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Influence of Heat and Mass Transfer on Mixed Conviction Flow of an Exothermic Fluid in a Vertical Channel

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This study investigates the effect of mass transfer on mixed convection flow of an exothermic fluid in a vertical channel, the fluid is assumed to be an exothermic fluid, the governing equations are set of ordinary differential equation (ODE) which were solved using perturbation technique, the physical quantities or profile of engineering interest such as velocity, temperature and concentration profiles were obtained, the effect of various parameters on the flow have been shown in the graph. It is found that the effect of controlling parameter has significant influence on the flow.

Keywords: Mixed convection, Mass transfer, exothermic fluid, Perturbation technique.

1. Introduction

Extensive research on heat and mass transfer in fluid flow has been performed, both analytically and numerically, in the present and past decades on steady-state heat and mass transfer of an exothermic fluid flow in a vertical channel. This effort was originally motivated by many industrial applications, such as geothermal reservoir, cooling of nuclear reactors, thermal insulation, energy storage and conservation, fire control, chemical, food and metallurgical industries, and petroleum reservoirs.

In many cases, such as condensation, evaporation and chemical reaction, the heat transfer process is often accompanied by a significant change process. Perhaps that's because studying the connection between heat and climate change helps understand many technological changes. Additionally, free convection flow with a combination of heat and mass transfer through vertical plates has been increasingly studied due to its technical and commercial applications. Many authors have contributed to this field, some of them are: Hamza (2016) investigated free convection slip flow of an exothermic fluid in a convectively heated vertical channel. Saleh et al. (2013) studied the flow of fully developed mixed convection in a vertical channel with chemical reaction. Das and Jana (2010) studied Heat and mass transfer effects on unsteady MHD free convection flow near a moving vertical plate in porous medium. Dileep and Vikas (2011) studied thermal radiation effects on mixed radiation effects on mixed convection flow and viscous heating in a vertical channel partially filled with a porous medium. Narahari and Sulaiman (2013) discussed thermal radiation effects on unsteady MHD natural convection flow past an infinite plate with ramped temperature. Seth *et al.* (2014) studied heat and mass transfer effects on unsteady MHD natural convection flow of a chemically reactive and radiating fluid through a porous medium past a vertical plate with arbitrary ramped temperature. The aim of this project work is to study the steady-state heat and mass transfer of an exothermic fluid flow in the presence of a vertical plate, momentum, temperature and concentration.

Steady state of heat transfer refers to transferring heat energy from one location to another in a system where the temperature and heat flow rates remain constant over time. This type of heat transfer can be observed in a wide range of situations, including the transfer of heat from a hot object to cold object in contact, the transfer of heat through a material or substance and the transfer of heat through a fluid or gas.

Extensive research has been conducted on the steady-state heat and mass transfer of an exothermic fluid flow in a vertical channel has been carried out through analysis and calculations of free and mixed convection in vertical and horizontal channels, both in the present and in the past. Historically, these efforts have been motivated by numerous industrial: Geothermal Storage, Nuclear Reactor Cooling, Thermal Insulation, Energy storage and conservation, Fire fighting, Medicine, Food and Metallurgical industries, and oil storage. These

problems arise in electronic packages, microelectronic devices in operation, as well as in the field of water and thermal sciences.
The steady-state heat and mass transfer of an exothermic fluid flow phenomenon in practice is useful from a practical standpoint. However, in some cases, superimposing oscillating temperature on the mean plate-temperature enhances free-flow.

An attempt has been made to study the Steady state heat mass transfer of an exothermic fluid flow in a vertical plate with periodic temperature variation. Analytical solution of the problem has been obtained depending on the physical parameters, including the Kamenetskii parameter, heat equation, concentration equation, and momentum equation. The influence of these parameters on the velocity field, species concentration, temperature field, skin-friction and the rate of heat and mass transfer at the plate are discussed graphically.

Hamza (2016) investigated the free convection slip flow of an exothermic fluid in a convectively heated vertical channel where many factors were put into considerations and many assumptions were tested. Ahmad *et al.* (2017) made extensive investigation on the "Effects of mass transfer on mixed convection flow of an exothermic fluid in a vertical channel".

