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Research Article

Influence of Chemical Reaction on Heat and Mass Transfer Flow of a Micropolar Fluid over a Permeable Channel with Radiation and Heat Generation

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The effects of chemical reaction on heat and mass transfer flow of a micropolar fluid in a permeable channel with heat generation and thermal radiation is studied. The Rosseland approximations are used to describe the radiative heat flux in the energy equation. The model contains nonlinear coupled partial differential equations which have been transformed into ordinary differential equation by using the similarity variables. The relevant nonlinear equations have been solved by Runge-Kutta-Fehlberg fourth fifth-order method with shooting technique. The physical significance of interesting parameters on the flow and heat transfer characteristics as well as the local skin friction coefficient, wall couple stress, and the heat transfer rate are thoroughly examined.

1. Introduction

The micropolar fluid theory is the one of the most important non-Newtonian fluid models described by Eringen [1]. This theory shows microrotation effects as well as microinertia and has many applications such as polymer fluids, liquid crystals, animal bloods, unusual lubricants, colloidal and suspension solutions, colloidal fluids, liquid crystals, and polymeric suspension. The extensive reviews of the micropolar fluid theory and its applications can be found in Eringen [2] and Lukaszewicz [3]. The unsteady mixed convection flow of a micropolar fluid from a vertical surface in the presence of viscous dissipation and the buoyancy force has been studied by El-Aziz [4]. Ashraf et al. [5] investigated the micropolar fluids flow through a porous channel. Sheikholeslami et al. [6] proposed the flow and heat transfer of micropolar fluid in a permeable channel. Prakash and Muthtamilselvan [7] investigated radiation effect on MHD micropolar fluid flow in porous vertical channel. Darvishi et al. [8] analyzed numerically the micropolar fluid flow from a porous channel. Sherief et al. [9] studied the motion along axis of a circular cylindrical pore in a micropolar fluid of a slip spherical particle. Mosayebidorcheh [10] analyzed the flow of micropolar fluid over a porous channel with changing walls. Recently, many authors [11–14] have studied the micropolar fluid flow for different fluid properties over different geometries. However, the effects of chemical reaction on micropolar fluid flow over a permeable channel in the presence of radiation and heat generation have not been considered in the above investigations.

Combined heat and mass transfer flows in the presence of chemical reaction have numerous applications in engineering and geophysics such as drying, geothermal reservoirs, dehydration at the surface of a water body, drying of porous solids, geothermal pool, thermal insulation, enhanced oil recovery, cooling of nuclear reactors, fibrous insulation, evaporation at the surface of a water body, pollution studies, cooling the polymer production and manufacturing of ceramics, energy transfer in a wet cooling tower, the flow in a desert, and oxidation and synthesis materials. Mohamed and Abo-Dahab [15] studied the effects of chemical reaction and thermal radiation on hydromagnetic free convection heat and mass transfer for a micropolar fluid bounded by a semi-infinite vertical porous plate in the presence of heat generation. In recent years, many researchers have studied and reported the effect of first-order chemical reaction [16–25].

Influence of thermal radiation on flow and heat transfer study has become more important industrially. The heat transfer and temperature profile of a micropolar fluid over different geometries can be affected significantly at high temperature. Bhattacharyya et al. [26] considered thermal radiation effect on micropolar fluid flow and heat transfer over a porous shrinking sheet. Hussain et al. [27] analyzed radiation effects on the thermal boundary layer flow of a micropolar fluid towards a permeable stretching sheet. Oahimire and Olajuwon [28] investigated the influence of Hall current and thermal radiation on heat and mass transfer of a chemically reacting MHD flow of a micropolar fluid through a porous medium. Mabood et al. [29] studied effects of nonuniform heat source/sink and Soret on MHD non-Darcian convective flow past a stretching sheet in a micropolar fluid with radiation.

The effect of heat generation on heat transfer is an important issue in view of various physical problems. Ziabakhsh et al. [30] analyzed the micropolar fluid flow with heat generation. Singh and Kumar [31] considered the melting effect in stagnation-point flow of micropolar fluid towards a stretching/shrinking surface. Bakr [32] investigated the effects of chemical reaction and heat source magnetoconvection and mass transfer flow of a micropolar fluid in a rotating frame of reference. The heat generation/absorption effects on MHD flow and heat transfer of micropolar fluid through a stretching surface have been proposed by Mahmoud and Waheed [33]. Abbasi et al. [34] examined the flow of Maxwell nanofluid in the presence of heat generation/absorption. Mliki et al. [35] investigated the influence of nanoparticle Brownian motion and heat generation/absorption over linear/sinusoidally heated cavity in the presence of magnetohydrodynamic natural convection. Sheikholeslami and Ganji [36] studied three-dimensional heat and mass transfer flow of nanofluid over a rotating system. Thermal radiation effects on mixed convection flow and heat transfer of a micropolar fluid through an unsteady stretching surface with heat generation/absorption are presented by Singh and Kumar [37].

Motivated by the above studies and applications, the present work explores effects of chemical reaction on heat and mass transfer flow of a micropolar fluid over a permeable channel in the presence of radiation and heat generation. The equations of continuity, momentum, angular momentum, energy, and concentration have been reduced to a system of nonlinear ordinary differential equations by similarity transforms which are solved by Runge-Kutta-Fehlberg method with shooting technique. It is expected that the results obtained from present paper will provide important information to the audience. To the best of our knowledge, such type of study is not investigated before in the scientific literature.

