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Analytical Study of Unsteady MHD Flow Over a Vertical Porous Plate with Exponentially Accelerating Velocity, Temperature, and Concentration in the Presence of Hall Current, Chemical Reaction, Heat Source, and Dufour Effect

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ABSTRACT

The erratic(unsteady) magnetohydrodynamic (MHD) natural convection-based HMT circulation throughout vertically permeable plate, about an exponentially varying rate, temperature and concentration respectively in occurrence of Hall phenomenon current, chemical reaction, heat source and Dufour effect is numerically analysed by using the Crank–Nicolson technique, subject to the specified conditions. A graphic representation and discussion of how the governing factors affect the speed(velocity) profiles are provided. The findings demonstrate that while the magnetic parameter, chemical reaction, and Schmidt number drops velocity, Hall parameter, thermal Grashof number, mass Grashof number, and permeability increase it.

Keywords: Crank Nicolson, Reaction, Schmidt, Permeability (Porous), Hall.

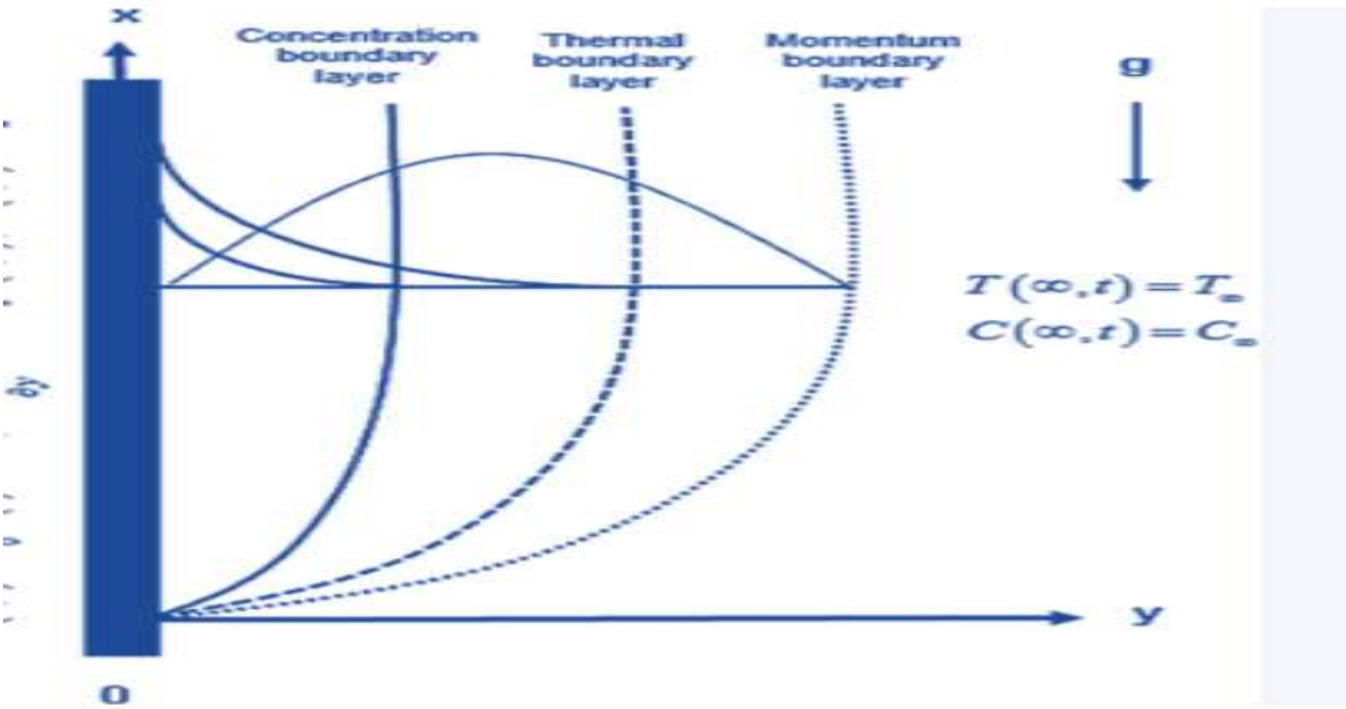
INTRODUCTION

As they speed up heat transmission, enhance reaction rates, and boost production efficiency, heat sources are essential in many industrial and engineering applications. In an effort to boost reaction rates while enhancing product quality, internal heat generation is frequently utilised in polymer extrusion, film coating, injection moulding, resin curing, drying procedures, and chemical reactors in the chemical and polymer industries. In order to improve food safety, texture, shelf life, and product stability during pasteurisation, sterilisation, drying, baking, evaporation, dehydration, canning, and edible film coating, controlled heat sources are crucial. In metallurgical processes like welding, casting, annealing, and heat treatment, where exact temperature control impacts the mechanical properties of materials, heat generation is also crucial. Heat sources are used in biomedical engineering for thermal imaging, tissue ablation, medical sterilisation, and hyperthermia treatment for cancer treatments. Nuclear reactors, solar thermal collectors, geothermal systems, and thermal energy storage technologies all rely heavily on internal heat generation. Batteries, microprocessors, semiconductor devices, and electronic cooling systems all produce internal heat that needs to be carefully controlled to guarantee dependable operation and avoid overheating. In environmental engineering, heat sources are also widely used in processes such as thermal desalination, biomass conversion, sludge drying, and wastewater treatment.

Ganesan Radha et al. [1,2] investigated the unsteady MHD (Casson) fluid movement through vertically oriented plate with parabolic acceleration considering uniform and varied temperature distributions and uniform mass diffusion. The analysis was extended further to add the effects of first-order chemical reaction and heat radiation. Jothi and A. Selvaraj [3,4] studied the MHD circulation through an exponentially accelerate vertically positioned plate through a medium with pores. Karthikeyan et al. [5,6], Dilip Jose and Selvaraj [7], and Kavitha et al. [8] examined unsteady MHD flow across accelerated vertical plates Dufour effect, rotation, thermal radiation, heat

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

and mass transfer, and chemical reaction. Their investigation revealed that the flow's temperature, concentration, velocity, and transport properties are all greatly impacted by these physical factors. Hetnarski [9] developed an efficient algorithm for generating inverse Laplace transforms (ILT) of exponential forms, providing a systematic analytical technique for solving transient heat transfer and fluid flow problems. Balamurugan et al. [10] and Rajakumar et al. [11,12] analyzed MHD naatural convection flow through porous plates under the combination of radiation, heat source, demonstrating their significant influence on the fluid transport and thermal characteristics. Lakshmikaanth et al. [13–18] examined MHD parabolic and exponentially accelerated flow over vertical porous plates of Hall current, heat source, chemical reaction, Radiation, Rotation.[13] studied Hall current and heated source with reaction and radiation, whereas [14] added the effect of rotation, [15] extended analysis to include Dufour effect and porous medium, [16] studied the combined effect of Hall current, Heat source, Dufour effect, rotation, radiation and chemical reaction, [17] studied exponentially accelerated MHD flow past a rotating vertical porous plate and [18] replaced Soret effect with Dufour effect in order to study cross-diffusion in parabolic flow. Parabolic MHD flow across accelerated vertical plates was studied by Dilip Jose et al. [19, 20] with a focus on mass and heat transport properties. While [19] concentrated on how Hall current and chemical reactions affected HMT, [20] looked at combined impacts of radiation and rotational dynamics and showed how they significantly affected the fluid's temperature, velocity, and transport behaviour. Ramesh et al. [21] investigated the combined effects of Hall current, Soret effect, heat source, thermal radiation, chemical reaction, and rotation on parabolic MHD flow past an infinite vertical plate embedded in a porous medium. Abirami et al. [22] performed a multiphysical analysis of radiatively accelerated Casson fluid flow past an inclined rotating porous plate by incorporating the effects of Hall current, Dufour effect, and chemical reaction.



