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Effect of variable porosity on composite heat transfer in a boundary layer flow

Puttabasavsetty Nagaraju
Vijaya Colege

EFFECT OF VARIABLE POROSITYON COMPOSITE HEAT TRANSFER IN A BOUNDARY LAYER FLOW

P.Nagaraju

Department of Physics, Vijaya college, Bangalore 560 004, INDIA

Email:godhundi@yahoo.co.in(M)919900656601®08026740255

Abstract: The effects of variable porosity and variable thermal conductivity of the medium and also the emission, absorption and scattering of radiation are studied in this paper. The comparative study has been made for three different situations, namely a) variable porosity b) constant porosity and c) absence of porous medium.In carrying out the solution, the momentum and energy equations are coupled and they are solved simultaneously by Runge-Kutta Gill method in conjunction with Newton-Raphson iterative scheme. The results of the analyses show that, in the cases of variable porosity and absence of porous medium the velocity profiles possess very small curvature at the wall, whereas, in the case of constant porosity situation the velocity profile is almost zero upto a certain distance and then increases. Nevertheless, it reaches unity asymptotically in all the three cases. The temperature profile becomes linear as the value of b (ratio of thermal conductivity of solid to fluid $-\lambda_s/\lambda_f$) increases. Another important result of the analysis is that the rise in temperature in variable porosity medium is about 25% more in comparison with absence of porous medium. Further, the results show that the total heat flux in the variable porosity medium is about 79% more as compared to constant porosity medium. And the variable conductivity enhances the total heat flux by about 33% as compared to constant conductivity of the medium.

Keywords: Variable porosity, heat transfer, Runge-Kutta Gill method, Newton Raphson

INTRODUCTION

The study of simultaneous radiative and convective heat transfer problems in porous media are of considerable practical importance in many engineering applications. Most of the studies in porous media carried out are based on the Darcy flow model, which in turn is based on the assumption of creeping flow through an infinitely extended uniform medium[1] such as fixed bed catalytic reactors, packed bed heat exchangers, drying, chemical reaction engineering, and metal processing.The permeability and porosity measurements by Roblee et al [2] and Benenati and Brosilow [3] show that, due to the packing of particles and porosity cannot be taken uniform but has a maximum value at the wall and a minimum value away from the wall. Hence, one has to incorporate the variation of porosity to study the heat transfer rate accurately.To account for the effects of the solid boundary, inertia forces, and variable porosity on fluid flow and heat transfer rate through porous media, Brinkman's extension of Darcy's law should be used[4].Chandrasekhara and Vortmeyer[5] and Vafai[6] have incorporated the variable permeability to study the flow past and through a porous medium and have shown that the variation of porosity and permeability have greater influence on velocity distribution and on heat transfer. Earlier publications on heat transfer in a variable porosity medium have considered convection and conduction only[7] and have neglected the effect of thermal radiation. It has been found that even under some of the most unexpected situations such as in fur [8] and building insulations, radiation heat transfer could account for a non-negligible amount of the total heat transfer. Tong et al [9] have reported in their work that the radiant heat transfer in light weight fibrous insulations accounts for as much as 30% of the total heat transfer even under moderate temperature (300-400 K). It is considered that as a practical application the fibrous materials or the sintered materials with very high porosity are installed in duct as pieces for absorbing radiant energy from the wall [10-13]. As a matter of fact in fluidized bed systems, convection and radiation are the important mechanisms of energy transfer as indicated by experimental studies of Goshayeshi et al [14]. In the works quoted above, the authors have not considered the effect of variable porosity as well as variable thermal conductivity of the medium. Thus, the aim of this paper is to study the role of variable porosity on composite heat transfer in a boundary layer flow. The correlation between porosity and permeability is brought through Kozeny-Blake expression. In aclosely packed system the scattering effect is neglected [15-19]. However, in a sparsely packed system the scattering effect cannot be neglected and hence it is incorporated by the absorption and scattering coefficients (K_a + K_s). Radiation combined with other modes of heat transfer is highly nonlinear integro-differential equation whose exact analytical solution is nearly impossible. Hence an efficient tool to deal with multidimensional radiative heat transfer is in strong demand. Thus the problem involves a set of coupled equations with variable coefficients, which are solved by Runge-kutta Gill method in conjunction with Newton-Raphson iterative scheme.

