0, \quad at \quad y = -\frac{1}{2}, \quad (15)$$

$$u = 0, \quad \theta = e^{i(\pi z - t)}, \quad at \quad y = \frac{1}{2}. \quad (16)$$

Substituting expressions (14) into equations (10) and (11), we get

$$\frac{d^2 u_0}{dy^2} - m^2 u_0 = -A - Gr\theta_0, \quad (17)$$

$$\frac{d^2 \theta_0}{dy^2} - n^2 \theta_0 = 0, \quad (18)$$

where $m = \sqrt{(\pi^2 + M^2 + K^{-1} - i\omega)}$ and $n = \sqrt{(\pi^2 + N - i\omega Pr)}$ with transformed boundary conditions

$$u_0 = 0, \quad \theta_0 = 0 \quad at \quad y = -\frac{1}{2}, \quad (19)$$

$$u_0 = 0, \quad \theta_0 = 1 \quad at \quad y = \frac{1}{2} \quad (20)$$

The ordinary differential equations (17) and (18) are solved under boundary conditions (19) and (20) and the solutions for the velocity and the temperature fields are obtained, respectively, as

$$u(y,z,t) = \left\{\frac{A}{m^2}\left(1 - \frac{\cosh my}{\cosh\frac{m}{2}}\right) + \frac{Gr}{(n^2 - m^2)}\left(\frac{\sinh m\left(y + \frac{1}{2}\right)}{\sinh m} - \frac{\sinh n\left(y + \frac{1}{2}\right)}{\sinh n}\right)\right\} e^{i(\pi z - t)} \quad (21)$$

$$\theta(y,z,t) = \left\{\frac{\sinh\left[n\left(y + \frac{1}{2}\right)\right]}{\sinh(n)}\right\} e^{i(\pi z - t)}. \quad (22)$$

From the velocity field in equation (21) we can obtain the skin-friction at the left wall, τ_L, in terms of its amplitude $|F|$ and the phase angle φ as

$$\tau_L = \left(\frac{\partial u}{\partial y}\right)_{y=-\frac{1}{2}} = |F|\cos(\pi z - t + \varphi), \quad (23)$$

Where

$$F_r + iF_i = \frac{A}{m}\tanh\frac{m}{2} + \frac{Gr}{(n^2 - m^2)}\left(\frac{m}{\sinh m} - \frac{n}{\sinh n}\right). \quad (24)$$

The amplitude and the phase angle of the skin-friction τ_L are respectively given by

$$|F| = \sqrt{F_r^2 + F_i^2}, \quad \text{and} \quad \varphi = \tan^{-1}\left(\frac{F_i}{F_r}\right).$$

From the temperature field given in equation (22) the heat transfer coefficient Nu (Nusselt number) in terms of its amplitude and the phase angle can be obtained as

$$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=-\frac{1}{2}} = |H|\cos(\pi z - t + \psi), \quad (25)$$

Where $H_r + i\,H_i = \frac{n}{\sinh n}$.

The amplitude $|H|$ and the phase angle ψ of the heat transfer coefficient Nu (Nusselt number) are given by

$$|H| = \sqrt{H_r^2 + H_i^2} \text{ and } \psi = \tan^{-1}\left(\frac{H_i}{H_r}\right) \text{ respectively.} \quad (26)$$

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IV. RESULTS AND DISCUSSION

The problem of unsteady MHD radiative and convective flow through a porous medium in a vertical channel is analyzed. The closed form solutions for the velocity and temperature fields are obtained analytically and then evaluated numerically for different values of parameters appeared in the equations. To have better insight of the physical problem the variations of the velocity, temperature, skin-friction rate of heat transfer in terms of their amplitudes and phase angles with the parameters like Hartmann number M, Grashof number Gr, permeability of the porous medium K, Prandtl number Pr, radiation parameter N, pressure gradient A and the frequency of oscillations ω are then shown graphically to assess the effect of each parameter. The variations of the velocity with the Hartmann number M is shown in Fig.2. It is evident from this figure that the velocity decreases with the increasing Hartmann number. This means that the flow retards with the increasing Lorentz force due to increasing magnetic field strength. The variations of the velocity profiles with the Grash of number Gr are presented in Fig.3. The velocity increases with the increasing Grashof number. The maximum of the velocity profiles shifts toward right half of the channel due to the greater buoyancy force in this part of the channel because of the presence of hotter plate. The velocity also increases with the increase of permeability of the porous medium K as depicted in Fig.4. Physically it means that the resistance posed by the porous medium reduces as the permeability of the medium increases because of which the velocity increases. However, a decrease in velocity with the increase of Prandtl number Pr is observed from Fig.5. Since the Prandtl number gives the relative importance of viscous dissipation to the thermal dissipation, therefore, for larger Prandtl number viscous dissipation is predominant and due to this velocity decreases. Thus, the velocity in the case of water (Pr = 7) as the fluid is less than that in the case of air (Pr = 0.7). From Fig.6 it is observed that the velocity decreases with the increase of radiation parameter N. It is clear from fig. 7 that the velocity increases rapidly as the pressure gradient increases in the channel. It is due to the fact that the flow for larger pressure gradient in the channel is faster. The velocity also decreases with the increasing oscillations ω shown in fig. 8. Temperature profiles are shown in fig. 9, 10, 11 and 12. From these figures it is observed that the temperature decreases with increase of Prandtl number Pr, radiation parameter N and frequency of oscillations ω.