Adams and Brown (2018), Williams (2021) and Olufemi (2019). Heat transfer along vertical surfaces, such as plates, has been extensively studied in numerous contexts These studies have examined boundary layer development, convective heat transfer, and the influence of surface conditions on heat transfer coefficients in vertical plate configurations. Abdullahi *et al. (2020)* in their studies investigated numerically Casson fluid effects on magneto-hydrodynamics (MHD) unsteady heat and mass transfer convective past an infinite vertical plate. Das and Jana (2010) studied Heat and mass transfer effects on unsteady MHD free convection flow near a moving vertical plate in porous medium while Dileep and Vikas (2011), thermal radiation effects on mixed radiation effects on mixed convection flow and viscous heating in a vertical channel partially filled with a porous medium. Krishna *et al* (2018) discussed heat and mass transfer on unsteady MHD oscillatory flow of blood through arteriole. Mishra (2016) investigates an influence of Rivlin-Ericksen fluid on MHD fluctuating flow with heat and mass transfer through a porous medium bounded by a porous plate. Narahari and Sulaiman (2013) investigated extensively on thermal radiation effects on unsteady magneto hydrodynamic (MHD) natural convection flow past an infinite plate with ramped temperature. Seth *et al.* (2014): researched on heat and mass transfer effects on unsteady MHD natural convection flow of a chemically reactive and radiating fluid through a porous medium past a vertical plate with arbitrary ramped temperature.
Previous works of Clarkson *et al.* (2016); Nguyen and Patel (2020); Yusuf and Ibrahim (2018) have explored the behavior of exothermic fluids in heat transfer processes, emphasizing the influence of reaction kinetics on heat transfer rates.

The perturbation technique is a powerful mathematical tool used to analyze and solve complex heat transfer problems (See Roberts (2019), Torres and Garcia (2020), Okeke and Amadi (2017)), this approach aids in obtaining approximate solutions for differential equations governing heat transfer phenomena, providing insights into challenging unsteady systems. The aim of the current work is to use perturbation technique to obtain the velocity and Temperature profiles and compare the results with the existing literature.

2. Mathematical Formulation

Consider the steady-state heat and mass transfer flow of viscous and incompressible fluid between two vertical parallel plate walls separated by a distance L. A coordinate system is chosen as in Ahmad *et al.* (2017) that x-axis is parallel to the gravitation acceleration g, but with the opposite direction. The y-axis is orthogonal to the channel walls and the origin of the axes is such that the position of the channel walls are y = 0 and y = L respectively.
In addition, the fluid is assumed to be Newtonian and to obey Boussinesq's approximation. The governing equations in dimensionless form can be written as;

$$\frac{d^2u}{dy^2} + \lambda\left[\theta + N\phi\right] = \gamma \tag{1}$$

$$\frac{d^2\theta}{dy^2} + Ke^{\theta} = 0 \tag{2}$$

$$\frac{d^2\phi}{dy^2} = 0 \tag{3}$$

Subject to the relevant boundary conditions;

$$\left.\begin{aligned} u=0, \quad \theta=\gamma_t, \quad \phi=\gamma c, y=0 \\ u=0, \quad \theta=-\gamma_t, \quad \phi=-\gamma c, y=1 \end{aligned}\right\} \quad (4)$$

Using assumed the solution

$$\left.\begin{aligned} U=U_o+KU_1 \\ \theta=\theta_o+K\theta_1 \\ \phi=\phi_o+K\phi_1 \end{aligned}\right\} \quad (5)$$

$$e^{\theta} \approx 1+\theta+\frac{\theta^2}{2} \quad (6)$$

The different parameters that govern the flow in dimensionless form are:

θ: Dimensionless Temperature
U: Dimensionless Velocity of the fluid
y: Dimensionless Co-ordinate perpendicular to the plate
N: Sustentation Parameter
K: Frank – Kamenetskii Parameter
λ: Mixed Convection parameter
γ: Constant pressure gradient
γc: Wall concentration
γt: Wall temperature

3. Analytical Solution

The governing equations presented in (1) to (3) are subjection to equation (4) and would be solved analytically by using Perturbation Technique.

Substituting equation (5) and (6) into equation (1) to (3), we have

$$K^0: \frac{d^2\phi_o}{dy^2}=0 \quad (7)$$

$$K^1: \frac{d^2\phi_1}{dy^2}=0 \quad (8)$$

$$k^0: \frac{d^2\theta_0}{dy^2}=0 \quad (9)$$

$$k^1: \frac{d^2\theta_1}{dy^2}+\left(1+\theta_0+\frac{\theta_0^{\,2}}{2}\right)=0 \quad (10)$$

$$k^0: \frac{d^2u_0}{dy^2}+\lambda\theta_0+\lambda\mu\theta_0=\gamma \quad (11)$$

$$k^1: \frac{d^2u_1}{dy^2}+\lambda\theta_1+\lambda\mu\theta_1=0 \quad (12)$$

$$:\phi_O=A_1y+A_2 \quad (13)$$

Now, to get A_1 and A_2, we apply the boundary conditions in equation (4)

$$:\phi_O=2\gamma_c y+\gamma_c$$
$$:\phi_O=\gamma_c[1-2y] \quad (14)$$

Integrating both sides of Equation (8) with respect to ‘y’ twice we have;

$$:\phi_1=B_1y+B_2 \quad (15)$$

Now, to get B_1 and B_2, we apply the boundary conditions in equation (4)

$$:\phi_1=0 \quad (16)$$

This implies that

$$\phi=2\gamma_c y+\gamma_c+K\,[0]$$
$$\phi=2\gamma_c y+\gamma_c+0$$
$$\phi=\gamma_c\,[1-2y] \quad (17)$$

