Hall Effects and Dufour on MHD Flow past an Exponentially Accelerated Isothermal Vertical Plate with variable Mass Diffusion

S. Constance Angela[1*], A. Selvaraj[2]

[1]Research Scholar, Department of Mathematics, Vels Institute of Science, Technology and Advanced Studies, Chennai 600 117, India.
*Faculty Member, Department of Mathematics, New Prince Shri Bhavani Arts and Science College, Medavakkam, Chennai 600 100, India
constance_angela@hotmail.com
[2]Department of Mathematics, Vels Institute of Science, Technology and Advanced Studies, Chennai 600 117, India
aselvaraj_ind@yahoo.co.in

Abstract: In this concept, the accurate act of the Dufour and Hall Effect is combined to examine the Magnetohydrodynamic flow over an isothermal vertical plate, which is exponentially accelerated with variable mass diffusion, is executed. An electrically conducting viscous fluid that is incompressible that does not scatter in any medium is used. To work out the Concentration, Temperature and Velocity factors of the fluid flow, the basic fundamental flow equations are answered using the technique of Laplace Transforms. The Temperature, Concentration and Velocity Profiles explained in the graph are decoded efficiently by applying them in MATLAB. The graph comes out with a rise in wall thickness when there is an increase in time and vice versa for the Schmidt number. We can see the same trend in temperature for Df, Sc and t. In contrast, for Prandtl number, the temperature has fluctuated. The velocity flow for Dufour Number showed up an increase, decrease and increase pattern. The graph visualises an increase in velocity for the parameters Mass Grashof Number (Gm), Thermal Grashof number (Gr) and time(t). On the other hand, for Prandtl Number (Pr), Schmidt Number (Sc), Hall Parameter (m), Hartmann Number (M), velocity tends to decrease decently.

Keywords: Magnetohydrodynamics, Dufour effect, Hall effect.

1 Introduction

An isothermal process is a thermodynamic procedure where the heat transfer occurs slowly inside and outside the system. The temperature remains constant throughout the process and maintains heat balance. Fluid Dynamics deals with studying the effects done by the movement of liquids and gases responsible for the transport and mixing substances in the manufacturing units, in nature, in various life forms. They are responsible for most of the intensity required to operate airliner, cruises and auto-vehicles, pump oil through ducts and much more. In nature, geophysics is the backbone of all transmission of toxic dissipates from one place to another. It also makes life easier by transporting primary gases and heat from where they are generated to places where they can be utilised or discarded. Hydrodynamics is the science of moving performance of incompressible fluids. Magnetohydrodynamics (MHD) tackles the integrating effects of hydraulics and electromagnetism. These days, the most promising area of MHD application appears to be a processing of materials in the industry where a magnetic field can be used to adjust the flow patterns which occur obviously in the production of a monocrystal of semiconductors, thereby make sure that the configuration of the product which contains trace volume of other elements to make it electrically active is uniform. The characteristically occurring flow patterns referred above come about because the flowing material rises or sinks from place to place is of the difference in temperature and composition. A run produced by these issues (effects) is called upthrust convection. Upthrust convection occurs in many currents in the environment, such as the transmission of fires in the rooms, energy in storage systems, atmospheric structures, and the coastal belt. Research in hydrodynamics focuses on improving its potential to design and control gadgets useful to develop materials to upgrade aerodynamic turbines, auto mechanism and balance the outflow in industries, nuclear reactors, and many more things helpful in our everyday life.

Radiation effects in the existence of hall current with Dufour effect were worked by [1] Balamurugan et al. [2] Chamkha et al. worked out the transfer of heat and mass a stretched surface in the existence of chemical reaction, Dufour and hall effects. Hydromagnetic oscillatory flow with Hall and thermal radiation on a nanofluid in a porous medium were worked out by [3] Gandluru et al. MHD natural convection of non-Newtonian fluid with Dufour, Hall effects and thermal radiation was worked out by [4] Huang et al. Rotating boundary layer flow of nanofluid in MHD over an infinite vertical plate with Hall and ion slip effect in a porous medium was worked out by [5] Krishna et al. [6] Muthucumaraswamy et al. examined the hall effects of an isothermal vertical plate with mass diffusion. Dufour, dissipation and radiation effects on Casson fluid through an oscillatory porous plate and ion slip current was worked out by [7] Umasankara et al. Hall effect on an impulsively started infinite horizontal porous plate in a rotating system on MHD transient flow was worked out by [8] Reddy. Also, [9] Reddy et al. worked out the finite element analysis of Hall current and rotation effects on a moving porous plate. Hall current and Dufour effects on the micropolar fluid in the presence of radiation and chemical reaction in a vertical plate was worked out by [10] Sreedhar et al. [11] Sharma worked out the influence of chemical reaction, radiation, and magnetic field on an isothermal circular cylinder which is horizontal by considering Soret and Dufour effects. moving vertical porous plate. [12] Soundalgekar et al. researched a finite difference analysis on the effects of mass transfer in a dissipative fluid. [13] Bhaskar Reddy et al. worked out a problem on heat and mass transfer effects on a non-isothermal moving vertical plate for Soret and Dufour effects with heat absorption and generation. [14] Uddin et al. l analysed the Hall with ion slip effect of fluids with the micropolar structure on MHD boundary layer flow over a wedge.