MATHEMATICAL FORMULATION AND BOUNDARY CONDITIONS

The physical model and co-ordinate system are depicted in Fig.1.It consists of a steady laminar flow of gray fluid flowing past a flat plate with negligible viscous dissipation and surface temperature of the plate is taken to be uniform.

ons at the wall and free stream

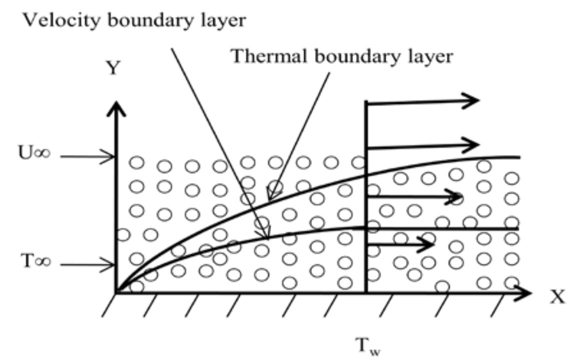

Fig. 1 Geometry and Physical system

The foregoing continuity, momentum, and energy equations for a radiating fluid are similar to those for a non-radiating fluid except for the radiative heat flux term $-\partial q_r/\partial y$ appearing in the energy equation.

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \qquad (1)$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\frac{\mu\partial^2 u}{\varepsilon(y)\partial y^2}-\frac{\mu}{k(y)}u \qquad (2)$$

$$where,\ \varepsilon(y)=\varepsilon_0\left(1+ce^{-\frac{yd}{d_p}}\right)$$

$$k(y)=\frac{\varepsilon(y)^3 d_p^2}{150[1-\varepsilon(y)]^2}$$

Here ρ-density of the fluid (kg/m^3), μ-dynamic viscosity(kg/ms), u,v-velocity components along x and y-axis respectively (m/s),ε(y) and k(y) are the expressions for variable porosity and permeability (Kozeny-Blake expression) respectively. ε_0 is the mean porosity and its value is chosen as 0.4, c and d are empirical constants which depend on the packing of spheres and d_p is the particle diameter.

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\lambda_e\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y} \qquad (3)$$

Where Cp- specific heat capacity at constant pressure (J/kg-K), T-temperature (K) and λe-effective thermal conductivity of the medium and it is given as [6]

$$\lambda_e=\varepsilon(y)\lambda_f+[1-\varepsilon(y)]\lambda_s \qquad (4)$$

λ_f ,λ_s thermal conductivity of fluid and solid (W/mK) respectively.
The boundary conditions are taken as

$$at\ y=0,\quad u=v=0,\quad T=T_w \qquad (5a)$$

$$as\ y\rightarrow\infty, u\rightarrow U_\infty, v=0,\quad T\rightarrow T_\infty \qquad (5b)$$

w, ∞ conditions at the wall and free stream respectively

ANALYSIS

In the analyses of radiation effects upon the boundary layer flow, Cess [20] hasintroduced a model, according to which conduction is restricted within the radiating fluid to a thin region adjacent to the plate surface. This conventional boundary layer is optically thin, τ_0<<1. However, the optically thin boundary layer represents only a portion of the entire temperature field, and consequently it is necessary to consider not only the boundary layer but also the adjacent radiation layer. In carrying out the solution, firstly the temperature profile within the radiation layer is determined. From this, the temperature at the outer edge of the boundary layer is obtained [21-24].
The basic equations are made non-dimensional through the introduction of the following similarity variables

$$\eta=y/\delta;\ f'(\eta)=u/U_\infty;\ \theta=T/T_\infty;\ \theta_w=T_w/T_\infty;$$

$$R_e=U_\infty x/v;\ \xi=\frac{2x\sigma(K_a+K_s)T_\infty^3}{\rho c_p U_\infty} \qquad (6)$$

