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An Analysis on Unsteady Heat and Mass Transfer Flow of Radiative Chemically Reactive Fluid past an Oscillating Plate Embedded In Porous Media in Presence of Soret Effect

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Abstract: ***The aim of the present paper is to analyze a basic theoretical fluid model depicting the parametric effect of the Peclet numbers on a two dimensional chemically reactive heat and mass transfer flow past an oscillating plate with Soret and first order chemical reaction effects. Rosseland radiative heat flux model is considered in the energy equation. The plate surface is considered to be permeable. Fouriers and Ficks empirical laws are used to quantify the constant heat and mass fluxes on the plate surface. The resulting system of partial differential equations with a set of favorable boundary conditions is first non-dimensionalized and then transform to a set of ordinary differential equations by using a set of normalized mode of transformations. Finally, the results are validating numerically through graphs and tables.***

Index Terms**: *Chemical reaction, Heat and Mass transfer, Soret effect, Thermal radiation, Peclet numbers.***

NOMENCLATURE

$\bar{C}$ Species concentration
c_p Specific heat at constant pressure
$\bar{C}_w$ Species concentration at the plate
$\bar{C}_\infty$ Species concentration in the free stream
D_M Co-efficient of mass diffusion
k Thermal conductivity
K Permeability parameter
K_l^* Chemical reaction parameter (non-dimensional)
Nu_R Nusselt number (real part)
Pe (Heat transfer) Peclet number
Pe_m Mass transfer Peclet number
Pr Prandtl number
q Constant heat flux per unit area
$\bar{Q}_l$ Heat sink parameter (non-dimensional)
Re_L Local Reynolds number
Sc Schmidt number
Sh_R Sherwood number (Real part)
t Time variable (non-dimensional)
$\bar{t}$ Time variable (dimensional)
$\bar{T}$ Fluid temperature
$\bar{T}_w$ Temperature at the plate
$\bar{T}_\infty$ Temperature in the free stream
u First component of fluid velocity (non-dimensional)
$\bar{u}$ First component of fluid velocity (dimensional)

$\bar{U}_0$ Mean plate velocity (non-dimensional)
u_0 Mean plate velocity (dimensional)
u_R Real part of u
y y – co-ordinate (dimensional)
$\bar{y}$ y – co-ordinate (non-dimensional)
v Second component of fluid velocity (non-dimensional)
V_0 Mean suction velocity
$\bar{v}$ Second component of fluid velocity (dimensional)

Greek Symbols

ρ Fluid density
ν Kinematic coefficient of viscosity
θ Non-dimensional temperature
ϕ Non-dimensional species concentration
θ_R Real part of θ
ϕ_R Real part of ϕ
ω Frequency of Oscillation

Subscripts

w Conditions on the walls
∞ Free stream conditions

I. INTRODUCTION

Many processes in engineering and industrial areas occur at high temperatures and knowledge of radiation heat transfer becomes very significant for the design of pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such areas such as heating and cooling chambers, fossil fuel combustion.

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The interaction of thermal radiation with free convection heat transfer was considered by Cess [1].Soundalgekar and Takhar [2] investigated radiation effects on free convection flow of a gas past a semi-infinite flat plate. Recently, Sengupta and Sen [3] investigated the thermal radiation on the free convective heat and mass transfer flow in presence of heat generation and thermo-diffusion effects. The study of free convective heat and mass transfer with chemical reactions is very significant due to its considerable importance in the chemical and hydrometallurgical industries and as such a large amount of research work has been reported in it. The flow and mass transfer on a stretching sheet with a magnetic field and chemically reactive species was investigated by Takhar et al. [4]. Kandasamy et al. [5] considered the effects of chemical reaction, heat and mass transfer along a wedge with heat source in the presence of suction or injection. Very recently, Sengupta [6], [7] investigated the first order chemical reaction in case of free convective heat and mass transfer flow. When heat and mass transfer occur simultaneously in a moving fluid, the relations between the fluxes and the driving potentials are of more intricate in nature. Mass fluxes influenced by temperature gradient are termed as Soret or thermal diffusion effect. The Soret effect for instance has been utilized for isotope separation and in mixtures between gases with very low molecular weight like (H_2 , He). Renuka et al. [8] have studied the Soret effect on unsteady MHD free convective mass transfer flow past an infinite vertical porous plate with variable suction. A new class of similarity solutions of an unsteady electrically conducting free-forced convection flow in a vertical porous surface in presence of Soret and Dufour effects was considered by Sattar and Ferdows [9]. Ahmed et al. [10] investigated the Soret effect in MHD free convection flow. Very recently Sengupta and Ahmed [11] investigated the Soret effect with chemical reaction in case of MHD free convective dissipative flow in velocity slip regime. Of late, Sengupta [12] considered the thermo-diffusion (Soret) effect on mixed convective mass transfer flow with chemical reaction and heat sink/ source effects.