2. Mathematical Formulation

The heat and mass transfer flow of a micropolar fluid in a permeable channel with chemical reaction is considered in the present work. The thermal radiation and heat source are incorporated in the energy equation. The graphical model of the problem has been given along with flow configuration and coordinate system in Figure 1. The assumptions of the problem in detail can be found in [6]. The governing equations of boundary layer are given in the following form:

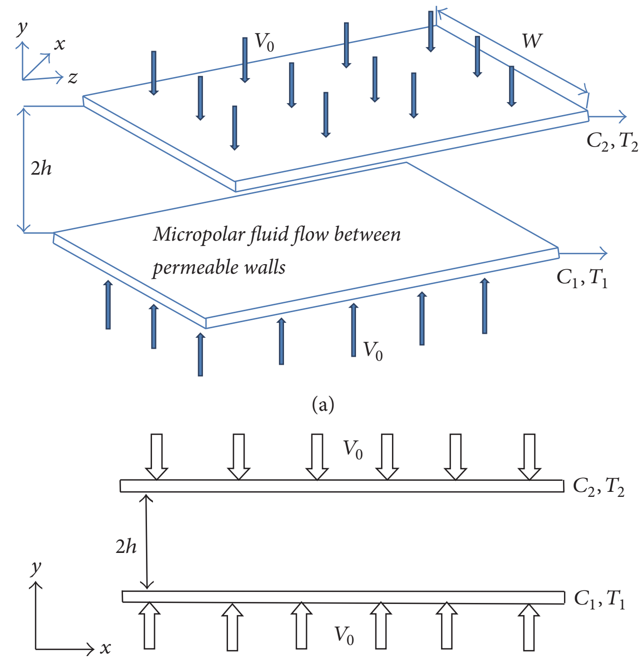

FIGURE 1: (a) Geometry of problem. (b) x-y view at $z = W/2$.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{(\mu+\kappa)}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{\kappa}{\rho}\frac{\partial N}{\partial y}, \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \frac{(\mu+\kappa)}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\kappa}{\rho}\frac{\partial N}{\partial y}, \tag{3}$$

$$u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y} = \frac{\mu_s}{\rho j}\left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right) - \frac{\kappa}{\rho j}\left(2N + \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right), \tag{4}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} + \frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{Q_0}{\rho C_p}(T - T_2), \tag{5}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D^*\frac{\partial^2 C}{\partial y^2} - \gamma_0 (C - C_2), \tag{6}$$

where u and v indicate the velocity components in the x and y directions, respectively, ρ is the fluid density, μ is the dynamic viscosity, κ is the material parameter, N is the angular or microrotation velocity, P is the fluid pressure, j is the microinertia density, $\mu_s = (\mu + \kappa/2)j$ is the microrotation viscosity, T is the fluid temperature, C_p is the specific heat at constant pressure, C is the fluid concentration, k is the thermal conductivity, q_r is the radiative heat flux, Q_0 is the heat generation coefficient, D^* is the molecular diffusivity, and γ_0 is the chemical reaction rate coefficient.

Using Rosseland's approximation for radiation, we obtain

$$q_r = -\left(\frac{4\sigma}{3k_0}\right)\frac{\partial T^4}{\partial y}, \tag{7}$$

where σ is the Stefan–Boltzmann constant and k_0 is the absorption coefficient. We consider that the temperature variation within the flow is such that T^4 may be expanded in a Taylor's series. Expanding T^4 about T_∞ and neglecting higher order terms, we get $T^4 = 4T_\infty^3 T - 3T_\infty^4$. Now (5) reduces to

$$\begin{aligned} u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} &= \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma T_\infty^3}{3k_1\rho C_p}\frac{\partial^2 T}{\partial y^2} \\ &\quad + \frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{Q_0}{\rho C_p}(T - T_2). \end{aligned} \tag{8}$$

The appropriate boundary conditions for the flow are

$$\begin{aligned} &u = v = 0, \\ &N = -n\frac{\partial u}{\partial y}, \\ &T = T_1, \\ &C = C_1, \\ &\qquad \text{at } y = -h, \\ &u = \frac{v_0 x}{h}, \\ &v = 0, \\ &N = \frac{v_0 x}{h^2}, \\ &T = T_2, \\ &C = C_2, \\ &\qquad \text{at } y = -h, \end{aligned} \tag{9}$$

where boundary parameters n $(0 \le n \le 1)$ indicate the degree to which the microelements are free to rotate near the channel walls. The case when $n = 0$ is called strong concentration of microelements, which implies $N = 0$ near the wall surface. This represents concentrated particle flow where the microelements close to the wall surface are unable to rotate. In the case when $n = 1/2$, this indicates vanishing of the antisymmetric part of the stress tensor and denoted weak concentration of microelement and $n = 1$ is used for the modeling of turbulent boundary layer flow. In this paper, the authors considered $n = 1/2$ for which the governing equations can be reduced to the classical problem of steady boundary layer flow of a viscous incompressible fluid near the channel wall.