Here in this paper, an act of the Dufour Effect and Hall effects on Magnetohydrodynamic Flow past an Exponentially Accelerated Isothermal Vertical Plate with variable mass diffusion are combined and examined accurately. In deriving the basic fundamental flow equations, one of the techniques in Laplace Transform was used. The analytic solutions that are obtained will be in terms of the Exponential and Complementary Error Function.

2 Mathematical Analysis

An infinite isothermal vertical plate, we have considered the Magnetohydrodynamic movement of a viscous fluid electrically conducting that is incompressible and does not scatter in any medium. Here we have taken the X-axis in the direction (upward) of motion of the plate, and the Y-axis is normal to the X-axis. To the flow, a uniform strength of Transverse Magnetic Field B_0 is applied, which is negligible. Initially, everywhere the fluid concentration and temperature C_∞ and T_∞ respectively is assumed to be at rest. With velocity $u=u_0e^{at}$, and the concentration and temperature of the plate are raised uniformly to C_w and T_w respectively and maintained invariably, the plate starts moving exponentially in its plane at time $t > 0$.

Under Boussinesq's Approximations, the basic fundamental flow equations are as follows:

There will be two components for Momentum Equation due to Hall Effect.

$$\frac{\partial u}{\partial t} = \vartheta \frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) - \frac{\sigma\mu^2 B_0^2}{\rho(1+m^2)}(u + mv) \qquad (1)$$

$$\frac{\partial v}{\partial t} = \vartheta \frac{\partial^2 v}{\partial y^2} + \frac{\sigma\mu^2 B_0^2}{\rho(1+m^2)}(mu - v) \qquad (2)$$

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_P}\frac{\partial^2 T}{\partial y^2} + \frac{D_m K_T}{C_s C_P}\frac{\partial^2 C}{\partial y^2} \qquad (3)$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial y^2} \qquad (4)$$

The primary and terminal conditions are:

$$\left.\begin{array}{c} u = 0;\ v = 0;\ T = T_0;\ C = C_0\ \ for\ each\ y : t \le 0 \\ u = u_0 e^{\omega t}; v = 0; T = T_w; C = C_\infty + (C_w - C_\infty)\ \frac{u_0^2 t}{\vartheta}\ at\ y = 0 :\ t > 0 \\ u \to 0; v \to 0; T \to T_\infty; C \to C_\infty\ as\ y \to \infty \end{array}\right\} \qquad (5)$$

Using the following dimensionless quantities

$$\left.\begin{array}{c} \bar{y} = \frac{y u_0}{\vartheta}, \bar{t} = \frac{t {u_0}^2}{\vartheta}, \bar{u} = \frac{u}{u_0}, \theta = \frac{T - T_\infty}{T_w - T_\infty}, \bar{C} = \frac{C - C_\infty}{C_w - C_\infty}, \\ Pr = \frac{\mu Cp}{k}, Sc = \frac{\vartheta}{D}, \mu = \vartheta\rho, \bar{\omega} = \frac{\omega\vartheta}{{u_0}^2},\ Gm = \frac{g\beta^*\vartheta(C_w - C_\infty)}{{u_0}^3}, \\ Gr = \frac{g\beta\vartheta(T_w - T_\infty)}{{u_0}^3}, M = \frac{\sigma\mu^2 {B_0}^2\vartheta}{\rho {u_0}^2(1+m^2)},\ Df = \frac{DmK_T(C_w - C_\infty)}{\vartheta CsCp(T_w - T_\infty)} \end{array}\right\} \qquad (6)$$