The objective of the present paper is to study the unsteady heat and mass transfer flow of viscous incompressible fluid past an oscillating horizontal flat plate in presence of thermal radiation, first order chemical reaction and Soret effects.

II. MATHEMATICAL FORMULATION AND SOLUTION OF THE PROBLEM

The flow is considered to be unsteady, laminar and two-dimensional, whereas the fluid and the porous media are in local thermo-dynamical equilibrium. A co-ordinate system ($\bar{x}$, $\bar{y}$) has been introduced, with $\bar{x}$ - axis along the length of the plate in the horizontal direction and $\bar{y}$ - axis perpendicular to the plate towards the fluid region. The plate oscillates about $\bar{y}$ - axis and is subjected to a constant suction velocity. Using boundary layer approximations, a two- dimensional fluid model has been developed as:

Continuity Equation

$$\frac{\partial \bar{v}}{\partial \bar{y}} = 0$$

(1)

Momentum Equation

$$\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = -\frac{1}{\rho}\frac{\partial p}{\partial \bar{x}} + \nu\frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \frac{\nu}{\bar{K}}\bar{u} \qquad (2)$$

Energy Equation

$$\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}} = \frac{k}{\rho c_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \frac{1}{\rho c_p}\frac{\partial \bar{q}_{r\bar{y}}}{\partial \bar{y}} \qquad (3)$$

Species Continuity Equation

$$\frac{\partial \bar{C}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{C}}{\partial \bar{y}} = D_M\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} + D_T\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \bar{K}_l(\bar{C} - \bar{C}_\infty)$$

(4)

The relevant initio-boundary conditions:

$\bar{u} = 0$, $\bar{T} = \bar{T}_\infty$, $\bar{C} = \bar{C}_\infty$, for every $\bar{y}$, when $\bar{t} \le 0$.

$\bar{u} = u_0 \exp(i\bar{\omega}\bar{t})$, $\frac{\partial \bar{T}}{\partial \bar{y}} = -\frac{q}{k}$, $\frac{\partial \bar{C}}{\partial \bar{y}} = -\frac{m}{D_M}$, at $\bar{y} = 0$,

when $\bar{t} > 0$ (5)

$\bar{u} \to 0$, $\bar{T} \to \bar{T}_\infty$, $\bar{C} \to \bar{C}_\infty$, for $\bar{y} \to \infty$, when $\bar{t} > 0$

We, take the constant suction velocity as:

$$\bar{v} = -V_0 \qquad (6)$$

The Roseland approximation, quantified the radiative heat flux for an optically thick boundary layer flow in a simplified differential form is considered as:

$$\bar{q}_r = -\frac{4\sigma^*}{3k^*}\frac{\partial \bar{T}^4}{\partial \bar{y}} \qquad (7)$$

Where σ^* and k^* are the Stefan-Boltzmann constant and Rosseland mean absorption coefficient, respectively. Assuming that the temperature differences within the flow are sufficiently small, as such $\bar{T}^4$ may be expressed as a linear function of temperature $\bar{T}$ and expanding $\bar{T}^4$ in Taylor's series about $\bar{T}_\infty$ and neglecting higher order terms we thus get,

$$\bar{T}^4 \approx \bar{T}_\infty^{\ 4} + (\bar{T} - \bar{T}_\infty)4\bar{T}_\infty^{\ 3} = 4\bar{T}_\infty^{\ 3}\bar{T} - 3\bar{T}_\infty^{\ 4} \qquad (8)$$

Using (6) and (7), equation (3) becomes,

$$\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}} = \frac{k}{\rho c_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{16\sigma^*\bar{T}_\infty^{\ 3}}{3\rho c_p k^*}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} \qquad (9)$$