Geometrical Representation

Mathematical Formulation

Let us consider a viscous, incompressible, electrically conducting fluid with an electrically non-conducting infinite vertical plate situated at (z = 0). The plate is oriented vertically and the (z)-axis is taken perpendicular to its surface. Initially (t = 0), the fluid and the plate are considered to be stationary with uniform temperature and concentration in the flow field. The velocity components describe the fluid motion under the assumption that the pressure is constant across the flow and the continuity equation is satisfied. Under these assumptions, the governing boundary layer equations of the problem are given by

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

$$\frac{\partial \overset{\tau}{u}}{\partial \overset{\tau}{t}} = \vartheta \frac{\partial^2 \overset{\tau}{u}}{\partial \overset{\tau}{z}^2} + g\beta\left[\left(\overset{\tau}{T} - \overset{\tau}{T}_\infty\right) + \left(\overset{\tau}{C} - \overset{\tau}{C}_\infty\right)\right] - \frac{\sigma B_0^2 \mu^2 \left(\overset{\tau}{u} + m_1 \overset{\tau}{v}\right)}{\rho\left(1 + m_1^2\right)} - \frac{\vartheta \overset{\tau}{u}}{K_1} \tag{1}$$

$$\frac{\partial \overset{\tau}{v}}{\partial \overset{\tau}{t}} = \vartheta \frac{\partial^2 \overset{\tau}{v}}{\partial \overset{\tau}{z}^2} - \frac{\sigma B_0^2 \mu^2 \left(m_1 \overset{\tau}{u} - \overset{\tau}{v}\right)}{\rho\left(1 + m_1^2\right)} - \frac{\vartheta \overset{\tau}{v}}{K_1} \tag{2}$$

$$\frac{\partial \overset{\tau}{\theta}}{\partial \overset{\tau}{t}} = \frac{1}{Pr} \frac{\partial^2 \overset{\tau}{\theta}}{\partial \overset{\tau}{z}^2} - R\overset{\tau}{\theta} + Q\overset{\tau}{\theta} + \frac{D_m K_T}{C_s C_p} \frac{\partial^2 \overset{\tau}{C}}{\partial \overset{\tau}{z}^2} \tag{3}$$

$$\frac{\partial \overset{\tau}{C}}{\partial \overset{\tau}{t}} = \frac{1}{Sc} \frac{\partial^2 \overset{\tau}{C}}{\partial \overset{\tau}{z}^2} - k\overset{\tau}{C} \tag{4}$$

Where $\overset{\iota}{u}$ and $\overset{\iota}{v}$ are components of velocities along and perpendicular to the plate x and y are distance along and perpendicular to the plate respectively, ρ is the density of the fluid, g is the acceleration due to gravity, σ is the electrical conductivity, β is the coefficient of volumetric expansion with concentration, ϑ is the kinematic viscosity, $\overset{\iota}{T}$ is the temperature of the fluid, $\overset{\iota}{T}_\infty$ is the temperature of the fluid in the free stream, Q is coefficient of heat source, $\overset{\iota}{C}$ is the concentration of the fluid, $\overset{\iota}{C}_\infty$ is concentration at infinity, k the chemical reaction.

The initial and boundary conditions are

$$\begin{aligned} &\overset{\iota}{t} \le 0: \overset{\tau}{u} = \overset{\tau}{v} = 0, \overset{\iota}{T} = \overset{\iota}{T}_\infty, \overset{\iota}{C} = c_\infty, \forall \overset{\tau}{z} \le 0, \\ &\overset{\tau}{t} > 0: \overset{\tau}{u} = \overset{\tau}{u}_0\left(e^{a\overset{\tau}{t}}\right), \overset{\tau}{v} = 0, \overset{\tau}{T} - \overset{\tau}{T}_\infty = \overset{\tau}{C} - \overset{\tau}{C}_\infty = 0 \ \forall \overset{\tau}{z} = 0, \\ &\overset{\tau}{t} > 0: \overset{\tau}{u} \to 0, \overset{\tau}{v} \to 0, \overset{\tau}{T} \to \overset{\tau}{T}_\infty, \overset{\tau}{C} \to \overset{\tau}{C}_\infty \text{ as } \overset{\tau}{z} \to \infty, \end{aligned} \tag{5}$$

By introducing the dimensionless quantities

$$\begin{aligned} &Z = \frac{\overset{\tau}{z} u_0}{\vartheta}, \ t = \frac{\overset{\tau}{t} u_0^2}{\vartheta}, U = \frac{\overset{\tau}{u}}{u_o}, \theta = \frac{\overset{\tau}{T} - \overset{\tau}{T}_\infty}{\overset{\tau}{T}_w - \overset{\tau}{T}_\infty}, \overset{\tau}{C} = \theta = \frac{\overset{\tau}{C} - \overset{\tau}{C}_\infty}{\overset{\tau}{C}_w - \overset{\tau}{C}_\infty} \\ &Gr = \frac{g\beta\vartheta\left(\overset{\tau}{T}_w - \overset{\tau}{T}_\infty\right)}{u_o^3}, Gc = \frac{g\beta\vartheta\left(\overset{\tau}{C}_w - \overset{\tau}{C}_\infty\right)}{u_o^3}, M^2 = \frac{\sigma B_o^2}{\rho}\left(\frac{\vartheta}{u_o^2}\right)^{1/3} \\ &Pr = \frac{\mu Cp}{k}, K = K_1\left(\frac{\vartheta}{u_o^2}\right)^{1/3}, Sc = \frac{\vartheta}{D} \end{aligned} \tag{6}$$

Eq. (1) + i×Eq.(2) , velocity $q = u+iv$ we get ,

$$\frac{\partial q}{\partial t} = G_r\theta + G_c C + \frac{\partial^2 q}{\partial z^2} - q\left(m + \frac{1}{K_1}\right) \quad \text{where} \quad m = \frac{M^2}{(1 + hi)}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial z^2} - R\theta + Q\theta + Df\frac{\partial^2 C}{\partial z^2}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial z^2} - kC$$