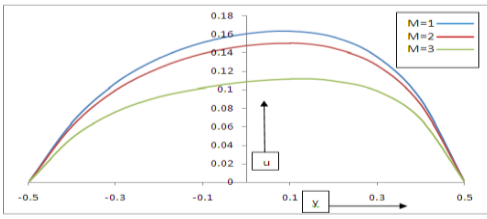

Fig. 2. Velocity variation with M for Gr=5, K=1, Pr=0.7, N=1, A=5, ω=5, z=0.5 and t=π/4.

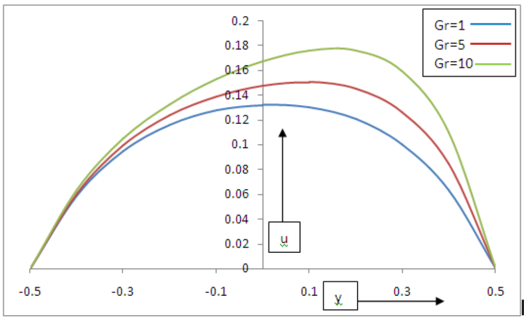

Fig.3. Velocity variation with Gr for M=2, K=1, Pr=0.7, N=1, A=5, ω=5, z=0.5 and t=π/4.

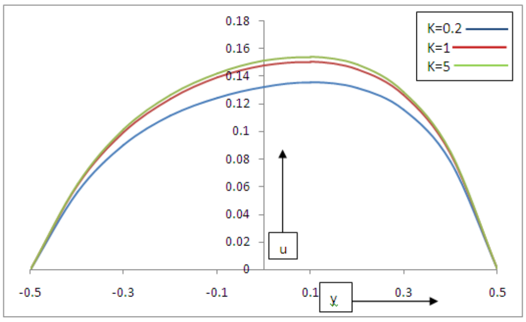

Fig.4. Velocity variation with K for M=2, Gr=5, Pr=0.7, N=1, A=5, ω=5, z=0.5 and t=π/4.

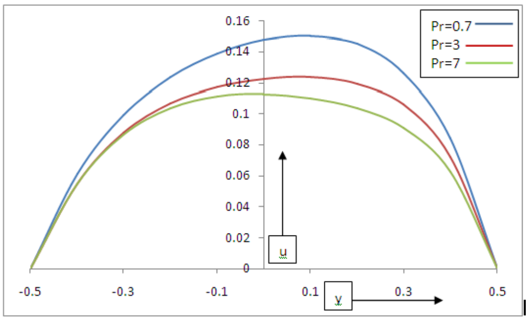

Fig.5.Velocity variation with Pr for M=2, Gr=5, K=1, N=1, A=5, ω=5, z=0.5 and t=π/4.

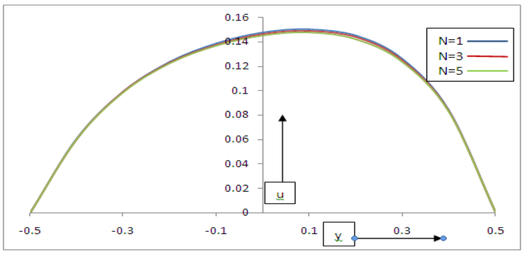

Fig.6. Velocity variation with N for M=2, Gr=5, Pr=0.7, K=1, A=5, ω=5, z=0.5 and t=π/4.