Equations (1) to (4) are transformed into the following dimensionless form,

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + Gr\theta + Gm\bar{C} - M(\bar{u} + m\bar{v}) \qquad (7)$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} = \frac{\partial^2 \bar{v}}{\partial \bar{y}^2} + M(m\bar{u} - \bar{v}) \qquad (8)$$

$$\frac{\partial \theta}{\partial \bar{t}} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial \bar{y}^2} + Df\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} \qquad (9)$$

$$\frac{\partial \bar{C}}{\partial \bar{t}} = \frac{1}{Sc}\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} \qquad (10)$$

The primary and terminal conditions become

$$\left.\begin{array}{l}\bar{u}=0;\ \bar{v}=0;\ \theta=0;\ \bar{C}=0 \quad \forall\, \bar{y}\ : \bar{t}\le 0\\ \bar{u}=e^{\overline{\omega t}};\ \theta=1;\ \bar{C}=t \quad at\ \bar{y}=0:\ \bar{t}>0\\ u\to 0; v\to 0;\ \theta\to 0; \bar{C}\to 0 \qquad as\ \bar{y}\to\infty\end{array}\right\} \tag{11}$$

Dropping bars from (7) to (11) and adding (7) and (8) q = u + iv, we get

$$\frac{\partial q}{\partial t}=\frac{\partial^2 q}{\partial y^2}+Gr\theta+GmC-aq \tag{12}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2}+Df\frac{\partial^2 C}{\partial y^2} \tag{13}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \tag{14}$$

where a= $M(1-im)$

The primary and terminal conditions become

$$\left.\begin{array}{l}u=0;\ v=0;\ \theta=0;\ C=0 \quad \forall\, y:\ t\le 0\\ u=e^{\omega t};\ \theta=1;\ C=t \quad at\ y=0:\ t>0\\ u\to 0; v\to 0;\ \theta\to 0; C\to 0 \qquad as\ y\to\infty\end{array}\right\} \tag{15}$$

subject to the boundary conditions (15), the dimensionless equations (12) to (14) are solved by one of the techniques in Laplace Transform.

The solution is obtained as under

$$C=t[(1+2\eta^2 Sc)erfc(\eta\sqrt{Sc})-\frac{2\eta\sqrt{Sc}}{\sqrt{\pi}}e^{-\eta^2 Sc}] \tag{16}$$

$$\theta=\frac{DfPrSc}{Sc-Pr}\left\{\left\{\mathrm{t}\left[\begin{array}{l}(1+2\eta^2\mathrm{Pr})\mathrm{erfc}(\eta\sqrt{\mathrm{Pr}})-\frac{2\eta\sqrt{\mathrm{Pr}}}{\sqrt{\pi}}\mathrm{e}^{-\eta^2\mathrm{Pr}}\\ -(1+2\eta^2 Sc)\ erfc(\eta\sqrt{Sc})+\frac{2\eta\sqrt{Sc}}{\sqrt{\pi}}\mathrm{e}^{-\eta^2 Sc}\end{array}\right]\right\} \quad +erfc(\eta\sqrt{Pr})\right\} \tag{17}$$

and

$$q=q_1+d(q_2-q_3)+e(q_4-q_5)+f(q_6-q_7) \tag{18}$$

where

$$q_1=\frac{e^{\omega t}}{2}\left[\begin{array}{l}e^{-2\eta\sqrt{(\omega+a)t}}erfc\left(\eta-\sqrt{(\omega+a)t}\right)\\ +e^{2\eta\sqrt{(\omega+a)t}}erfc\left(\eta+\sqrt{(\omega+a)t}\right)\end{array}\right] \tag{18.1}$$

$$\left.\begin{array}{l}q_2=-\frac{1}{2b}\left[e^{-2\eta\sqrt{at}}erfc(\eta-\sqrt{at})+e^{2\eta\sqrt{at}}erfc(\eta+\sqrt{at})\right]\\ +\frac{e^{bt}}{2b}\left[e^{-2\eta\sqrt{(a+b)t}}erfc\left(\eta-\sqrt{(a+b)t}\right)+e^{2\eta\sqrt{(a+b)t}}erfc\left(\eta+\sqrt{(a+b)t}\right)\right]\end{array}\right\} \tag{18.2}$$