Equations (2), (3), (4), (6), and (8) can be transformed into a set of nonlinear ordinary differential equations by using the following similarity transformations:

$$\begin{aligned} \eta &= \frac{y}{h}, \\ \psi &= -v_0 x f(\eta), \\ N &= \frac{v_0 x}{h^2} g(\eta), \\ \theta(\eta) &= \frac{T - T_2}{T_1 - T_2}, \\ \phi(\eta) &= \frac{C - C_2}{C_1 - C_2}, \end{aligned} \tag{10}$$

where $T_2 = T_1 - Ax$ and $C_2 = C_1 - Bx$, with A and B as constants. The stream function ψ is defined as

$$\begin{aligned} u &= \frac{\partial \psi}{\partial y}, \\ v &= -\frac{\partial \psi}{\partial x}. \end{aligned} \tag{11}$$

The coupled system of transformed nonlinear ordinary differential equations is

$$\begin{aligned} (1 + N_1) f^{\mathrm{IV}} - N_1 g - \mathrm{Re}\left(ff''' - f'f''\right) &= 0, \\ N_2 g'' + N_1\left(f'' - 2g\right) - N_3\mathrm{Re}\left(fg' - f'g\right) &= 0, \\ (1 + R)\theta'' + \mathrm{Pe}_h\left[\mathrm{Ec} f''^2 + f'\theta - f\theta' + H\theta\right] &= 0, \\ \phi'' + \mathrm{Pe}_m\left(f'\phi - f\phi' - \gamma\phi\right) &= 0. \end{aligned} \tag{12}$$

Boundary conditions in nondimensional form are

$$\begin{aligned} &f(-1) = f'(-1) = g(-1) = 0, \\ &\theta(-1) = \phi(-1) = 1, \\ &f(1) = \theta(1) = \phi(1) = 0, \\ &f'(1) = -1, \\ &g(1) = 1, \end{aligned} \tag{13}$$

where $N_1 = \kappa/\mu$ is the coupling number, $N_2 = v_s/\mu h^2$ is the spin-gradient viscosity parameter, $N_3 = j/h^2$ is the micropolar material constant, $\mathrm{Ec} = v_0^2 x v/h^3 c_p A$ is the local Eckert number, $H = \theta_0 h/\rho C_p v_0$ is the heat generation parameter, $\mathrm{Pe}_h = \mathrm{Pr}\,\mathrm{Re}$ and $\mathrm{Pe}_m = \mathrm{Sc}\,\mathrm{Re}$ are the Peclet numbers for the diffusion of heat and the diffusion of mass, $\mathrm{Re} = (v_0/v)h$

is the Reynolds number, $R = 3k_0k/16\sigma T_\infty^3$ is the thermal radiation parameter, $\mathrm{Gr} = g\beta_T A h^4/\upsilon^2$ is the Grashof number, $\mathrm{Pr} = \upsilon\rho c_p/k$ is the Prandtl number, $\mathrm{Sc} = \upsilon/D^*$ is the Schmidt number, and $\gamma = \gamma_0 h/\nu_0$ is the chemical reaction parameter.

The other parameters of physical interest are the local Nusselt Nu_x and Sherwood Sh_x numbers, which are defined as follows:

$$\mathrm{Nu}_x = \frac{xq_w}{k(T_1 - T_2)}, \qquad \mathrm{Sh}_x = \frac{xm_w}{D^*(C_1 - C_2)}, \tag{14}$$

where q_w and m_w are the local heat flux and mass flux, respectively, which are defined as

$$q_w = -k\left(\frac{\partial T}{\partial y}\right)_{y=-h}, \qquad m_w = D^*\left(\frac{\partial C}{\partial y}\right)_{y=-h}. \tag{15}$$

Now using (10) and (15) in (14), we get

$$\mathrm{Nu}_x = -\theta'(-1), \qquad \mathrm{Sh}_x = -\phi'(-1). \tag{16}$$

3. Method of Solution

In this present paper, Runge-Kutta-Fehlberg fourth fifth-order method has been employed to solve the system of non-linear ordinary differential equations (12) with the boundary conditions given by (13) for different values of governing parameters. The RKF45 method has a procedure to determine if the appropriate step size h is being used. The formula of fifth-order Runge-Kutta-Fehlberg method can be defined as follows:

$$z_{n+1} = z_n + \left(\frac{16}{135}k_0 + \frac{6656}{12{,}825}k_2 + \frac{28{,}561}{56{,}430}k_3 - \frac{9}{50}k_4 + \frac{2}{55}k_5\right)h, \tag{17}$$

where the coefficients k_0 to k_5 are given by

$$\begin{aligned}
k_0 &= f(x_n, y_n),\\
k_1 &= f\left(x_n + \frac{1}{4}h, y_n + \frac{1}{4}hk_0\right),\\
k_2 &= f\left(x_n + \frac{3}{8}h, y_n + \left(\frac{3}{32}k_0 + \frac{9}{32}k_1\right)h\right),\\
k_3 &= f\left(x_n + \frac{12}{13}h, y_n + \left(\frac{1932}{2197}k_0 - \frac{7200}{2197}k_1 + \frac{7296}{2197}k_2\right)h\right),\\
k_4 &= f\left(x_n + h, y_n + \left(\frac{439}{216}k_0 - 8k_1 + \frac{3680}{513}k_2 - \frac{845}{4104}k_3\right)h\right),\\
k_5 &= f\left(x_n + \frac{1}{2}h, y_n + \left(-\frac{8}{27}k_0 + 2k_1 - \frac{3544}{2565}k_2 + \frac{1859}{4104}k_3 - \frac{11}{40}k_4\right)h\right).
\end{aligned} \tag{18}$$

The computation of the error can be achieved by subtracting the fifth-order from the fourth-order method:

$$y_{n+1} = y_n + \left(\frac{25}{216}k_0 + \frac{1408}{2565}k_2 + \frac{2197}{4101}k_3 - \frac{1}{5}k_4\right)h. \tag{19}$$

If the error goes beyond a specified antechamber, the results can be recalculated using a smaller step size. The approach to computing the new step size is shown as follows:

$$h_{\mathrm{new}} = h_{\mathrm{old}}\left(\frac{\varepsilon h_{\mathrm{old}}}{2\left|z_{n+1} - y_{n+1}\right|}\right)^{1/4}. \tag{20}$$

The numerical computations were carried out with $\Delta\eta = 0.01$. The variation of the dimensionless velocity, microrotation, temperature, and concentration is ensured to be less than 10^{-6} between any two successive iterations for the convergence criterion.