The corresponding initial and boundary conditions are

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

$q = 0,\ \theta = C = 0 \text{ for all } z, t \le 0$

$q = \theta = e^{at} =, C \text{ for all } z, t = 0$

$\text{all } q, \theta, C \to 0 \text{ as } z \to \infty.$

RESULTS & DISCUSSION

Applying Using Crank Nicolson Method we have

$$\frac{q_i^{n+1} - q_i^n}{\Delta t} = \left[\frac{\left(q_{i+1}^{n+1} + q_{i+1}^n - 2\left(q_i^{n+1} + q_i^n\right) + q_{i-1}^{n+1} + q_{i-1}^n\right)}{2(\Delta z)^2}\right]$$

$$+ G_r \cos\alpha \frac{\theta_i^{n+1} + \theta_i^n}{2} + G_r \cos\alpha \frac{C_i^{n+1} + C_i^n}{2} - \left(m + \frac{1}{K1}\right)\left(\frac{q_i^{n+1} + q_i^n}{2}\right)$$

$$\frac{\theta_i^{n+1} - \theta_i^n}{\Delta t} = \frac{1}{\Pr}\left[\frac{\left(\theta_{i+1}^{n+1} - \theta q_i^{n+1} + \theta_{i-1}^{n+1}\right) + \left(\theta_{i+1}^n - 2\theta_i^n + \theta_{i-1}^n\right)}{2(\Delta z)^2}\right]$$

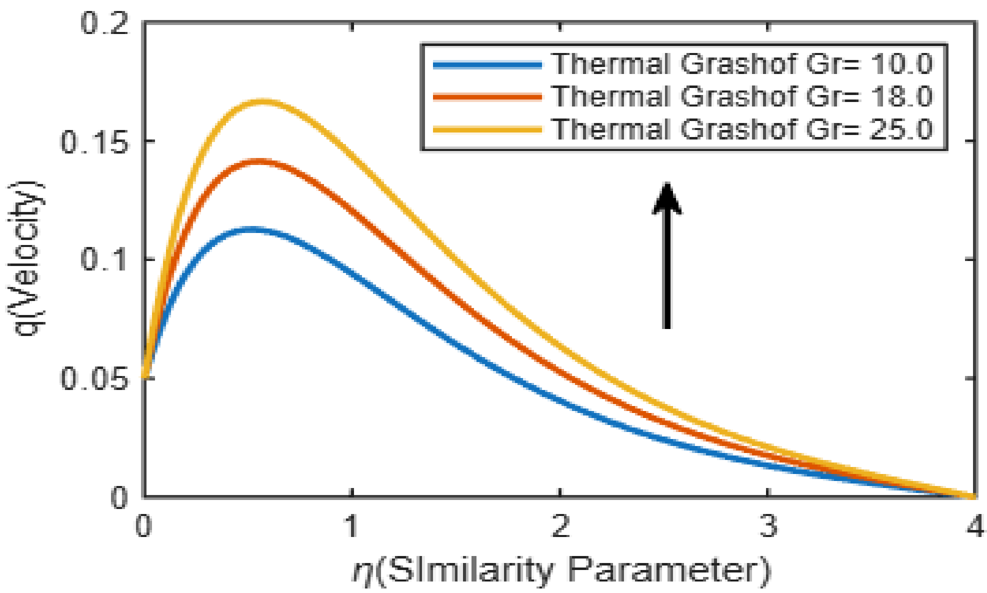
$$-(R - Q)\left(\frac{\theta_i^{n+1} + \theta_i^n}{2}\right) + Df\left[\frac{\left(C_{i+1}^{n+1} + C_{i+1}^n - 2\left(C_i^{n+1} + C_i^n\right) + C_{i-1}^{n+1} + C_{i-1}^n\right)}{2(\Delta z)^2}\right]$$

$$\frac{C_i^{n+1} - C_i^n}{\Delta t} = \frac{1}{Sc}\left[\frac{\left(C_{i+1}^{n+1} + C_{i+1}^n - 2\left(C_i^{n+1} + C_i^n\right) + C_{i-1}^{n+1} + C_{i-1}^n\right)}{2(\Delta z)^2}\right] - k\left(\frac{C_i^{n+1} + C_i^n}{2}\right)$$

$$\text{Skin Friction } (\tau) = -\left(\frac{\partial q}{\partial z}\right)_{z=0},$$

$$\text{Nussult Number} (Nu) = -\left(\frac{\partial \theta}{\partial z}\right)_{z=0}$$

$$\text{Sherwood Number} (Sh) = -\left(\frac{\partial C}{\partial z}\right)_{z=0}$$