$$q_3=-\frac{1}{b}erfc(\eta\sqrt{Pr})+\frac{e^{bt}}{2b}\left[\begin{array}{l}e^{-2\eta\sqrt{Prbt}}erfc(\eta\sqrt{Pr}-\sqrt{bt})\\ +e^{2\eta\sqrt{Prbt}}erfc(\eta\sqrt{Pr}+\sqrt{bt})\end{array}\right] \tag{18.3}$$

$$\left.\begin{array}{l}q_4=\left[\frac{\eta\sqrt{t}}{2b\sqrt{a}}-\frac{1}{2b^2}-\frac{t}{b}\right]\left[e^{-2\eta\sqrt{at}}erfc(\eta-\sqrt{at})+e^{2\eta\sqrt{at}}erfc(\eta+\sqrt{at})\right]\\ +\frac{e^{bt}}{2b^2}\left[e^{-2\eta\sqrt{(a+b)t}}erfc\left(\eta-\sqrt{(a+b)t}\right)+e^{2\eta\sqrt{(a+b)t}}erfc\left(\eta+\sqrt{(a+b)t}\right)\right]\end{array}\right\} \tag{18.4}$$

$$q_5=-\frac{1}{b^2}erfc(\eta\sqrt{Pr})-\frac{t}{b}\left[(1+2\eta^2\mathrm{Pr})\mathrm{erfc}(\eta\sqrt{\mathrm{Pr}})-\frac{2\eta\sqrt{\mathrm{Pr}}}{\sqrt{\pi}}\mathrm{e}^{-\eta^2\mathrm{Pr}}\right]+\frac{e^{bt}}{2b^2}[e^{-2\eta\sqrt{Prbt}}erfc(\eta\sqrt{Pr}-\sqrt{bt})+e^{2\eta\sqrt{Prbt}}erfc(\eta\sqrt{Pr}+\sqrt{bt})] \tag{18.5}$$

$$\left.\begin{array}{l}q_6=-\frac{1}{c^2}erfc(\eta\sqrt{Sc})-\frac{t}{c}\left[(1+2\eta^2\mathrm{Sc})\mathrm{erfc}(\eta\sqrt{\mathrm{Sc}})-\frac{2\eta\sqrt{\mathrm{Sc}}}{\sqrt{\pi}}\mathrm{e}^{-\eta^2\mathrm{Sc}}\right]\\ +\frac{e^{ct}}{2c^2}[e^{-2\eta\sqrt{Scct}}erfc(\eta\sqrt{Sc}-\sqrt{ct})+e^{2\eta\sqrt{Scct}}erfc(\eta\sqrt{Sc}+\sqrt{ct})]\end{array}\right\} \tag{18.6}$$

$$\left.\begin{array}{l}q_7=\left[\frac{\eta\sqrt{t}}{2c\sqrt{a}}-\frac{1}{2c^2}-\frac{t}{2c}\right]\left[e^{-2\eta\sqrt{at}}erfc(\eta-\sqrt{at})+e^{2\eta\sqrt{at}}erfc(\eta+\sqrt{at})\right]\\ +\frac{e^{ct}}{2c^2}\left[e^{-2\eta\sqrt{(a+c)t}}erfc\left(\eta-\sqrt{(a+c)t}\right)+e^{2\eta\sqrt{(a+c)t}}erfc\left(\eta+\sqrt{(a+c)t}\right)\right]\end{array}\right\} \tag{18.7}$$

$$a = M(1 - im), b = \frac{a}{Pr - 1}, c = \frac{a}{Sc - 1}, d = \frac{Gr}{Pr - 1}, e = \frac{DfPrScGr}{(Sc - Pr)(Pr - 1)} \text{ and}$$

$$f = \frac{DfPrScGr}{(Sc - Pr)(Sc - 1)} - \frac{Gm}{Sc - 1}$$

In the Nomenclature Section, we have abbreviated the particular constants used in the above mathematical analysis.

3 Results and Discussion with Graphs

The equations (16) to (18) reveal the effects of a primary Magnetohydrodynamic flow over a vertical semi-infinite plate with exponential acceleration as the temperature is constant by the Laplace Transforms Technique with a set of boundary conditions from equation (12) to (15) of the basic fundamental flow equations. To measure the fields of concentration, velocity, and temperature, the solutions are used to find the new trend calculated for the Dufour and Hall effect combination. Numerical values like m=3, M=2, w=1, Gr=Gm=10, Df=0.5, Pr=0.71, Sc=0.16 are commonly used to solve the equations graphically.