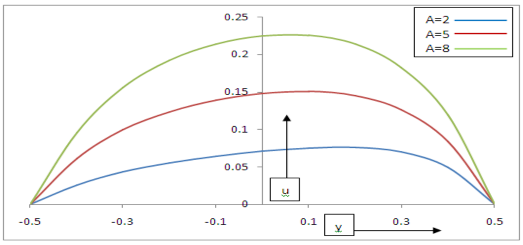

Fig.7. Velocity variation with A for M=2, Gr=5, Pr=0.7, K=1, N=1, ω=5, z=0.5 and t=π/4.

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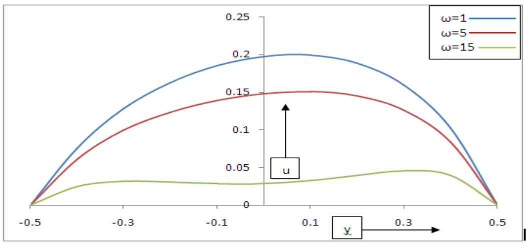

Fig.8. Velocity variation with ω for M=2, Gr=5, Pr=0.7, K=1, N=1, A=5, z=0.5 and t=π/4.

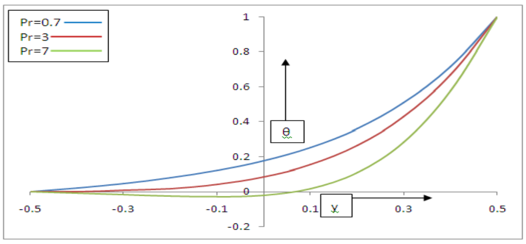

Fig.9. Temperature variation with Pr for N=1, ω=5, z=0.5 and t=π/4.

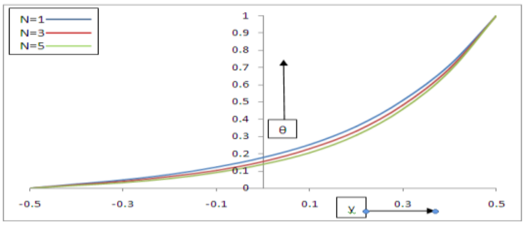

Fig.10. Temperature variation with N for Pr=0.7, ω=5, z=0.5 and t=π/4.

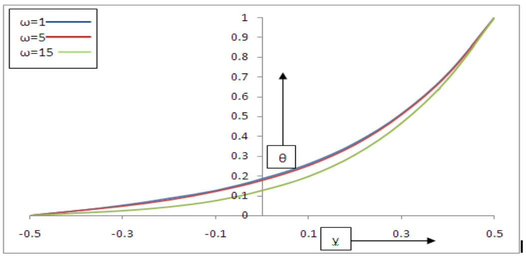

Fig.11. Temperature variation with ω for Pr=0.7, N=1, z=0.5 and t=π/4.

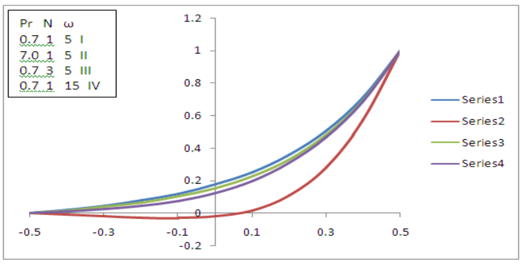

Fig.12.Temperature profiles.

The amplitude $|F|$ of the skin-friction against the frequency of oscillations is presented in Fig.13 for different parameters. Comparing different curves in this figure with the dotted curve I reveals that the amplitude increases with the increase of Grashof number Gr, permeability of the porous medium K and the pressure gradient parameter A, however, it decreases with the increase of Hartmann number M, Prandtl number Pr and the radiation parameter N. Similarly the comparison of curves with the dotted curve I in fig. 14 exhibits that the phase angle of the skin-friction increases with increase of Grash of number Gr, and permeability K of the porous medium while the phase angle decreases with the increase of Hartmann number M, Prandtl number Pr, radiation parameter N and pressure gradient A. From these two fig.13 and 14it is depicted that the amplitude and the phase angle of the skin-friction respectively decrease and increase with increasing frequency of oscillations ω.

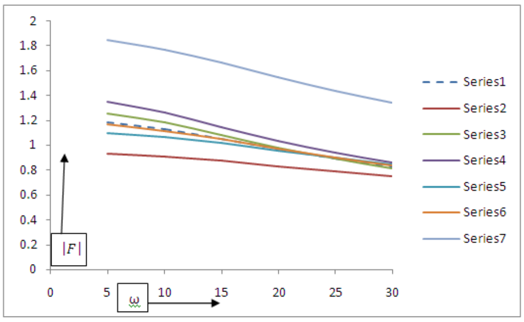

Fig.13. Amplitude $|F|$ of skin-friction.