Velocity Profile for Thermal Grashof (Gr)
Gc = 18.0,M=2.0,h=0.25,K1= 0.5

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Figure 1

Fig 1 shows Velocity raises as Warmth Grashof Values raises

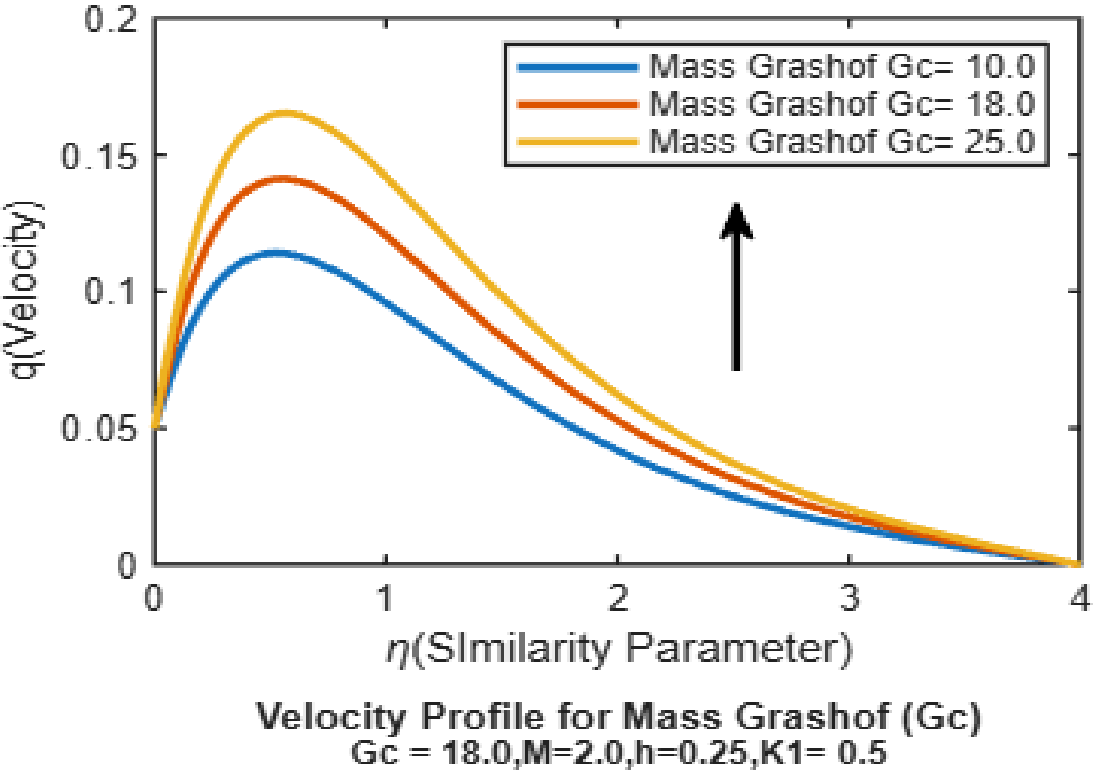


Figure 2

Fig 2 shows that Velocity raises as Mass Grashof Values raises

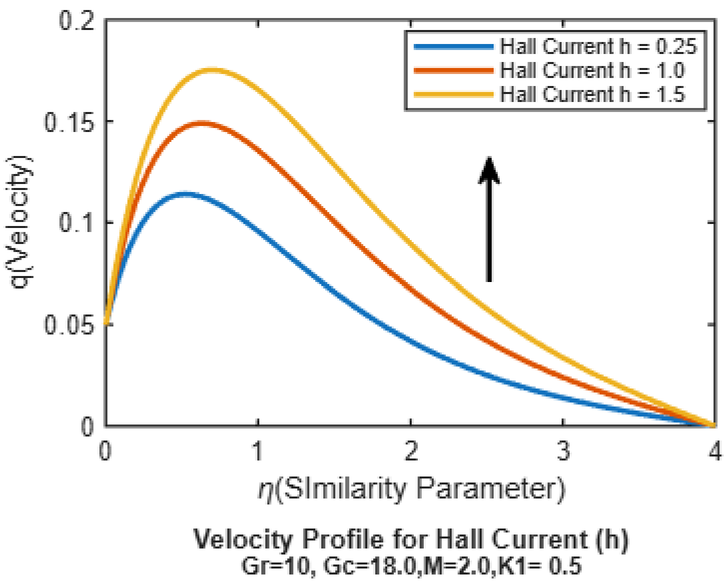


Figure 3

In Fig 3 Velocity increases as hall current increases.

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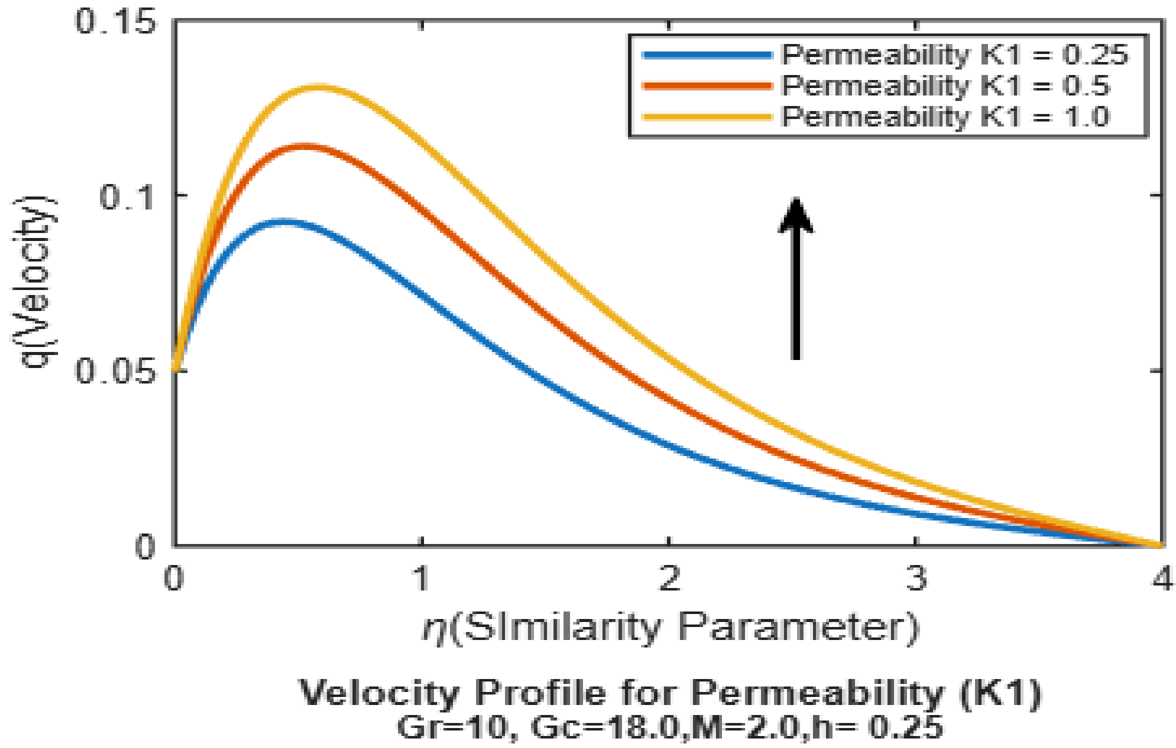