Where δ - boundary layer thickness and ξ- ratio of radiative flux to the incoming enthalpy flux and it also involves the absorption and scattering of the medium. It should be noted that the boundary layer 'y' varies from 0 at the wall (w) to δ at the boundary limit. Thus δ is not a function of x but can be determined at x=L.
Continuity equation is satisfied by introducing a stream function $\psi(x,y)=\sqrt{vxU_\infty}f(\eta)$
Using the above notations, momentum Eq.(2) takes the form

$$2f'''+\varepsilon_0[1+ce^{-d\gamma\eta}]ff'-\frac{2p_m^2[1-\varepsilon_o\{1+ce^{-d\gamma\eta}\}]^2}{R_e[1+ce^{-d\gamma\eta}]^2}f'=0 \qquad (7)$$

$$where\ p_m^2=150x^2/\varepsilon_0^2 d_p^2,\ R_e=U_\infty x/v,\ \gamma=\delta/d_p,$$

$d = x/d_p$

p_m -porous parameter and Re- Reynolds number. The value of c = 0 for constant porosity and absence of porous medium and c=1 for variable porosity.The constant d is based on the length of the flat plate and particle diameter.For constant porosity situation Eq. (7) reduces to

$$2f''' + ff'' - \frac{2\rho_m^2}{R_e}f' = 0 \quad (8)$$

The transformed boundary conditions are

$$at\ \eta = 0, f = f' = 0 \quad (9a)$$

$$as\ \eta \to \infty,\ f' = 1 \quad (9b)$$

The solution of energy equation will now be intheform[6]

$$\theta = [1 + (\theta_w - 1)\theta_0(\eta)] + (\theta_w^4 - 1)[\theta_1(\eta) + (\epsilon_w - 1)\theta_2(\eta)]\xi + \ldots \quad (10)$$

From the above equations, we now get the ordinary differential equations in terms ofθ_0 ,$\theta_1$and θ_2 as describedbelow

$$\frac{\theta_0''(\eta)}{P_r}\Lambda_1 + \frac{f(\eta)}{2}\theta_0'(\eta) = 0 \quad (11)$$

$$\frac{\theta_1''(\eta)}{P_r}\Lambda_1 + \frac{f(\eta)}{2}\theta_1'(\eta) - f'(\eta)\theta_1(\eta) = -H_0(\eta) \quad (12)$$

$$\frac{\theta_2''(\eta)}{P_r}\Lambda_1 + \frac{f(\eta)}{2}\theta_2'(\eta) - f'(\eta)\theta_2(\eta) = -1 \quad (13)$$

Where $\Lambda_1 = \varepsilon_0[1 + ce^{-d\gamma\eta}] + b[1 - \varepsilon_0\{1 + ce^{-d\gamma\eta}\}]$

$$Ho(\eta) = \frac{1}{(\theta_w^4 - 1)}[1 + \theta_w^4 - 2\{1 + (\theta_w - 1)\theta_0\}^4] (14)$$

Where b = λ_s/λ_f.The transformed boundary conditions using Equations (5) and (10) will now take the form

$$at\ \eta = 0, \quad \theta_0(0) = 1, \theta_1(0) = \theta_2(0) = 0 \quad (15a)$$

$$as\ \eta \to \infty, \quad \theta_0(\infty) = 0, \theta_1(\infty) = \theta_2(\infty) = 1 \quad (15b)$$

According to Cess [20] and Krishnameti et al [21] the function $\theta_0(\eta)$ is the temperature distribution for the case of negligible radiationinteraction (ξ = 0) and the second bracketed term in Eq. (10) denotes the first order radiation effect on the temperature profile within the gas.