The Velocity, Temperature and Concentration Sketches that are resolved using MATLAB are shown in Fig. 1 to 14. As an outcome of the calculations, the combined effects of the Dufour and Hall are very well scrutinised as a research tool that helps in the efficient outcome of the flow equations.

Fig 1. Concentration Trend for t

Fig. 1. depicts concentration sketch for particular values of t. As Time increases, the thickness of the wall considerably increases. Fig. 2. depicts the concentration sketch for Particular values of Schmidt Number. As the Schmidt Number increases, we can observe a descent in the wall thickness. Fig. 3. portrays temperature sketch for particular values of Dufour Number. As the Dufour Number increases, there is a hike in the temperature of the flow of the liquid, followed by a drop in temperature.

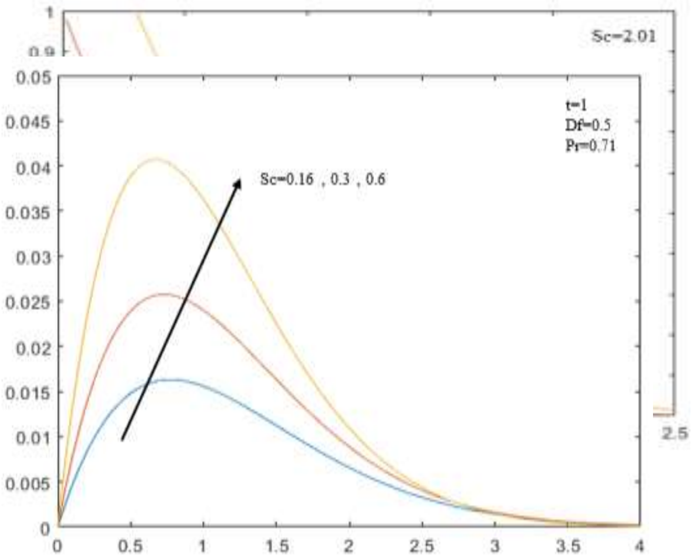


Fig 2. Concentration Trend for Sc

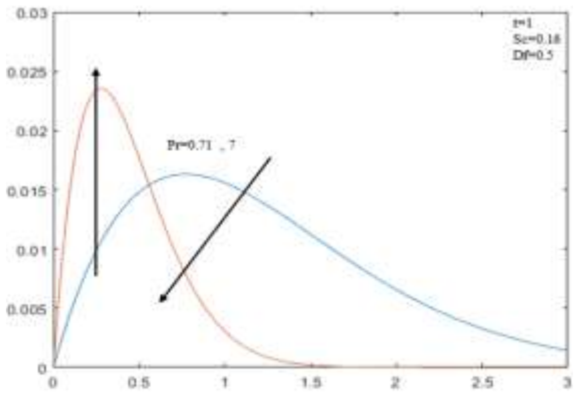


Fig 3. Temperature Trend for Df

Fig. 4. portrays a temperature sketch for particular values of Prandtl Number. In Air Medium (Pr=0.71), we can observe a decent increase followed by a smooth decrease in the fluid flow temperature. However, in Water Medium (Pr=7), we can observe a rapid increase followed by a steep drop in the temperature of the flow of the fluid. Fig. 5. portrays the Temperature Sketch for Particular values of Schmidt Number. As the Schmidt Number increases, there is an intensification in the temperature and reaches its max when the Schmidt Number is Maximum. Fig. 6. portrays the temperature sketch for particular values of the time. As time increases, there is a sharp rise in the Fluid Flow temperature as time moves on.