4. Results and Discussion

In order to study, the effects of various governing physical parameters on the flow, heat, and mass transfer numerical computations are carried out for $0.1 \le N_1 = N_2 = N_3 \le 1$, $0 \le H \le 10$, $-2 \le \mathrm{Re} \le 5$, $0 \le R \le 4$, $0 \le \mathrm{Pe}_h \le 2$, $0 \le \mathrm{Pe}_m \le 2$, and $0 \le \gamma \le 10$ while the Eckert number $\mathrm{Ec} = 0.01$ is fixed. A critical analysis with previously published work is done in Table 1 and these results are found to be in very good agreement.

The effects of the Reynolds number Re on velocity $f'(\eta)$ and microrotation $g(\eta)$ are shown in Figures 2 and 3. It is seen from Figure 2 that velocity profile $f'(\eta)$ decreases near the lower channel wall, while it increases near the upper channel wall when the Reynolds number Re increases. It is clear from Figure 3 that an increase in the magnitude of Re leads to decrease in microrotation profile $g(\eta)$.

Table 1: Comparison of values of $\phi(\eta)$ for various values of η, Pe_m, and Re when $\mathrm{Pe}_h = 0.2$, $N_1 = N_2 = N_3 = 0.1$, $N_1 = N_2 = N_3 = 0.1$, and $\mathrm{Ec} = R = \gamma = 0$.

η	Sheikholeslami et al. [6]		Present results	
	$\mathrm{Pe}_m = 0.2$, $\mathrm{Re} = 0.5$	$\mathrm{Pe}_m = 0.5$, $\mathrm{Re} = 1$	$\mathrm{Pe}_m = 0.2$, $\mathrm{Re} = 0.5$	$\mathrm{Pe}_m = 0.5$, $\mathrm{Re} = 1$
−1.0	1	1	1	1
−0.6	0.814341	0.835986	0.814346	0.835992
−0.2	0.621160	0.653497	0.621165	0.653501
0.0	0.521109	0.553582	0.521114	0.553590
0.2	0.419033	0.448495	0.419039	0.448499
0.6	0.210678	0.227352	0.210684	0.227358
1.0	0	0	0	0

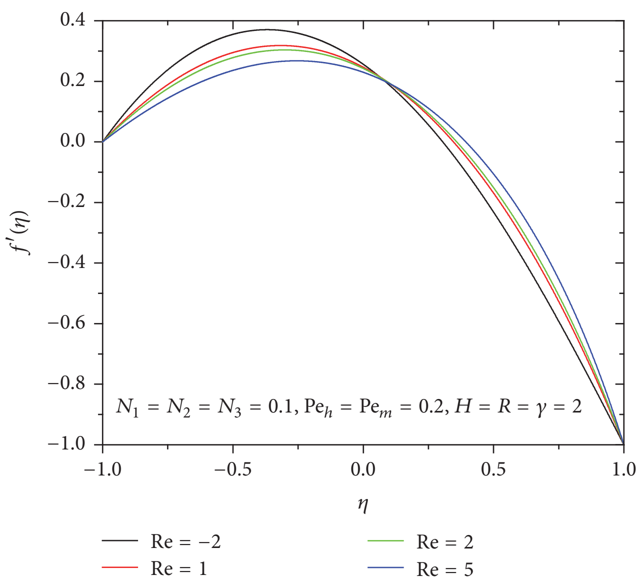

Figure 2: Velocity profile $f'(\eta)$ for various values of Re.

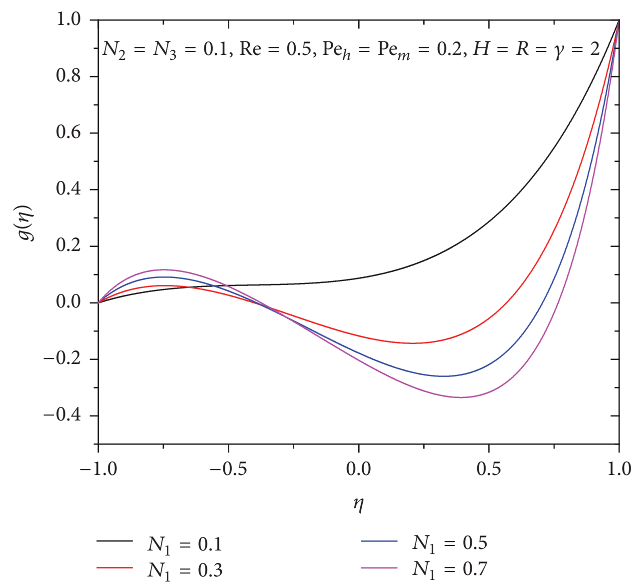

Figure 4: Microrotation profile $g(\eta)$ for various values of N_1.