Introduce the non-dimensional quantities as:

$$u = \frac{\bar{u}}{V_0},\quad v = \frac{\bar{v}}{V_0},\quad y = \frac{\bar{y}}{L},\quad t = \frac{\bar{t}V_0}{L},\quad \theta = \frac{(\bar{T} - \bar{T}_\infty)k}{qL},$$

$$\phi = \frac{(\bar{C} - \bar{C}_\infty)D_m}{mL},\quad \mathrm{Re}_L = \frac{V_0 L}{\nu},$$

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$$\omega=\frac{\bar{\omega}L}{V_0}\ ,\qquad \Pr=\frac{\nu\rho c_p}{k}$$

$$Pe_h=\frac{V_0 L\rho c_p}{k}\ ,\ Sc=\frac{\nu}{D_M}\ ,\ Pe_m=\frac{V_0 L}{D_m}\ ,\ R=\frac{4\sigma^* \bar{T}_\infty^{\,2}}{kk^*},$$

$$F=\frac{K_l^{\,*}L}{V_0},\ Sr=\frac{D_M D_T q}{kmLV_0},U_\infty=\frac{\bar{U}_\infty}{V_0}.$$

Expressions (1) after non-dimensionalizing gives,
v=-1.
(10)
The non-dimensional forms of equations (2) to (4) are,

$$\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=\frac{1}{\mathrm{Re}_L}\frac{\partial^2 u}{\partial y^2} \tag{11}$$

$$Pe_h\left(\frac{\partial\theta}{\partial t}+\frac{\partial\theta}{\partial y}\right)=\lambda\frac{\partial^2\theta}{\partial y^2}$$

$$Pe_m\left(\frac{\partial\phi}{\partial t}-\frac{\partial\phi}{\partial y}\right)=\frac{\partial^2\phi}{\partial y^2}+Pe_m Sr\frac{\partial^2\theta}{\partial y^2}+Pe_m F\phi \tag{13}$$

With non-dimensional boundary conditions as,

$$\left.\begin{array}{l} u=u_0,\ \dfrac{\partial\theta}{\partial y}=-1,\ \ \dfrac{\partial\phi}{\partial y}=-1, \text{ at } y=0 \\ u\to u_0\exp(i\omega t),\theta\to 0,\ \phi\to 0,\text{ for } y\to\infty \end{array}\right\} \tag{14}$$

To solve equations (10) to (12) subject to (13), it is preferred to use a normal mode of solutions in terms of a set of transformations as:

$$\left.\begin{array}{l} u(y,t)=U_0(y)\exp(i\omega t), \\ \theta(y,t)=\theta_0(y)\exp(i\omega t),\phi(y,t)=\phi_0(y)\exp(i\omega t). \end{array}\right\} \tag{15}$$

On using (15), expressions (10) to (13) become,

$$\frac{d^2U_0}{dy^2}+\mathrm{Re}_L\frac{dU_0}{dy}-i\omega\mathrm{Re}_L U_0=0 \tag{16}$$

$$\lambda\frac{d^2\theta_0}{dy^2}+Pe_h\frac{d\theta_0}{dy}-i\omega Pe_h\theta_0=0 \tag{17}$$

$$\frac{d^2\phi_0}{dy^2}+Pe_m\frac{d\phi_0}{dy}-(F-i\omega)Pe_m\phi_0=-Sr\,Pe_m\frac{d^2\theta_0}{dy^2} \tag{18}$$

With boundary conditions as:

$$\left.\begin{array}{l} U_0=u_0,\ \dfrac{d\theta_0}{dy}=-1,\ \dfrac{d\phi_0}{dy}=-1, \text{ at } y=0 \\ U_0\to 0,\theta_0\to 0,\phi_0\to 0, \text{ for } y\to\infty \end{array}\right\} \tag{19}$$