Figure 4

In Fig 4 Velocity changes as Permeability changes in same direction

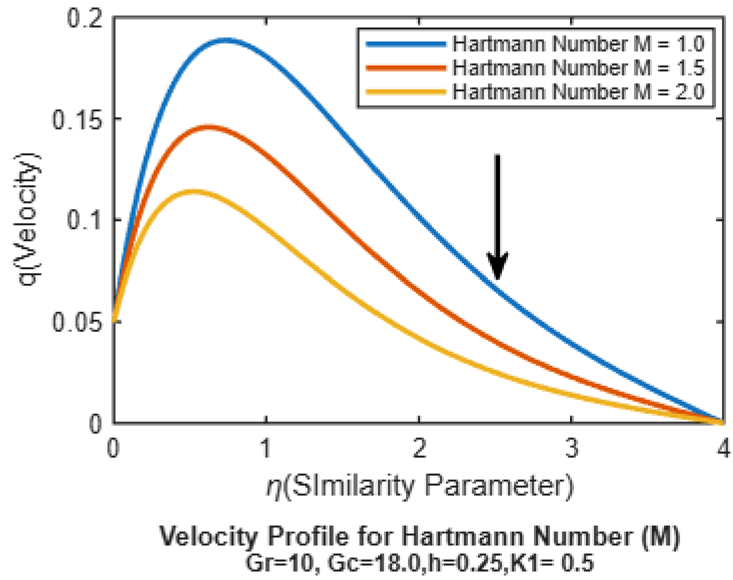


Figure 5

In Fig 5 Velocity changes as Hartmann Number changes in opposite direction

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

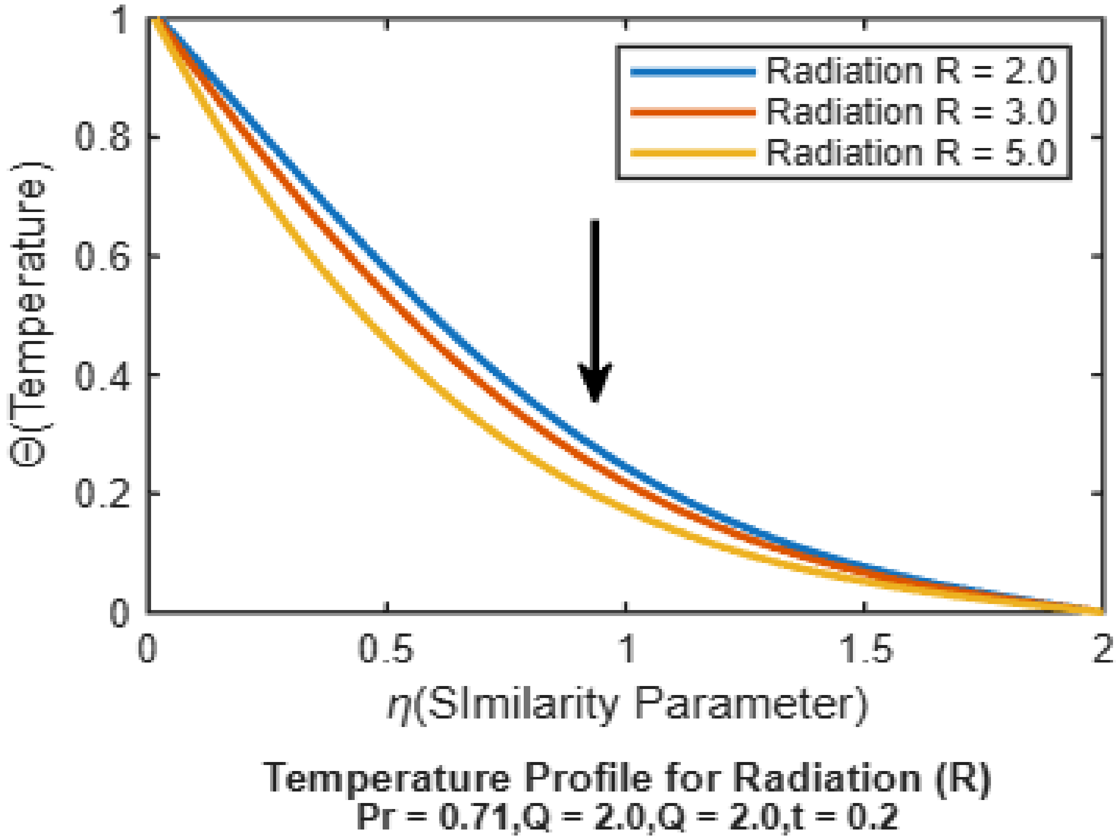


Figure 6

In Fig 6 Temperature(θ) decreases when Radiation raises.

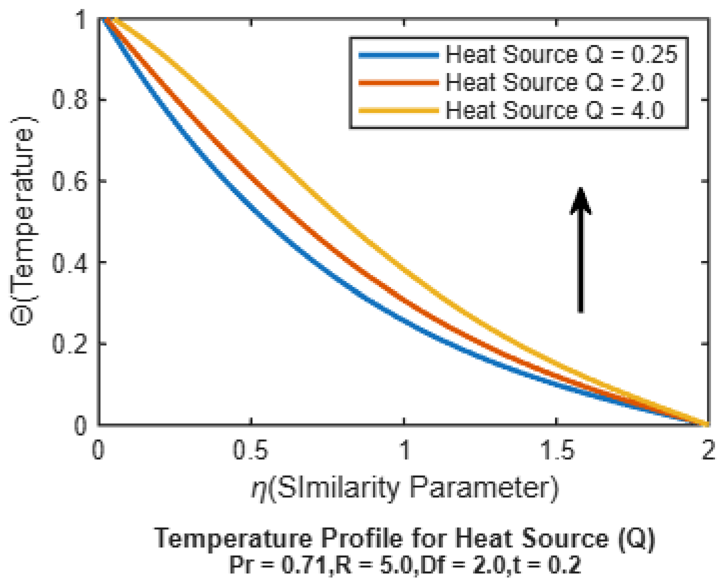


Figure 7

In Fig 7 Temperature(θ) raises when Heat Source raises.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

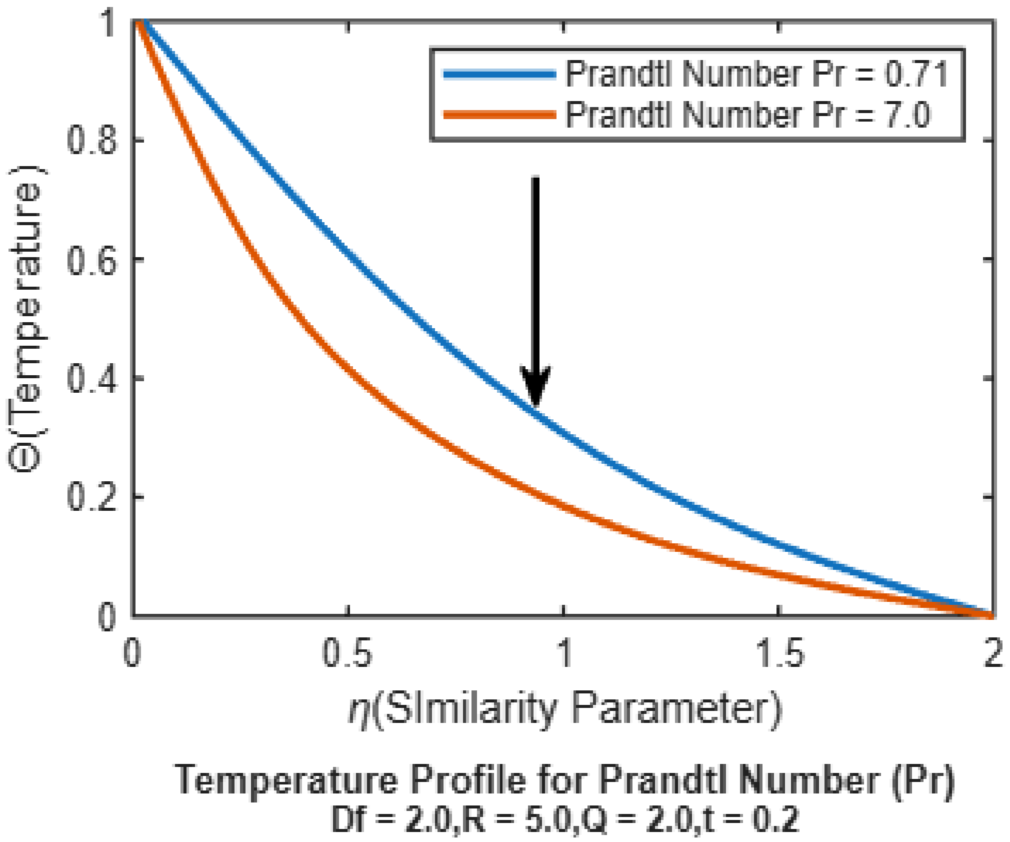
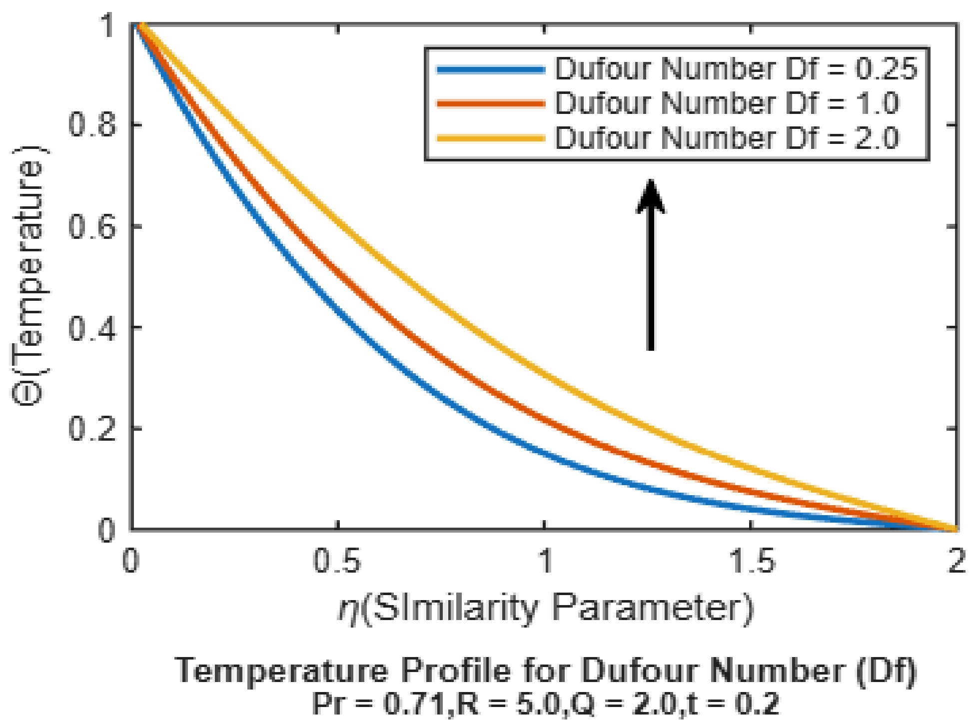