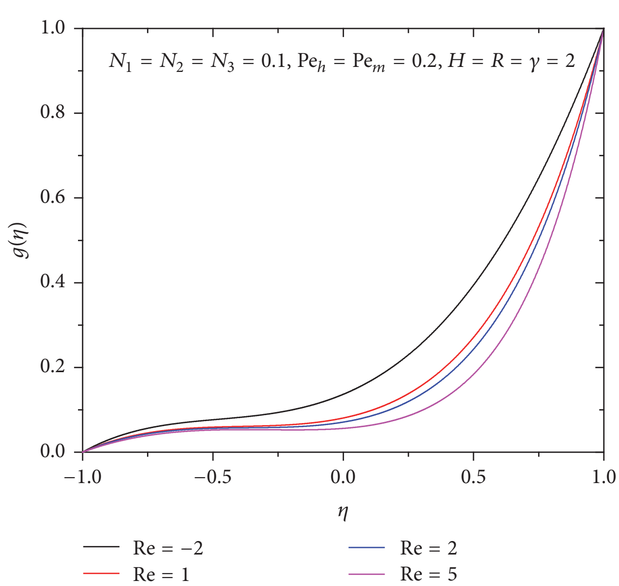

Figure 3: Microrotation profile $g(\eta)$ for various values of Re.

The microrotation profile $g(\eta)$ for the coupling number N_1, the spin-gradient viscosity parameter N_2, and the micropolar material constant N_3 are displayed in Figures 4–6. It is noticed from Figure 4 that the microrotation profile increases with N_1 at lower channel wall for $0 \leq \eta < -0.65$, but reverse trend is found for the case $\eta > -0.65$. It is depicted from Figure 5 that the value of microrotation profile $g(\eta)$ increases as the value of N_2 increases. It is evident from Figure 6 that the values of microrotation are lower for higher values of N_3.

Figures 7–9 show the temperature distribution $\theta(\eta)$ with collective variation in heat source parameter H, thermal radiation parameter R, and Peclet number Pe_h. Figure 7 exhibits that temperature $\theta(\eta)$ considerably increases with an increase in H. Figure 8 indicates that an increase in R induces a decrease in temperature $\theta(\eta)$. It is noticed from Figure 9 that a rise in Pe_h causes rapid increase in temperature.

The effects of the Peclet number Pe_m and chemical reaction parameter γ on the concentration profile $\phi(\eta)$ are shown in Figures 10 and 11. Figures 10 and 11 indicate that

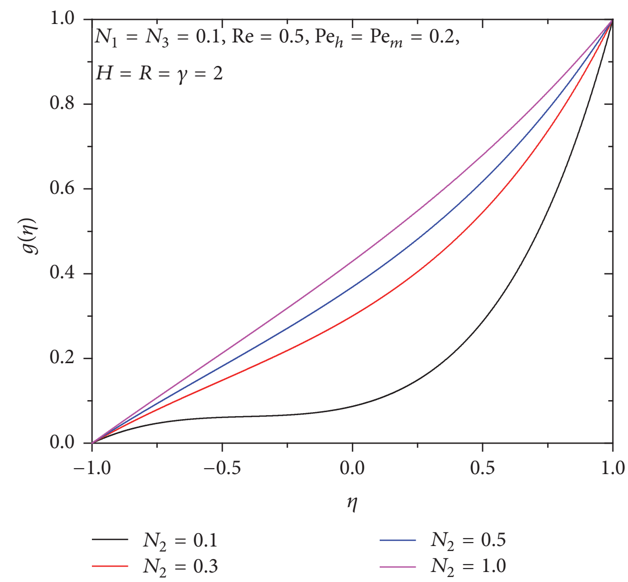

FIGURE 5: Microrotation profile $g(\eta)$ for various values of N_2.

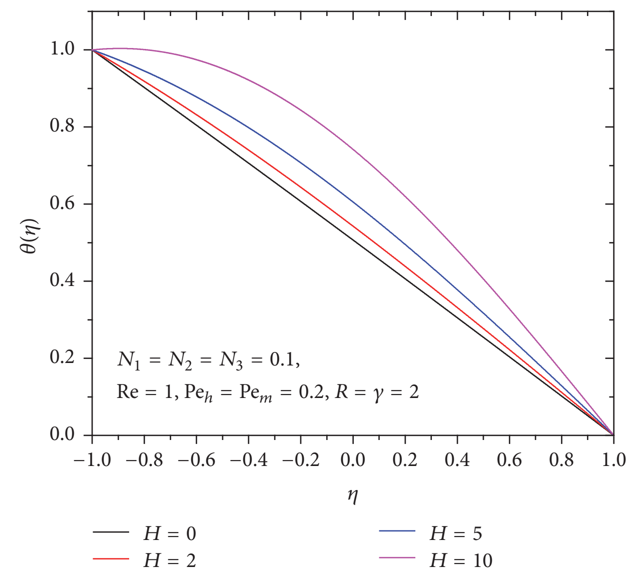

FIGURE 7: Temperature profile $\theta(\eta)$ for various values of H.