Temperature Profile

Substituting eqn (6) into equation (2) we have,

$$\frac{d^2\theta}{dy^2}+k\left[1+\theta+\frac{\theta^2}{2}\right]=0 \quad (18)$$

But

$$\theta=\theta_0+k\theta_1 \quad (19)$$

$$\theta^2=(\theta_0+k\theta_1)(\theta_0+k\theta_1)$$
$$=\theta_0^{\,2}+k\theta_0\theta_1+k\theta_0\theta_1+k^2\theta_1^{\,2}$$
$$\theta^2=\theta_0^{\,2}+2k\theta_0\theta_1+k^2\theta_1^{\,2} \quad (20)$$

Substituting equations (19) and (20) into (18) we have,

$$\frac{d^2}{dy^2}\left(\theta_0+k\theta_1\right)+k\left[1+\left(\theta_0+k\theta_1\right)+\left(\theta_0^{\,2}+2k\theta_0\theta_1+k^2\theta_1^{\,2}\right)\right]=0$$

(21)

Simplifying equation (21), neglecting higher powers of k and solving the resulting equations, we have

$$\theta_0 = C_1 y + C_2$$

(22)

$$\theta_1 = -\frac{d_3 y^2}{2}-\frac{d_4 y^3}{6}-\frac{d_5 y^4}{12}+e_1 y+e_2 \qquad (23)$$

Where C1, C2, d3, d4, d5, e1 and e2 are constants.

Substituting equations (14), (15), (22) and (23) into (1) we have

$$\frac{d^2}{dy^2}\left(u_0+ku_1\right)+\lambda\left[\theta_0+k\theta_1+\mu\left(\theta_0+k\theta_1\right)\right]=\gamma$$

(24)

Solving equation (24) we have

$$u_0 = -\frac{F_1 y^2}{2}-\frac{F_2 y^3}{6}+F_3 y+F_4 \qquad (25)$$

$$u_1 = \lambda\left[\frac{d_3 y^4}{24}+\frac{d_4 y^5}{120}+\frac{d_5 y^6}{360}-\frac{e_1 y^3}{6}\right]+g_1 y+g_2$$

(26)

4. Results and Discussion

The results are presented in Figures 1 to 5.