Figure 8

In Fig 8 Temperature downs as Prandtl Number raises



ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Figure 9

In Fig 9 Temperature raises as Dufour Number raises.

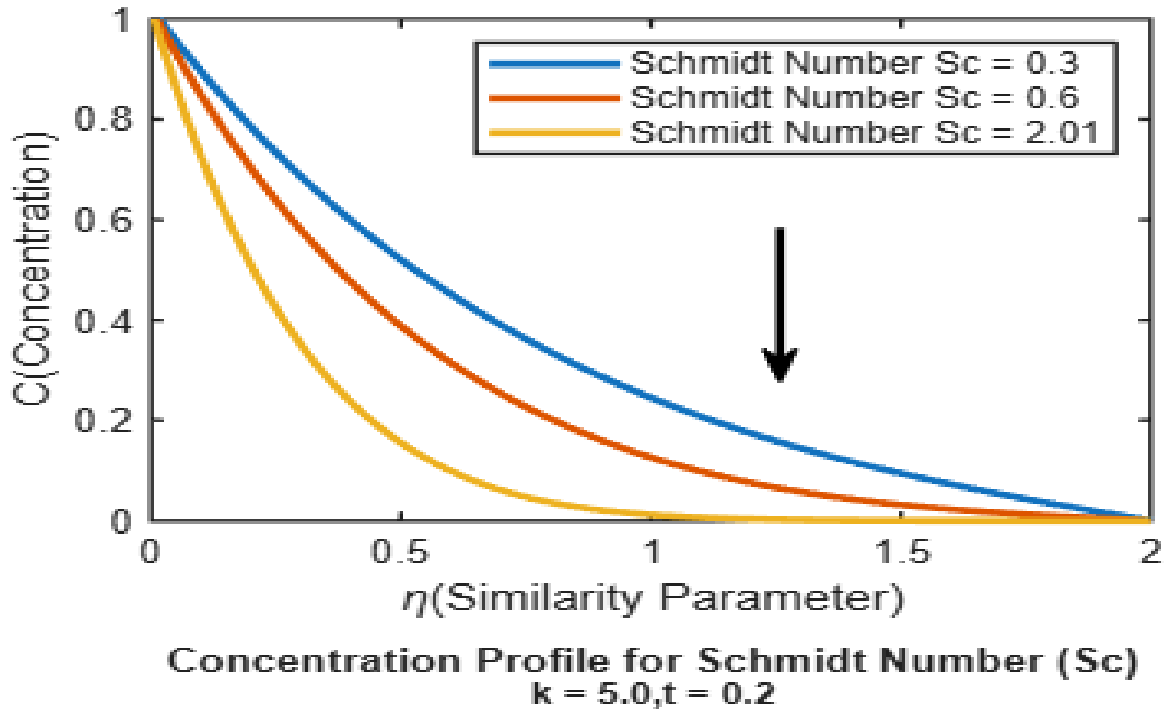


Figure 10

In Fig 10 Concentrations decreases as Schmidt Number raises.

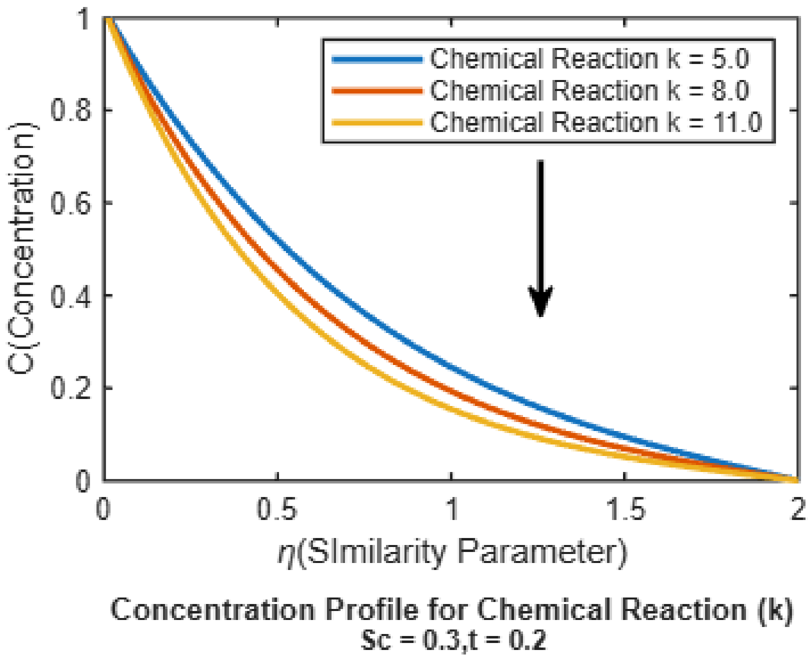
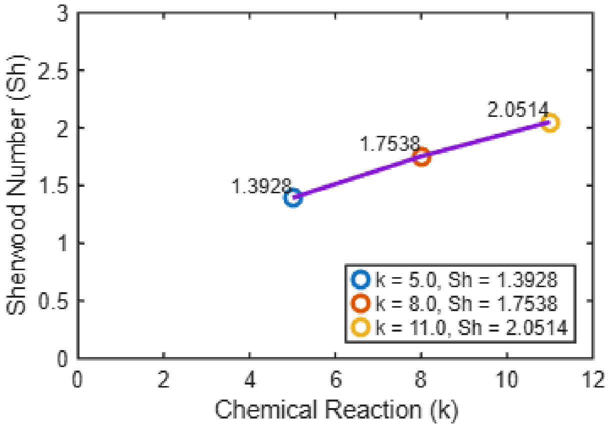