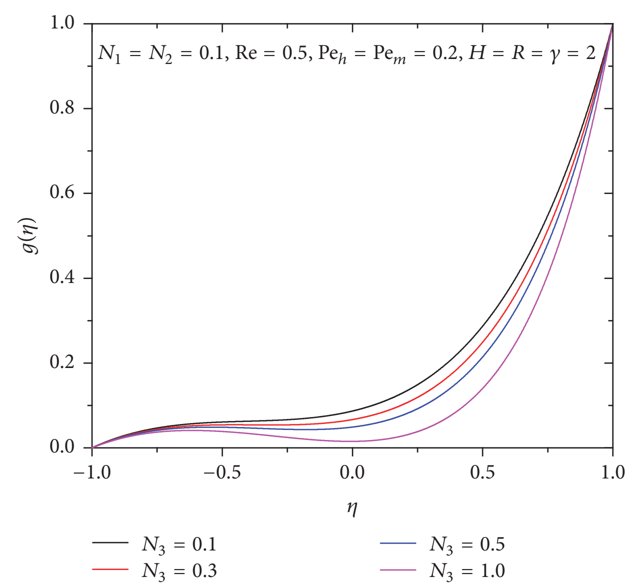

FIGURE 6: Microrotation profile $g(\eta)$ for various values of N_3.

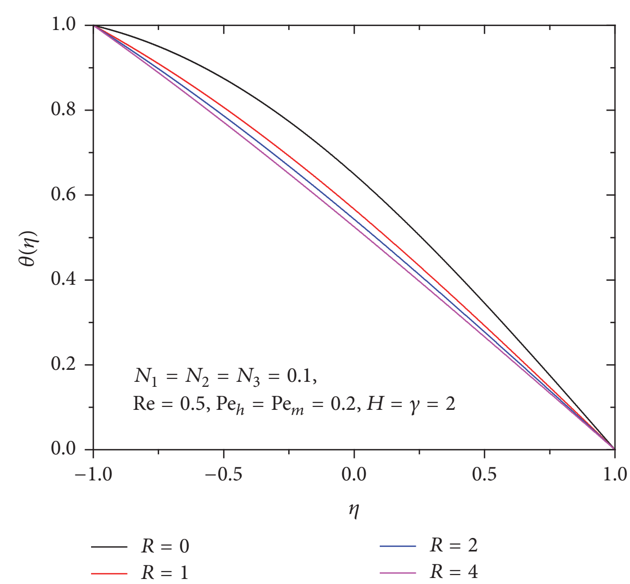

FIGURE 8: Temperature profile $\theta(\eta)$ for various values of R.

concentration decreases with increasing values of Pe_m and γ.

The variation of the Nusselt number (dimensionless heat transfer rate at the surface) is displayed for different parameters in Figures 12–14. Figure 12 depicts the behavior of the Nusselt's number against Reynolds number Re with various values of heat source parameter H. It is clear that, with the increasing of H, the heat transfer rate decreases. Figure 13 enlightens the variation of the heat transfer rates with Reynolds number Re for various values of thermal radiation parameter R. It is evident from Figure 13 that Nusselt number monotonically increases with a rise in R values. Figure 14 depicts the variation of Nusselt number as function of Reynolds number Re and Peclet number Pe_h. It is noted that heat transfer rate decreases with a rise in Pe_h values. Also, a negligible change in heat transfer rate with increasing values of Reynolds number Re is seen from Figures 12–14.

Figures 15 and 16 displayed the variation of the Sherwood number or mass transfer rate for different parameters. Figures 15 and 16 depict the behavior of the mass transfer rate against Reynolds number Re with different values of Peclet number Pe_m and chemical reaction parameter γ. The mass transfer rate rises with increasing values of the Peclet number Pe_m and chemical reaction parameter γ. It is also clear from these figures that there is no change in mass transfer rate with rise in Reynolds number Re values.

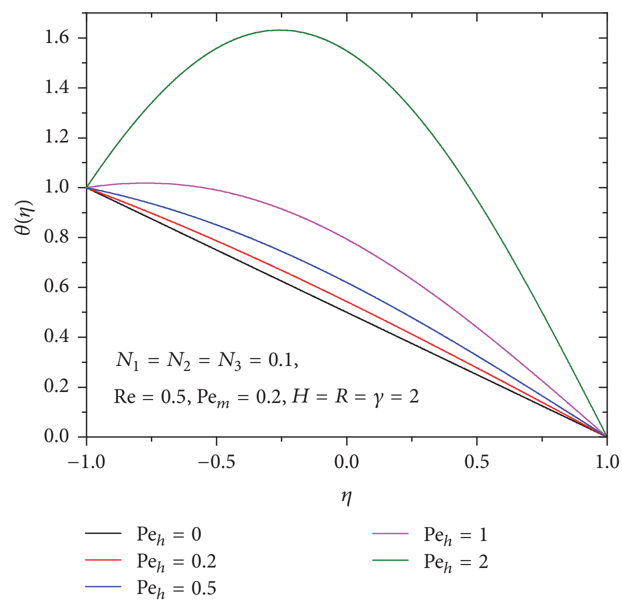

FIGURE 9: Temperature profile $\theta(\eta)$ for various values of Pe_h.