Wall heat flux: The net heat flux at the wall is of interest in most engineering applications. For a wall that is impermeable to flow,the net heat flux at the wall $q_w$iscomposed of the conductive and radiative heat fluxes and given as [23]

$$\psi = \frac{q_w}{\sigma T_w^4} = \left[-\frac{2\tau_0}{P_r\xi}\frac{d\theta}{d\eta} + \Phi\right]_{\eta=0} \quad (16)$$

Where P_r-Prandtlnumber,Φ-non-dimensional radiation flux,τ_0 = (K_a+ K_s) x /$\sqrt{R_e}$=(K_a+ K_s)δ, is a measure of optical thickness of the boundary layer, which is based on the characteristic dimension δ. In evaluating the heat transfer between the plate surface and the medium, it is convenient to consider separately the radiative and convective transfers. Thus the expression for the radiative flux is

$$\Phi = \epsilon_w(\theta_w^4 - 1)[1 - G(\theta_w)\tau_0] + .. \quad (17)$$

Where G (θ_w) is given as

$$G(\theta_w) = \frac{2}{(\theta_w^4 - 1)}\int_0^\infty [\{1 + (\theta_w - 1)\theta_0(\eta)\}^4 - 1]d\eta \quad (18)$$

By differentiating Eq. (18) w.r.t η one obtains

$$G'(\theta_w) = \frac{2}{(\theta_w^4 - 1)}[\{1 + (\theta_w - 1)\theta_0(\eta)\}^4\ 1] \quad (19)$$

In order to solve the above equation, the boundary condition is taken as

$G(\theta_w)$=0at η =0 (20)

The dimensionless conductive heat flux at the wall can be obtained as

$$\Lambda = -\frac{2\tau_0}{P_r\xi}\frac{d\theta}{d\eta} = -\frac{2\tau_0}{P_r\xi}[(\theta_w - 1)\theta_0'(0) + (\theta_w^4 - 1)H\xi] \quad (21)$$

Where $H = [\theta_1'(0) + (\epsilon_w - 1)\theta_2'(0)]$

Generally the convective heat transfer is expressed in terms of the Nusselt number

$$Nu = \frac{q_{cw}\,x}{\lambda_e(T_w - T_\infty)} = -\frac{x\theta'(\eta)}{(\theta_w - 1)\delta} \quad (22)$$

The convective heat transfer between the gas and the plate can be determined from equations (10) and (22)

$$\frac{\boldsymbol{Nu}}{\sqrt{\boldsymbol{R_e}}} = -\theta_0'(0) - \frac{(\theta_w^4 - 1)}{(\theta_w - 1)}H\xi \quad (23)$$

SOLUTION METHOD

In the present analyses, equationsare solved simultaneously by Runge-Kutta-Gill method in conjunction with the Newton-Raphson iterative scheme.Here f″(0) is the only unknown in equations (7) and (8). A rough estimate is made for f ″(0) for any specified value of η and then momentum equation is integrated. Computations are performed in double precision with 16000 steps for η i.e., η varying from 0 to 40 with constant step size $\Delta\eta$ = 0.0025. The convergence criterion followed is that the difference between the current and the previous iteration is 10^{-6}.

For solving $G(\theta_w)$ η is taken 40. In order to assess the validity of the solution, firstly the results are obtained in the absence of porous media. These results are in complete agreement with the results of Cess [20] and Krishnameti [21]. Further, the values of f, f ′ and f ″ are exactly matching with the values given in Chandrasekara and Nagaraju[18].

RESULTS AND DISCUSSION

In the present study the following typical values are used; mean porosity ε_o = 0.4, particle diameter d_p = 0.01 and 0.02 m, and the free stream velocity U_∞=1 ms^{-1}. With air as the reference fluid for a typical bed of length x=0.1 m, a local distance from the leading edge of the plate, the values of d, γ, R_e and P_m become 5, 0.01086, 70559 and 153 respectively. In the case of absence of porous medium ε_0 is taken as unity.Further, for the cases of constant porosity and absence of porous medium the value of c is taken as zero. For the free stream temperature T_∞=1000 K and wall temperature T_w = 500 K the value of ξ becomes approximately 0.01.