The real part of expressions for non-dimensional temperature, concentration and velocity of fluid particles in the boundary layer are obtained as:

$$u_R(y,t)=u_0\exp(-\alpha_1 y)[\cos(\beta_1 y)\cos(\omega t)+\sin(\beta_1 y)\sin(\omega t)] \tag{20}$$

$$\theta_R(y,t)=\frac{\exp(-\alpha_2 y)}{\alpha_2^{\,2}+\beta_2^{\,2}}[\{\alpha_2\cos(\beta_2 y)-\beta_2\sin(\beta_2 y)\}\cos(\omega t)+\{\alpha_2\sin(\beta_2 y)+\beta_2\cos(\beta_2 y)\}\sin(\omega t)] \tag{21}$$

$$\begin{aligned}\phi_R(y,t)=&[\exp(-\alpha_3 y)\{\gamma_3\cos(\beta_3 y)+\gamma_4\sin(\beta_3 y)\}+\exp(-\alpha_2 y)\{\delta_1\cos(\beta_2 y)+\delta_2\sin(\beta_2 y)\}]\cos(\omega t)\\ &-[\exp(-\alpha_3 y)\{\gamma_4\cos(\beta_3 y)-\gamma_3\sin(\beta_3 y)\}+\exp(-\alpha_2 y)\{\delta_2\cos(\beta_2 y)-\delta_1\sin(\beta_2 y)\}]\sin(\omega t)\end{aligned} \tag{22}$$

Rate of heat transfer coefficient:

The real part of the rate of the heat transfer coefficient in terms of the Nusselt number is given as,

$$Nu_R=\frac{1}{Pe_h(\theta_R)_{y=0}}=\frac{1}{Pe_h}\frac{\alpha_2^{\,2}+\beta_2^{\,2}}{(\alpha_2\cos(\omega t)+\beta_2\sin(\omega t))} \tag{23}$$

Rate of mass transfer coefficient:

The real part of the rate of the mass transfer coefficient in terms of the Sherwood number is

$$Sh_R=\frac{1}{Pe_m(\phi_R)_{y=0}}=\frac{1}{Pe_m((\gamma_3+\delta_1)\cos(\omega t)\text{-}(\gamma_4+\delta_2)\sin(\omega t))} \tag{24}$$

III. RESULTS AND DISCUSSION

The influence of various pertinent parameters developed in the study, such as local Reynolds number (Re_L), Prandtl number (*Pr*), Schmidt number (*Sc*), (heat transfer) Peclet number (Pe_h), mass transfer Peclet number (Pe_m), chemical reaction parameter (*F*), frequency parameter (ω) and permeability parameter (*K*) on the velocity, temperature, and concentration fields along with Nusselt and Sherwood numbers, skin-friction and vorticity vectors have been obtained analytically and computed values are shown numerically through graphs.

Figure 1 demonstrates the effect of local Reynolds number (Re_L) on the velocity profile (u_R, y) for fixed values of *K*=0.5, *t* =0.2 and ω =7.857. It is observed that, as the parametric values of Re_L increase, the effect of suction velocity increases, which reduces the main flow rate and thus the values of u_R decrease. In figures 2 and 3, the influence of (heat transfer) Peclet number (Pe_h) and radiation parameter (*R*) on the temperature profile (θ_R, y) for fixed values of *K*=0.5, *t* =0.2, ω =7.857, *R*=0.315 (for fig.2) and Pe_h = 0.71(for fig.3) are depicted graphically. Due to increase in values of Pe_h, the convection mode of heat transfer is more significant than its conduction mode and as such the thermal boundary layer gets thinner results of which reduces the value of θ_R. Again due to increase in *R*, significant amount of heat is generated near the plate as such the thickness of the thermal boundary layer increases, which thus increase the values of θ_R. Figures 4 and 5 present graphically the influences of *Sr* and Pe_m on the concentration profile (ϕ_R, y) for fixed values of *K*=0.5, *t* =0.2, ω =7.857, *R*=0.315, *Sr* =0.5 (for fig.5), Pe_h = 0.71 and Pe_m = 0.78(for fig.4) respectively.

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It is observed that, due to increase in values of *Sr*, the concentration boundary layer gets increase results of which increases the values of ϕ_R . On the other hand, as the values of Pe_m increase, the advective mode of mass transfer becomes more prominent than its diffusive mode, which results in decreasing the concentration boundary layer and thus the values of ϕ_R get decrease. The increase in values of Pe_h on Nu_R against time *t* is expressed graphically in figure 6. It is observed that, the heat transfer rate gets decelerate due to increase in Pe_h , while initially the rate of heat transfer decrease for approximately $0 \le t \le 2.5$ and starts increasing as $t > 2.5$. Finally in figure 7, the effect of Pe_m on the mass transfer rate Sh_R against *t* is depicted graphically. It is observed that, due to increase in Pe_m , the values of Sh_R increase and the values of Sh_R are found increasing steadily for increase in *t*.