Fig 4. Temperature Trend for Pr

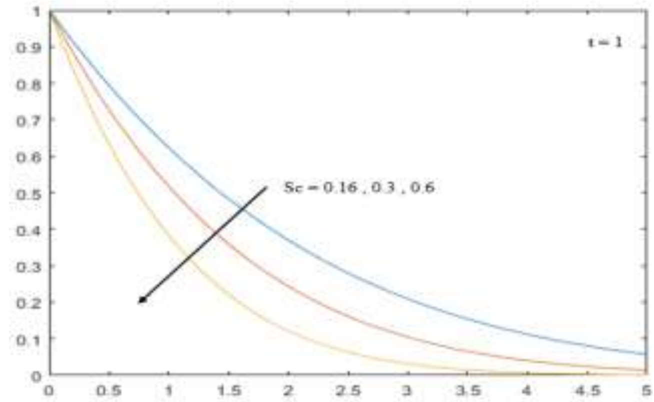


Fig 5. Temperature Trend for Sc

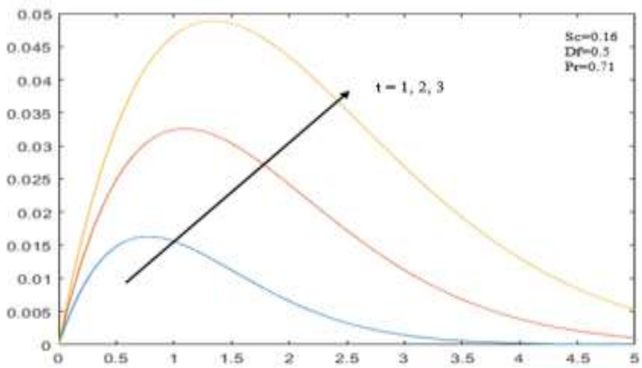


Fig 6. Temperature Trend for t

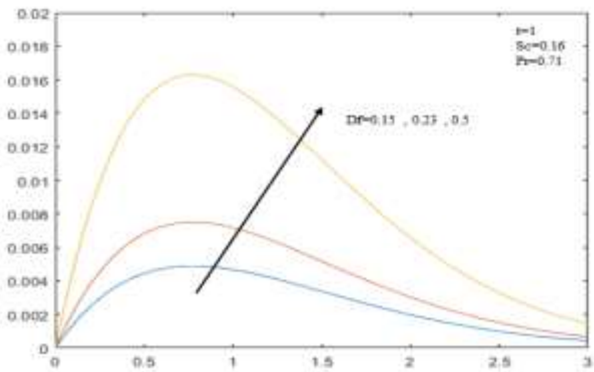


Fig. 7. to Fig. 14. visualises the Velocity Sketch for the various values of the Dimensional and Non-Dimensional quantities. In Fig. 7. there is a considerable decrease in the velocity as the Hall Parameter increases. There is a slow and gradual rise in the speed of the fluid in Fig 8 as the Mass Grashof Number increases. Gr characterises the relative strength of thermal buoyancy force to viscous force. As the Thermal Grashof Number increases, there is an abrupt increase in the speed of the liquid in Fig. 9.