The dimensionless velocity component $f'(\eta)$ is represented in Fig.2 for three different cases, namely variable porosity, constant porosity and absence of porous media. In the cases of variable porosity and the absence of porosity media the velocity profiles possess very small curvature at the wall, whereas, in the case of

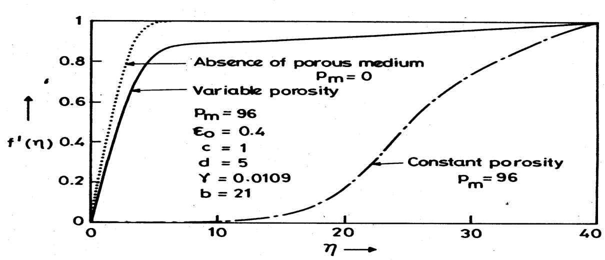

Fig. 2 Velocity Profile forPr =*0.7,* θ_w *= 0.5,* R_e *= 7.0599 x*10^4

A constant porosity situation, the velocity is zero almost upto a certain distance from the wall. However, after a certain distance the velocity goes on increasing and approaches unity asymptotically.The rise in temperature is found to be about 25% more in the presence of variable porosity in comparison with the absence of porous medium.

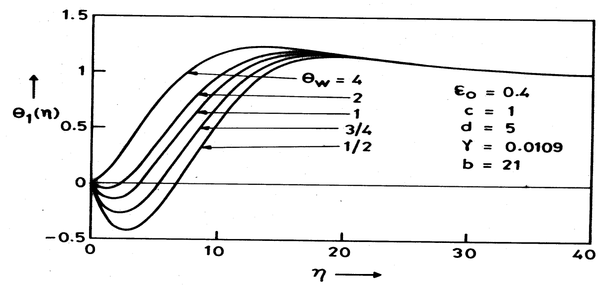

Fig. 3 Influence of θ_w on Temperature $\theta_1(\eta)$ for P_m = 153, Pr = 0.7, R_e = 7.0599 x 10^4.

Figure 3 exhibits the temperature profile in the presence of radiation ($\xi \approx 0.01$). It shows that the presence of radiation increases the temperature distribution. For a cold plate, θ_w=0.5 the profile is concave downward in the limited value of $\eta(\approx 5)$, representing heat transfer from the medium to the wall. The cooling of the gas in the radiation wall layer reduces markedly the temperature at the outer edge of the boundary layer. As a result of this, the thermal processes occurring have little effect on the radiant flux density incident on the plate surface. The peak value in the negative direction occurs around η=2, and then the change of sign takes place between η=5 and 6. From η=6 onwards, the temperature increases. It can also be noticed that with increase in θ_w, the peak value in the negative direction decreases and for θ_w>2, the temperature distribution becomes totally positive and increases with η and reaches its maximum value at η=8.

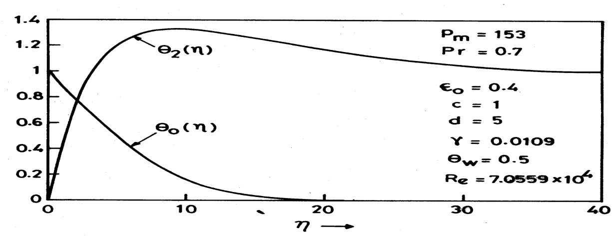

Fig. 4 Temperature Function in the presence of radiation $\theta_2(\eta)$ and absence of Radiation$\theta_0(\eta)$

Figure 4 shows the temperature distribution in the presence as well as in absence of radiation. As would be expected, the temperature distribution decreases in the absence of radiation and increases in the presence of radiation.