IV. CONCLUSIONS

A two dimensional unsteady heat and mass transfer flow of an incompressible viscous fluid past a suddenly oscillating plate embedded in Darcian porous media with thermal radiation, chemical reaction and thermo-diffusion (Soret) effects is considered for study in this paper. The investigation leads to the following conclusion:

- The primary velocity increases due to increase in values of local Reynolds number.
- The temperature decreases due to increase in (heat transfer) Peclet number, while it is found increasing due to increase in thermal radiation.
- The concentration increases as the Soret number increases and the concentration decreases as the mass transfer Peclet number increases.
- The rate of heat transfer decelerates as the (heat transfer) Peclet number increases.
- The mass transfer rate enhances due to increase in mass transfer Peclet number.

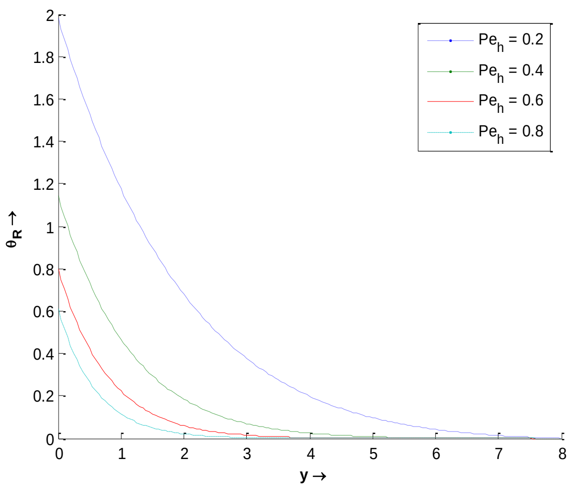

Figure1. Graph of u_R **vs *y* for change in values of** Re_L

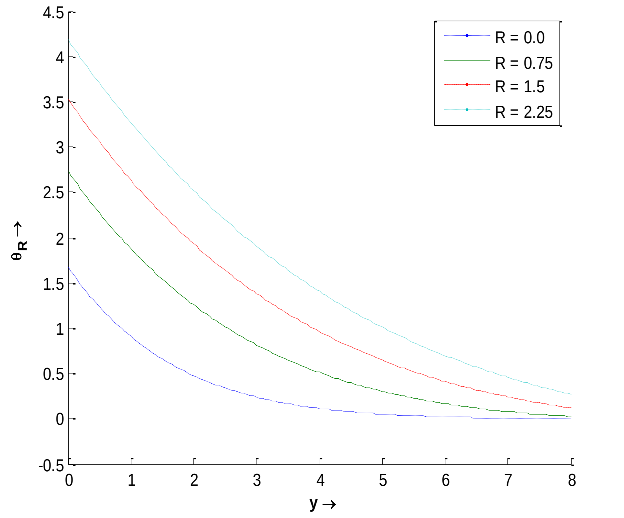

Figure2. Graph of θ_R **vs *y* for change in values of** Pe_h

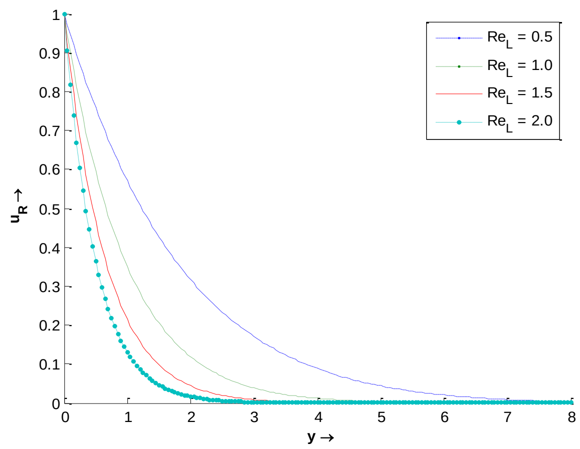

Figure3. Graph of θ_R **vs *y* for change in values of *R***

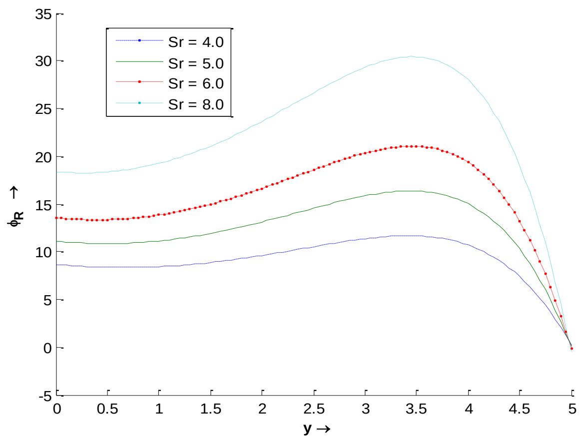

Figure4. Graph of ϕ_R **vs *y* for change in values of *Sr*.**

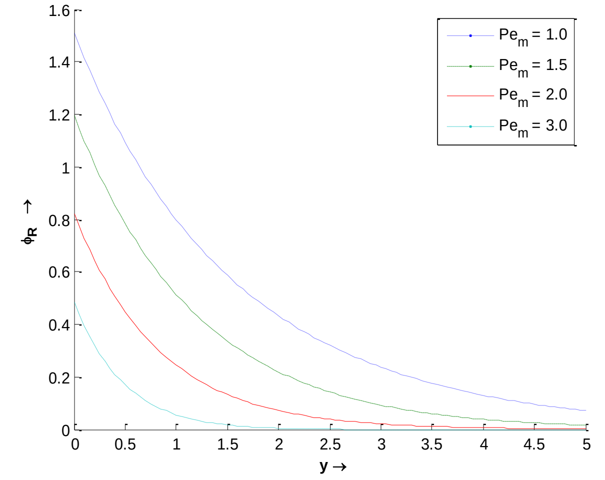

Figure5. Graph of ϕ_R vs *y* for change in values of Pe_m .

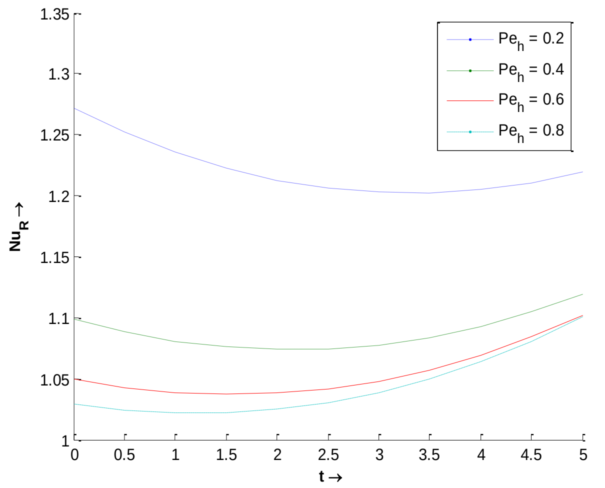

Figure6. Graph of Nu_R vs *t for* change in values of Pe_h .

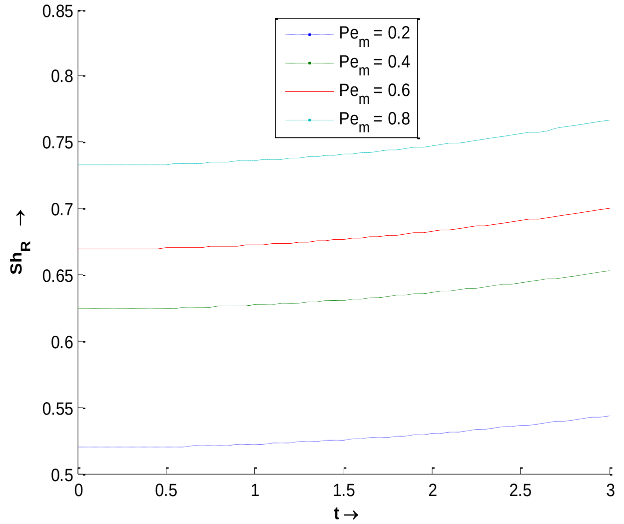

Figure7. Graph of Sh_R vs *t* for change in values of Pe_m .

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