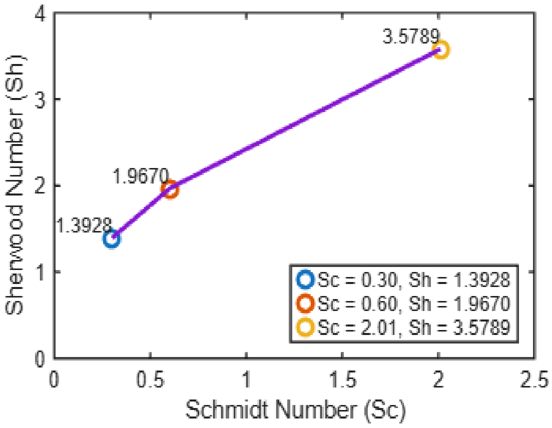
Figure 11

In Fig 11 Concentrations decreases as Chemical Reaction raises.

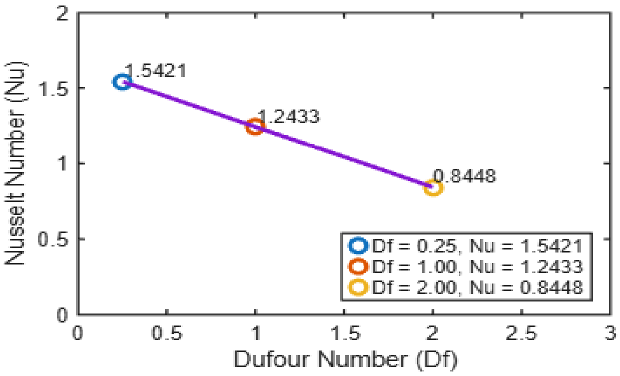
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026



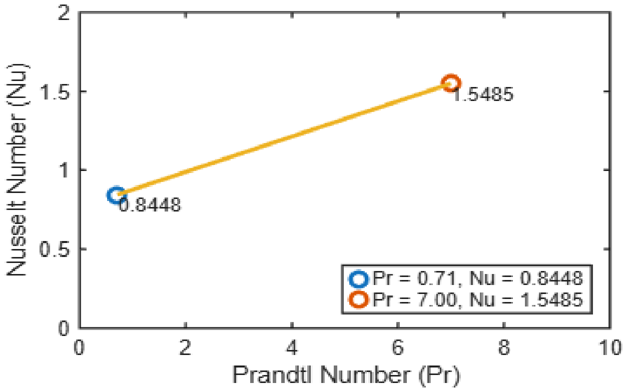
Sherwood Number (Sh) Vs Chemical Reaction (k)



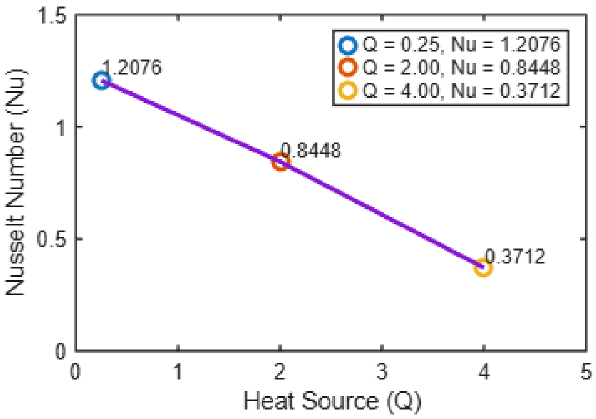
Sherwood Number (Sh) Vs Schmidt Number (Sc)



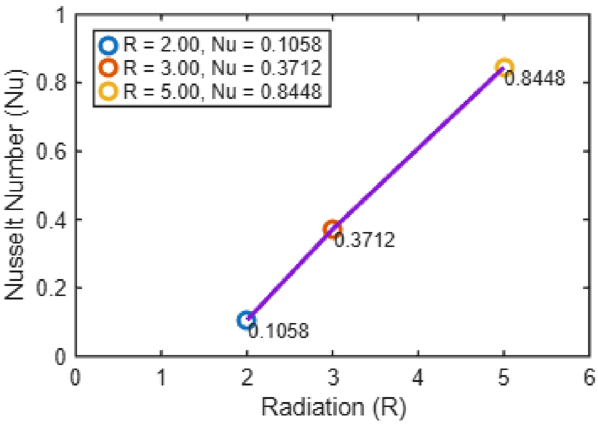
Nusselt Number (Nu) Vs Dufour Number (Df)



Nusselt Number (Nu) Vs Prandtl Number (Pr)

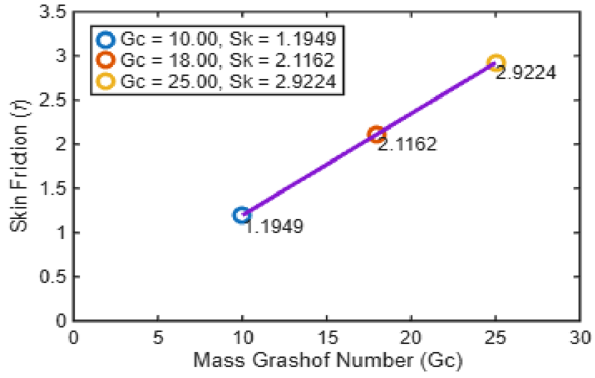


Nusselt Number (Nu) Vs Heat Source (Q)

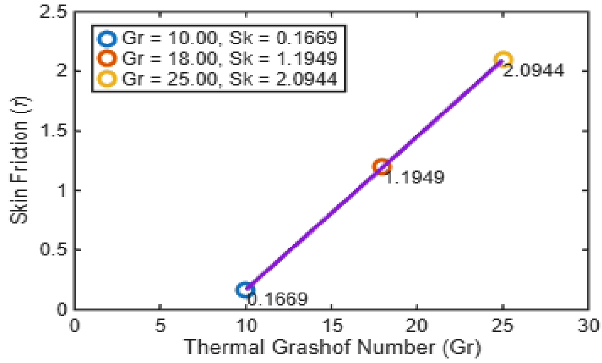


Nusselt Number (Nu) Vs Radiation (R)