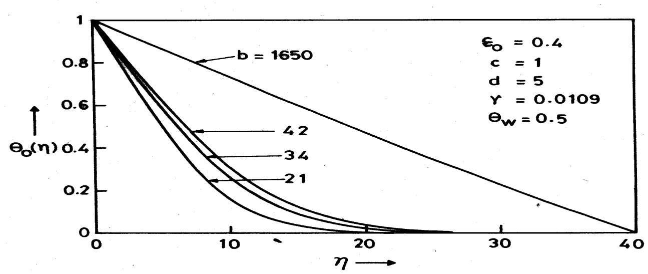

Fig. 5 Influence of ‘b’on Temperature profile for $P_m = 153$, $Pr = 0.7$, $R_e = 7.0599 \times 10^4$.

Figure 5shows that the temperature increases with increasein b.Thishas a considerable influence on the flow and heat transfer characteristics. According to Vedhanayagam et al [23] as the value ‘b’ increases, the effective thermal diffusivity of the saturated porous medium close to the boundary layer decreases. This results in a steeper temperature gradient close to the wall and a slowly decaying temperature profile away from the wall. It is also noticed from Fig.5 that for b=1650, the temperature profile decreases linearly. In fact, the values of ‘b’ are chosen from the experimental data provided by Jaguaribe et al [25]

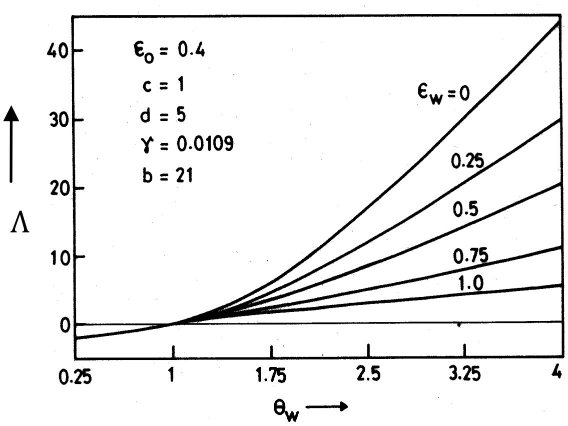

Fig. 6 Conductive Heat Transfer for $P_m = 153$, $Pr = 0.7$, $R_e = 7.0599 \times 10^4$

The conductive heat transfer between the gas and the medium is depicted in Fig.6.It may be seen from Fig. 6 that theemissivity of the medium has a relatively strong influence upon the conductive heat transfer. The decrease of ϵ_w results in increase in heat transfer, which can be explained as follows; the gas near the surface receives netradiation from the heated surface andgives up net radiation to the cooler free stream gas. Thus, a reduction in emissivity of the medium decreases the radiation heat transfer to this portion of the gas, and hence the conductive heat transfer increases. It may also be noted that from Table 1 that $G(\theta_w)$ is always positive. This may be explained from the fact that the gas within the boundary layer differs from the free stream temperature. Thus, the radiation exchange between the portion of the gas and plate is reduced. The quantities $\theta_0'(0)$ and $\theta_1'(0)$ are also listed in Table1. It is to be noted that from Eq (21) the first order radiation term depends only upon the optical thickness $\tau_o$and the temperature θ_w for an isothermal medium of unit emissivity.

Table 1 R_e= 70559, P_m = 153.1, P_r= 0.7, τ_o= 0.1, ε_o = 0.4, c=1, d=5, γ = 0.0186, b=21

θ_w	$G(\theta_w)$	$-\theta_0'(0)$	$-\theta_1'(0)$
½	15.8638	0.1055	0.2686
1	11.4363	0.1055	0.1424
2	7.3492	0.1055	0.0038
4	5.3032	0.1055	-0.0783

In Fig.7 both cooling ($T_w < T_\infty$) and heating ($T_w > T_\infty$) cases are shown for the radiative flux (Φ). If the plate surface is cooled ($T_w < T_\infty$),Φ becomes positive and increases with increase in τ_o. On the other hand, if the plate surface is heated ($T_w > T_\infty$) Φ becomes negative and increases considerably in the negative direction.