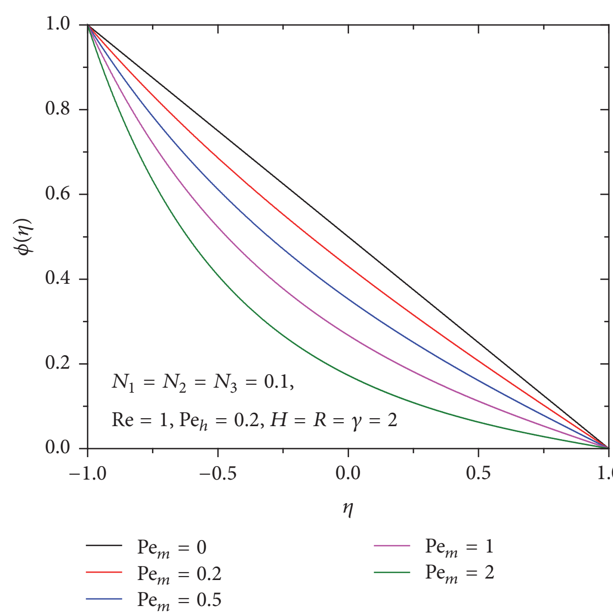

FIGURE 10: Concentration profile $\phi(\eta)$ for various values of Pe_m.

5. Conclusions

The present paper deals with numerical analysis of chemical reaction effects on heat and mass transfer flow of a micropolar fluid over a permeable channel in the presence of radiation and heat generation. The system of nonlinear partial differential equations was converted to a system of ordinary differential equations and then is solved numerically using the Runge-Kutta-Fehlberg method along with shooting method. From the above discussion, the important results are summarized as follows:

(i) Velocity and Reynolds number are inversely proportional to each other at lower channel wall, while velocity and Reynolds number are proportional to each other at upper channel wall.

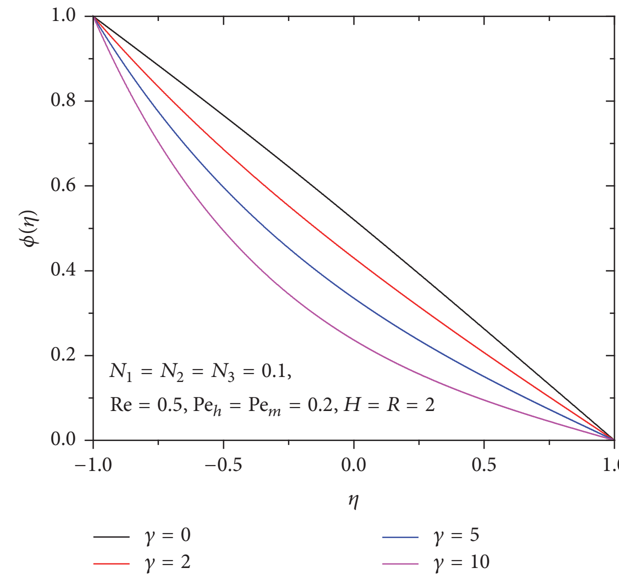

FIGURE 11: Concentration profile $\phi(\eta)$ for various values of γ.

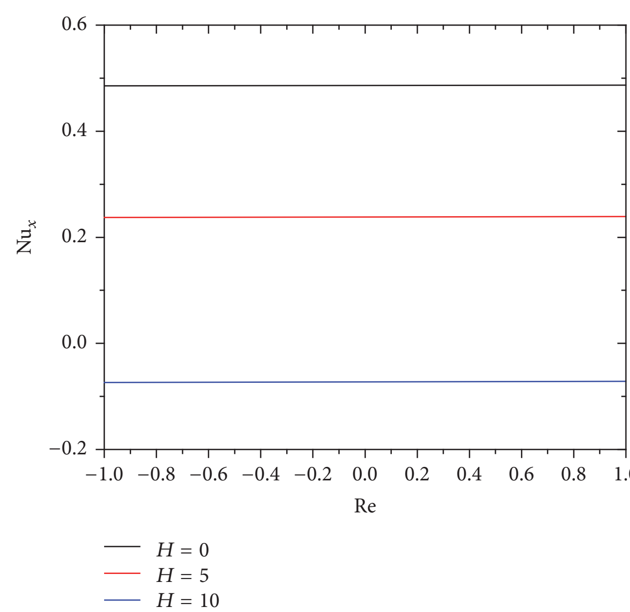

FIGURE 12: Variation of Nusselt's number with H and Re.

(ii) Microrotation decreases with increase in the value of coupling number, micropolar material constant, and Reynolds number, but it increases with increase in the value of spin-gradient viscosity parameter.

(iii) Temperature increases with heat generation parameter and Pe_h and Pe_m are the Peclet numbers for the diffusion of heat and the diffusion of mass, and temperature decreases with thermal radiation parameter.

(iv) Concentration is inversely proportional to the Peclet number for the diffusion of mass and chemical reaction parameter.

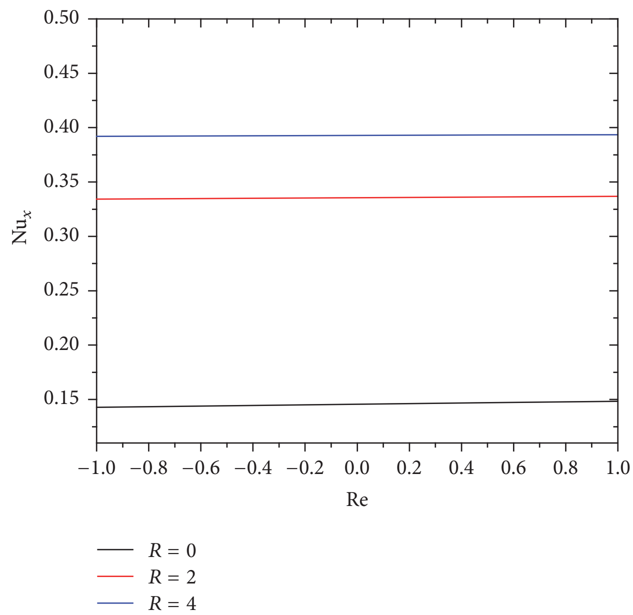

FIGURE 13: Variation of Nusselt's number with R and Re.