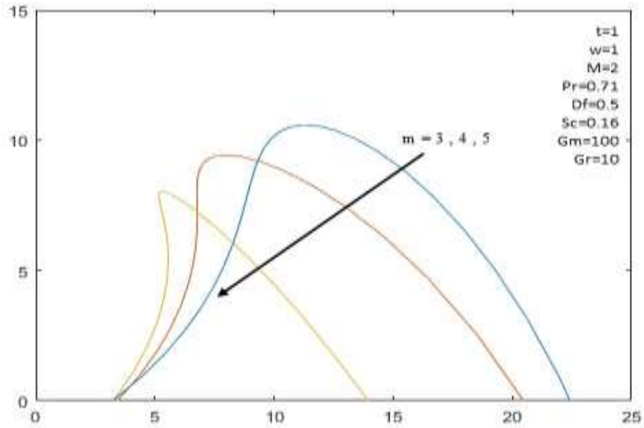


Fig 7. Velocity Trend for m

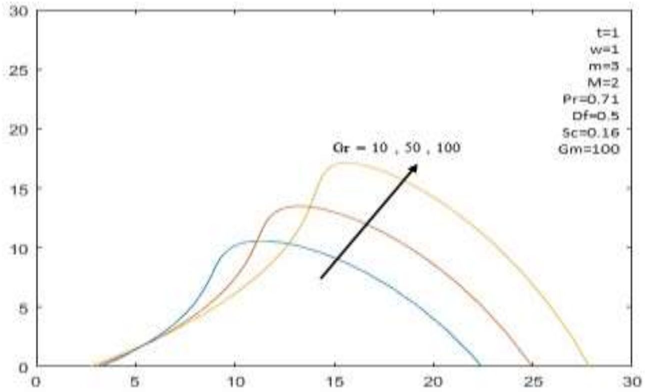


Fig 8. Velocity Trend for Gm

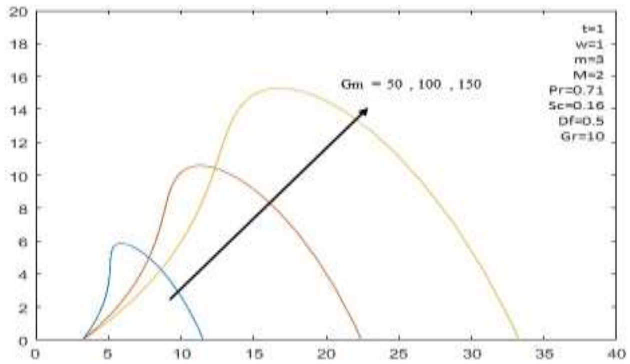


Fig 9. Velocity Trend for Gr

In Fig. 10. when the Magnetic field is induced, we can visualise a decrease in the speed of the fluid, and the range decreases over a period. The fluid initially showed up an increase in velocity. It exhibited a slight decrease in the speed as the Dufour number is at its peak. At its lower points, it again showed an increase in the velocity in Fig. 11. In Fig. 12. the velocity seems to travel uniquely for both air and water at the beginning period. After it reaches its maximum, the velocity has a decrease. In Fig. 13. when the Schmidt Number increases, the velocity tends to decrease. Fig. 14. visualises an increasing tendency in the speed of the fluid as time flies.

Fig 10. Velocity Trend for M

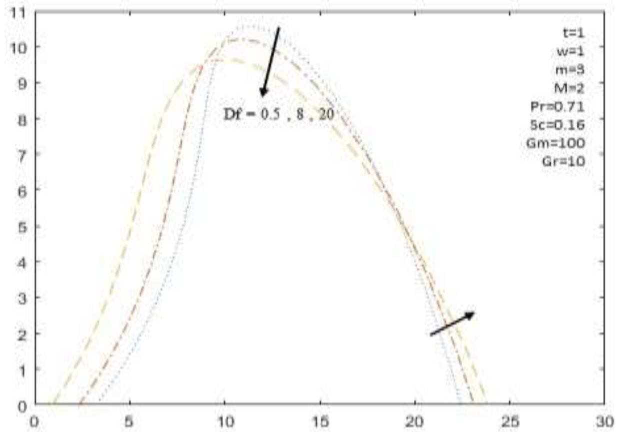
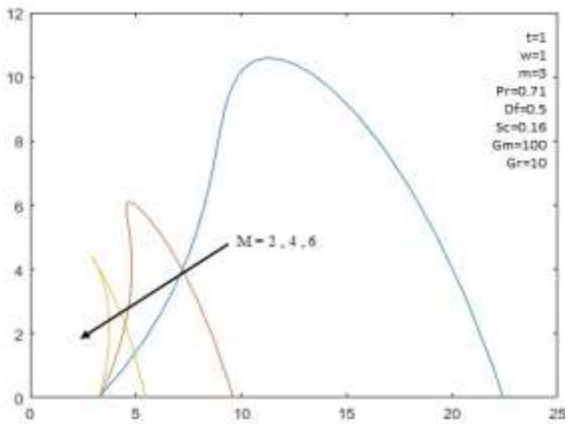