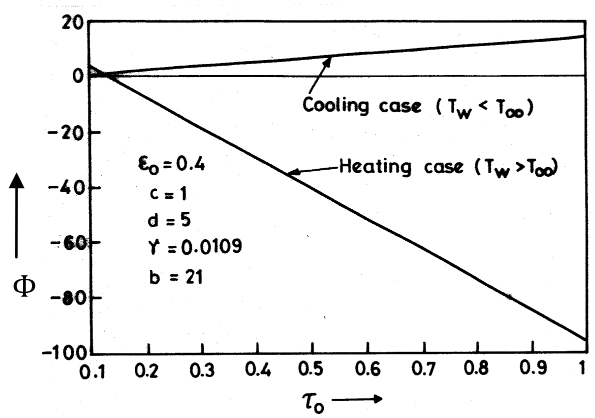

Fig. 7 Radiative Transfer for $P_m = 153$,

$Pr = 0.7$, $Re = 7.0599 \times 10^4$

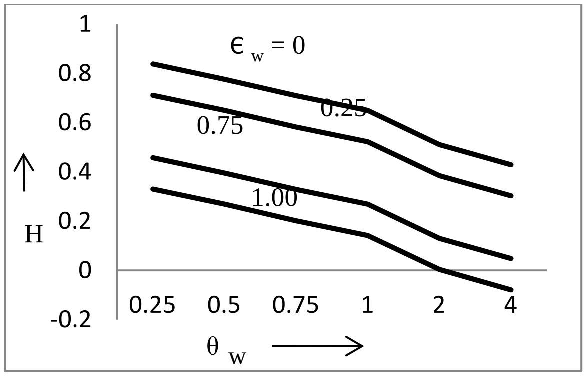

Fig. 8 Convective Heat Transfer for P_m=153, P_r=0.7, ε_0=0.4 C=1,d=5, γ=0.0109, b=21.

The first term on the right side of Eq. (23) represents convective heat transfer in the absence of radiation effects, while the second term denotes the first order radiation influence. For the given set of parameters, we get $-\theta_0'(0) = 0.1055$ and $\theta_2'(0) = 0.5076$, which shows that the radiative contribution is more in the presence of variable porosity.The variation of H with ϵ_W ϵ_w is shown in Fig. 8. This figure exhibits that, when $\epsilon_W = 1$ the radiation interaction results in an increase in the convection heat transfer for $\theta_w < 2.1$, but it decreases for $\theta_w > 2.1$. This trend is similar to the observation made by Cess [20], but in this paper, the reversal from an increase to a decrease in convection heat transfer is found to occur for $\theta_w \approx 1.7$. The enhanced value of θ_w ($\approx$2.1) is due to the presence of porous medium.

Table 2: Comparison of values for R_e= 70559, p_m =306.2, P_r= 0.7, τ_o= 0.1

	$-\theta_2'(0)$	Ψ	ξ	Ψ
Const. Porosity	6.146	3.080	0.01	4.210
Variable P_m and Variableλ (d=10, γ=0.0217)	0.5076	4.210	0.10	0.994
Absence of porous medium same as Cess [20];	1.418	–	0.10	0.520

Table 2 gives the comparative study of different physical quantities such as constant porosity, variable porosity, and variable conductivity of the medium. This table shows that the total heat flux in the variable porosity medium is about 79% more as compared to constant porosity medium. And the variable conductivity enhances the total heat flux by about 33% as compared to constant conductivity of the medium. It also shows that as ξ increases the total heat flux Ψ decreases. Thus, the Nusselt number decreases with increase in P_m.

CONCLUSIONS

1 The rise in temperature due to radiation transfer in a variable porosity medium is about 25% more as compared to constant porosity medium.
2.For higher values of b (=1650) the temperature profile decreases linearly.
3.The total heat flux in the variable porosity medium is about 79% more as compared to constant porosity medium.
4.The total heat flux in the presence of variable conductivity is about 33% more as compared to constant conductivity.
5. The total heat flux decreases with increase in ξ.

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