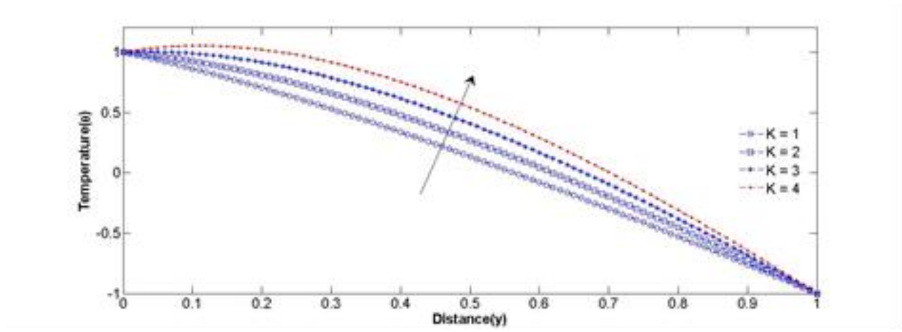

Figure 1: Effects Kamenetskii parameter (K) on Temperature profile

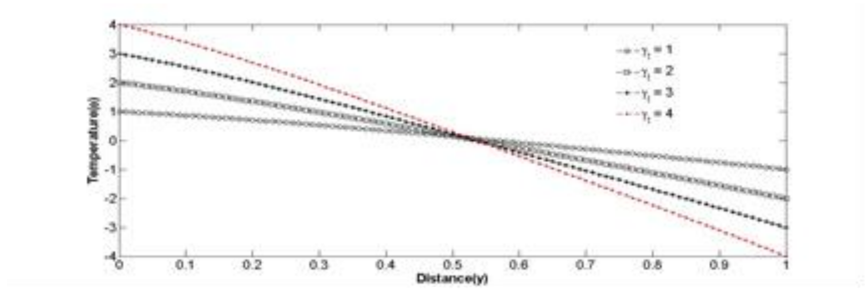

Figure 2: Effects of convection parameter (γ_t) on Temperature profile

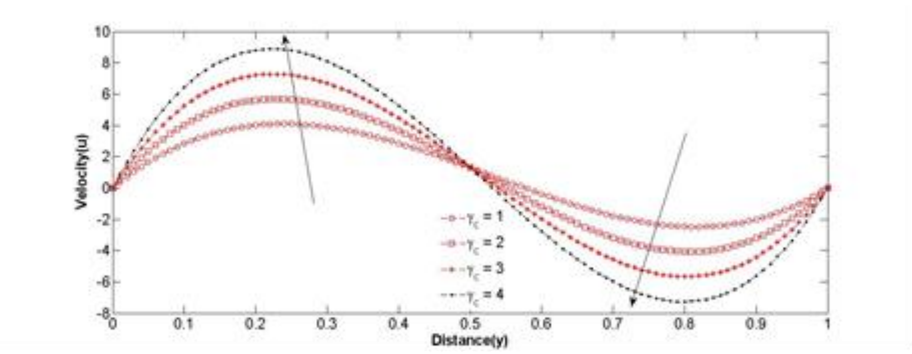

Figure 3: Effects of convection parameter (γ_c) on Velocity profile

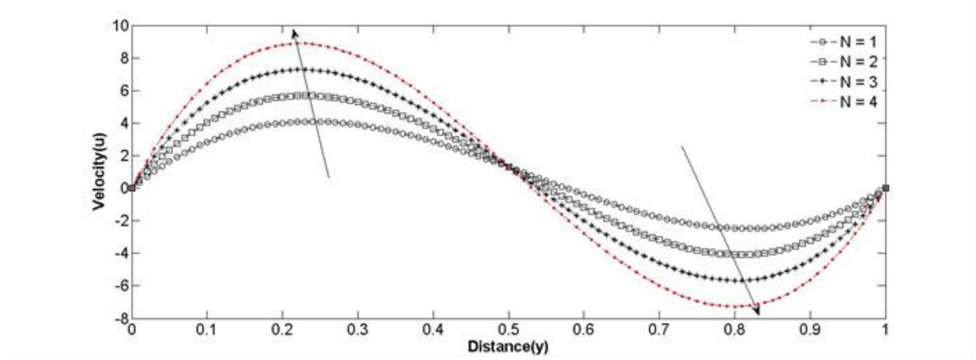

Figure 4: Effects of Sustention parameter (N) on Velocity profile

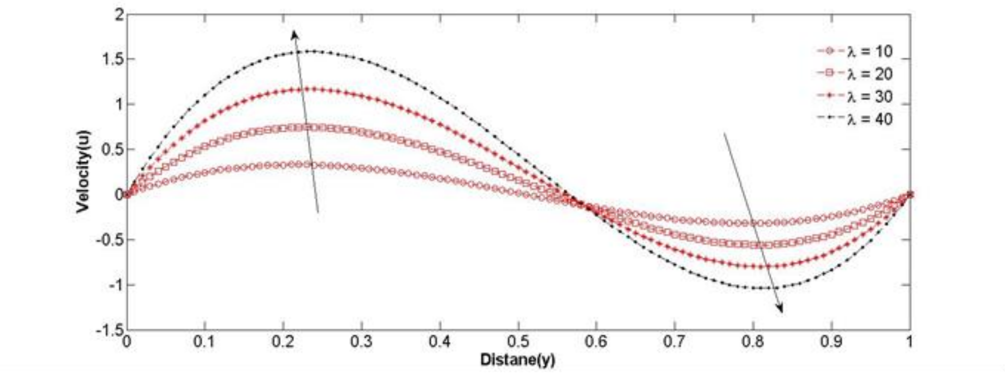

Figure 5: Effects of heating parameter (λ) on the Velocity profile

Figure 1 shows the effects of Kamenetskii parameter (K) on Temperature profile, it is evident from the figure that increasing (K) retard the temperature profile significantly, also reducing the value of (K), the temperature will appreciate. Figure 2 is drawn to capture the effects of convection parameter on temperature; it is as shown in the figure that increasing (λ) swirls the temperature profile likewise reducing it. Figure 3 represents the effect of convection parameter(λ) on the velocity profile, it shows that velocity increases in a swirl form when the parameter value increases by certain number; the profile significantly explains the effect of the parameter on the velocity profile. Figure 4 depicts the effect of the Sustentation parameter (N) on the velocity profile, in which the value increases thereby showing its increase and decrease on the velocity profile, it is observed that the variation of the velocity, temperature and concentration with the parameters occurring in the governing equations. Figure 5 shows the effect of the heating parameter on the velocity and temperature profiles. This figure clearly shows that the velocity and temperature of the fluid increases as the heating parameter (λ) increases.

5. Conclusion

The problem of steady – state heat mass transfer of an exothermic fluid in a vertical plate has been studied by taking into account the perturbation effect. The governing equations were solved by using perturbation method. The expression of velocity, temperature, concentration, skin friction, rate of heat and mass transfer have been presented. The numerical computation shows that, flow formation is strongly dependent on the mixed convection parameter, Frank-Kamenetskii parameter, symmetric wall temperature and concentration.

Conflict of interest

The authors declare no conflict of interest.

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