Fig 11. Velocity Trend for Df



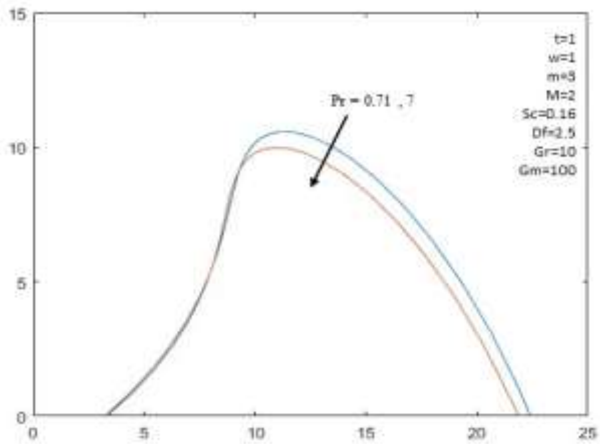


Fig 12. Velocity Trend for Pr

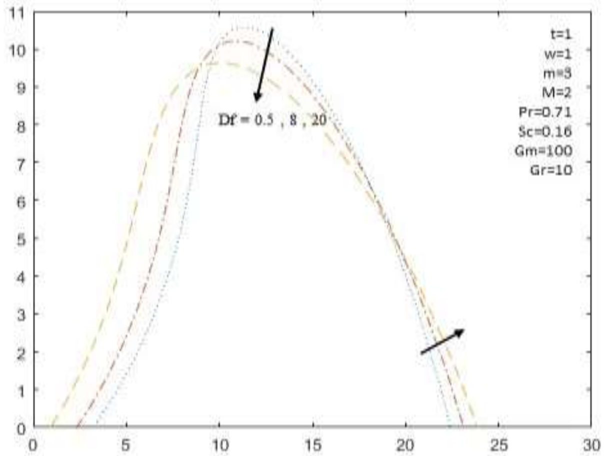


Fig 13. Velocity Trend for Df

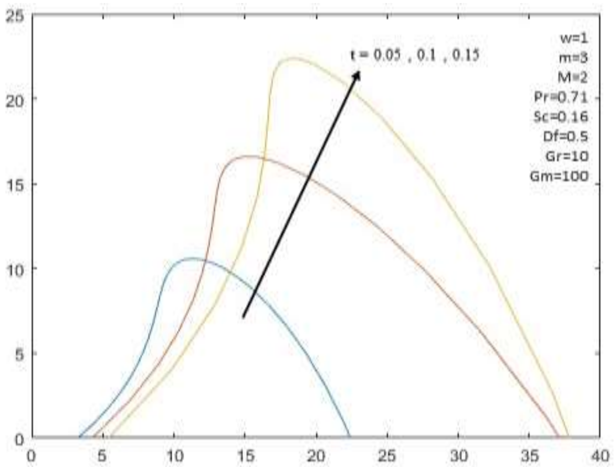


Fig 14. Velocity Trend for t

5 Conclusion

In this paper, the accurate act of the combination of Dufour Effect and Hall effects on Magnetohydrodynamic Flow past an Isothermal Vertical Plate, which is exponentially accelerated with variable mass dissemination, is observed and investigated. The basic fundamental flow mathematical statements are decoded utilising the techniques in Laplace Transforms and understanding the equations better. All the consequences are uncovered with the assistance of graphs, which is an effective way of presenting data and demonstrating its difference.

The outcomes of the study are that the Temperature, Concentration and Velocity Sketches of the schemes are:

- The graph comes out with an increase in wall thickness when there is a rise in time and vice versa for the Schmidt number.
- There is an increase in the temperature sketches for increasing Df values, Sc and t. In contrast, for the Prandtl number, there is a fluctuation in the temperature in both air and water medium.
- All the velocity graphs showed up a parabolic pattern that has gone up and down over the period. We can see a fluctuation in the Dufour Number graph. The velocity flow for Dufour Number shows an initial increase. When it reaches its maximum, a decrease in the velocity is showed up, followed by a gradual downfall.
- The graph comes out with a decent increase in velocity for the parameters Mass Grashof Number (Gm), Thermal Grashof number (Gr) and time(t) while on the contrary for Prandtl Number (Pr), Schmidt Number (Sc), Hall Parameter (m), Hartmann Number (M) velocity tends to decrease gradually.

6 Appendix

6.1 Dimensional Quantities

(u, v, w) factors of velocity field q

(x, y, z) Cartesian Co-ordinates

m	Hall parameter
g	gravitational acceleration
β	Volumetric Co-efficient of thermal expansion
β^*	Volumetric Co-efficient of Concentration expansion
t	Time
T	Temperature of fluid
T_∞	The temperature of the plate at y$\rightarrow \infty$
T_w	The temperature of the plate at y$=0$
C	Species concentration in the fluid
C_∞	Species concentration at y$\rightarrow \infty$
C_w	Species concentration at y=0
C_p	Specific heat at constant pressure
C_s	Concentration Susceptibility
υ	Kinematic Viscosity
ρ	Density
k	Thermal Conductivity of the fluid
D	Mass diffusion constant

K_T	Thermal diffusion ratio
D_m	Effective mass diffusivity rate
B_0	Uniform magnetic field
σ	Electrical conductivity

6.2 Non-Dimensional Quantities

$(\bar{u}, \bar{v}, \bar{w})$	Non-Dimensional velocity components
M	Hartmann number
Gr	Thermal Grashof number
Gm	Mass Grashof number
Pr	Thermal Prandtl number
Df	Dufour number
Sc	Schmidt number
θ	Dimensionless Temperature
$\bar{C}$	Dimensionless Concentration
$\bar{t}$	Dimensionless Time

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