Values of parameters plotted in Figs. 13 & 14.

M	Gr	K	Pr	N	A	Curve
2	5	0.2	0.7	1	5	I
4	5	0.2	0.7	1	5	II
2	10	0.2	0.7	1	5	III
2	5	5.0	0.7	1	5	IV
2	5	0.2	7.0	1	5	V
2	5	0.2	0.7	5	5	VI
2	5	0.2	0.7	1	8	VII

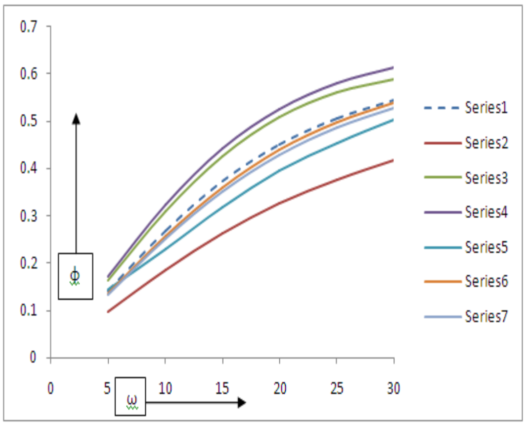

Fig.14. Phase angle φ of the skin-friction.

The amplitude $|H|$ and phase angle ψ of the rate of heat transfer are shown in fig.15 and 16 respectively. The amplitude decreases with the increase of Prandtl number and the radiation parameter. fig. 16 shows that with increasing oscillations ω the phase angle ψ of the rate of heat transfer oscillates between the phase lag and the phase lead.

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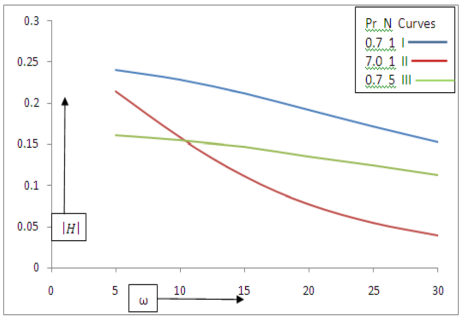

Fig.15. Amplitude |H| of rate of heat transfer.

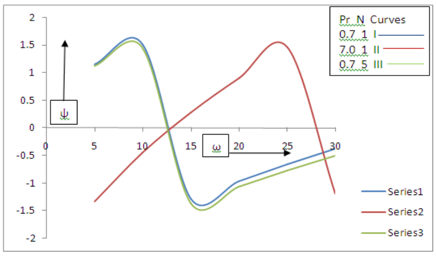

Fig.16. Phase angle ψ of the rate of heat transfer.

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AUTHOR'S PROFILE

BP Garg(b. 1969) is Director-Principal of one of the reputed engineering colleges (Adesh Institute of Engineering & Technology, Faridkot) affiliated to PTU Jallandhar, India. He attained his Post graduate and Doctorate degree from H.P. University, Shimla. His field of specialization is Fluid Mechanics. He has twenty seven international and national research papers in his credit. He is life member of various academic and professional bodies. He is serving as Referee of many prestigious and internationally reputed journals. He has been awarded 'Best Educationist Award' for outstanding achievements in the field of education by International Institute of Education & Management and 'Rashtriya VidyaGaurav Gold Medal Award' for outstanding achievements in the field of education by Indian Solidarity Council, New Delhi.

Prof. K. D. Singh, Professor and Head of the Department of Mathematics, International Centre for Distance Education and Open Learning, Himachal Pradesh University Shimla-171005, India. He has about 35 years of teaching experience for teaching under graduation and Post graduation classes. He has published about hundred research papers in the National and International Journals of repute. He has attended a number of National and International level conferences. Nine students received their Ph. D. Degrees under his guidance. Large numbers of students have also received their M. Phil. Degrees under his guidance. He has also produced instructional material for the under graduation and Post graduation classes. He act as referee to number of International and National Journals. He has also served as Director, International Centre for Distance Education and Open Learning.

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NeerajBansal received his M.Sc in Mathematics from DAV College, Jallandhar (Guru Nanak Dev University, Amritsar) in 2008. Presently he is research scholar in Applied Sciences Department (Mathematics) of Punjab Technical University, Jallandhar. He is currently serving as Assistant Professor in Guru Kashi University, Talwandi Sabo (Bathinda, Punjab). He is Lifetime member of ISTE and Vigyan Bharti, Punjab.