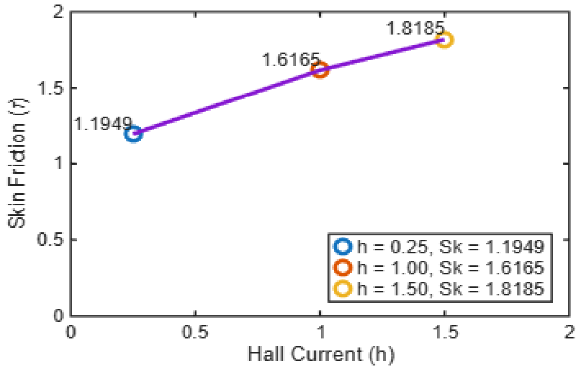
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026



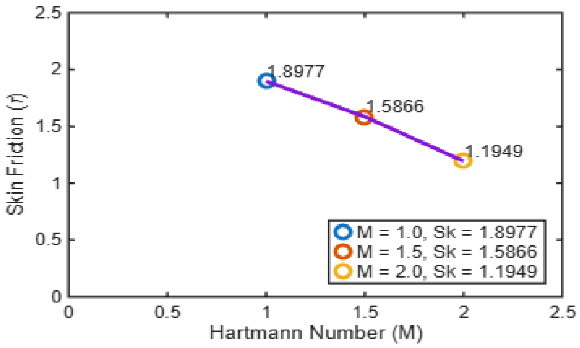
Skin Friction (Sk) Vs Mass Grashof (Gc)



Skin Friction (Sk) Vs Thermal Grashof (Gr)



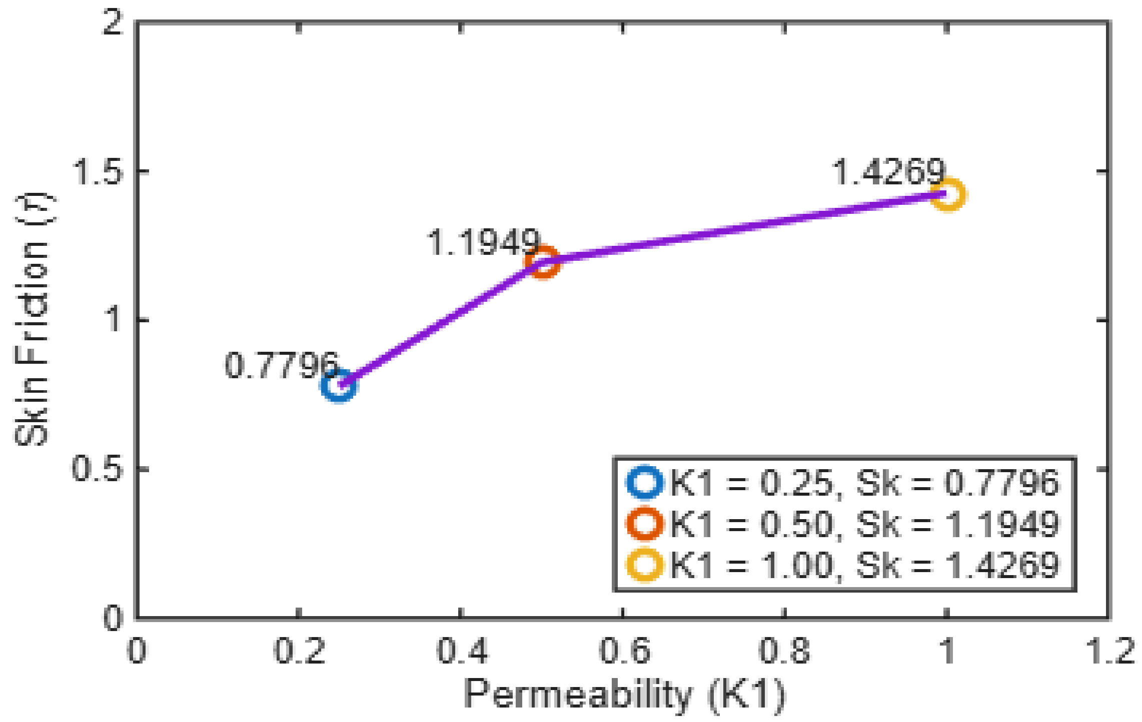
Skin Friction (Sk) Vs Hall Current (h)



Skin Friction (Sk) Vs Hartmann Number (M)

R	**Q**	**Df**	**Pr**	**Nu**	
2.0	2.0	2.0	0.71	0.1058	**R**
3.0	2.0	2.0	0.71	0.3712	
5.0	2.0	2.0	0.71	0.8448	
5.0	**0.25**	2.0	0.71	1.2076	**Q**
5.0	**2.0**	2.0	0.71	0.8448	
5.0	**4.0**	2.0	0.71	0.3712	
5.0	2.0	**0.25**	0.71	1.5421	**Df**
5.0	2.0	**1.0**	0.71	1.2433	
5.0	2.0	**2.0**	0.71	0.8448	
5.0	2.0	2.0	**0.71**	0.8448	**Pr**
5.0	2.0	2.0	**7.0**	1.5485	

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026



Skin Friction (Sk) Vs Permeability (K1)

Nusselt Number (Nu)

Sc	**k**	**Sh**	
0.3	5.0	1.3928	
0.6	5.0	1.9670	**Sc**
2.01	5.0	3.5789	
0.3	**5**	1.3928	
0.3	**8**	1.7538	**k**
0.3	**11**	2.0514	

Sherwood Number (Sh)

Gr	Gc	K1	M	h
10.0	10.0	0.5	2.0	0.25
18.0	10.0	0.5	2.0	0.25

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

25.0	10.0	0.5	2.0	0.25
18.0	18.0	0.5	2.0	0.25
10.0	10.0	0.5	2.0	0.25
18.0	18.0	0.5	2.0	0.25
25.0	18.0	0.5	2.0	0.25
18.0	18.0	0.25	2.0	0.25
10.0	10.0	0.25	2.0	0.25
18.0	10.0	0.5	1.0	0.25
18.0	10.0	0.5	1.5	0.25
18.0	10.0	0.5	2.0	0.25
18.0	10.0	0.5	2.0	0.25
18.0	10.0	0.5	2.0	1.0
18.0	10.0	0.5	2.0	1.5

Skin Friction (τ)

CONCLUSION

1. Speed raises with a rise in the Hall Current, while it decreases with raise in Hartmann Number
2. Temperature (θ) drops as radiation levels rise whereas the Heat Source raises, the temperature (θ) raises.
3. The concentration(C) of the species involved tends to decline as the rate of the Schmidt & Chemical Reaction raises.
4. The (Sk)Skin friction increases as Permeability whereas skin friction decreases when Hartmann number increases.
5. The Nusselt Number increases when Prandtl number and radiation value increases whereas Dufour Number and Heat Source values raises , the Nusselt Number decreases.
6. The Sherwood Number increases when Schmidt number and Chemical reaction parameter value increases

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