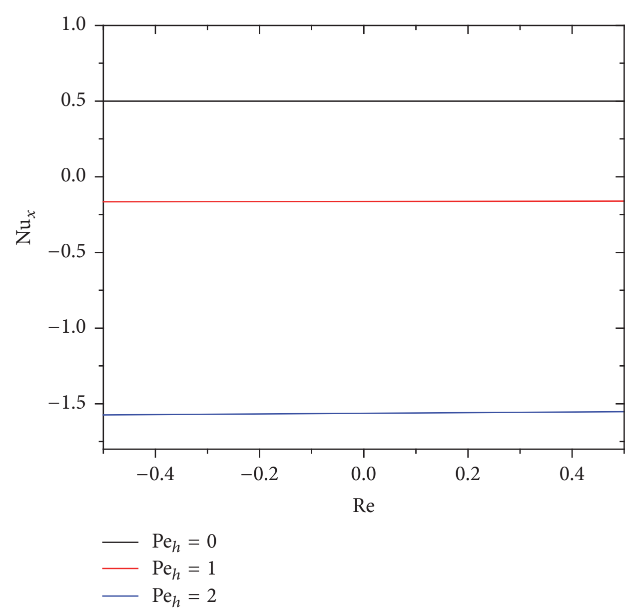

FIGURE 14: Variation of Nusselt's number with Pe_h and Re.

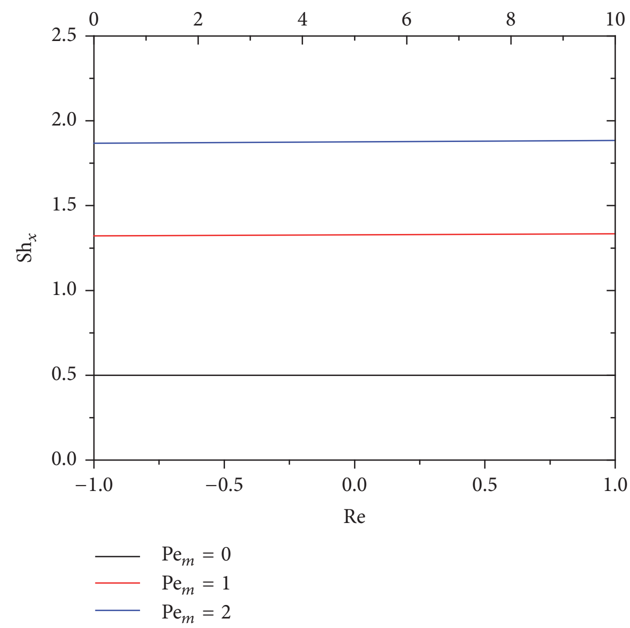

FIGURE 15: Variation of Sherwood number with Pe_m and Re.

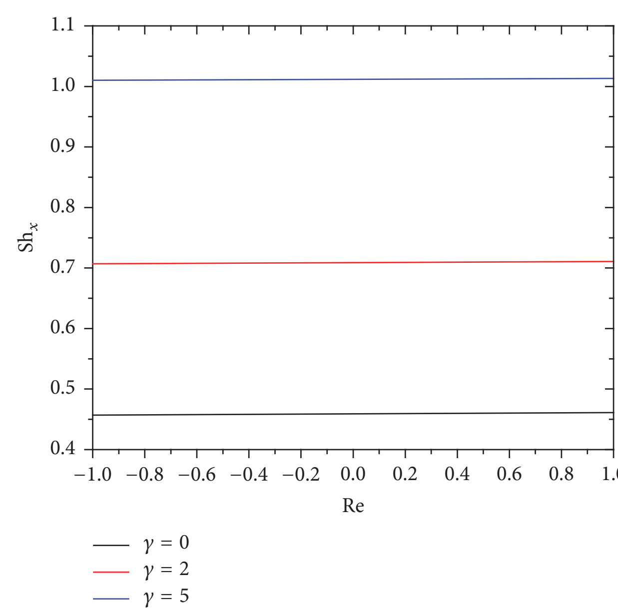

FIGURE 16: Variation of Sherwood number with γ and Re.

(v) The rate of heat transfer increases with thermal radiation parameter and rate of heat transfer decreases with Peclet number Pe_h and heat generation parameter.

(vi) The rate of mass transfer rises with increase Peclet number Pe_m and chemical reaction parameter.

Nomenclature

C: Species concentration
D^*: Molecular diffusivity
f: Dimensionless stream function
g: Dimensionless microrotation
h: Width of the channel
j: Microinertia density
N: Microrotation/angular velocity
$N_{1,2,3}$: Dimensionless parameter
Nu: Nusselt number
Sh: Sherwood number
Sc: Schmidt number
p: Pressure
Pt: Prandtl number
Pe: Peclet number
q: Mass transfer parameter
q_r: Radiative heat flux
Re: Reynold number
T: Fluid temperature
s: Microrotation boundary condition

(u, v): Cartesian velocity components
(x, y): Cartesian coordinate components parallel and normal to cannel axis, respectively.

Greek Symbols

η: Similarity variable
θ: Dimensionless temperature
μ: Dynamic viscosity
κ: Material parameter
ρ: Fluid density
μ_s: Microrotation/spin-gradient viscosity
ψ: Stream function.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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