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RESEARCH ARTICLE

Analysis of mixed convection near a stagnation point on a vertical porous plate and heat generation

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ABSTRACT - This study explores the heat transfer characteristics of mixed convection flow near a stagnation point on a vertical plate in the presence of internal heat generation. The analysis assumes a steady, two-dimensional laminar flow and considers the combined effects of forced and natural convection. The boundary layer equations are employed to develop a model that considers heat generation and buoyancy. Similarity transformations are used to transform the governing partial differential equations into a system of ordinary differential equations which are then numerically solved using BVP4C solver in (MATLAB). The variation of the heat transfer coefficients $\theta'(0)$ is the focus of the numerical results for different values of the mixed convection parameter λ, heat generation parameter Q and the Prandtl number Pr. The findings illustrate that when Prandtl number Pr increases, the heat transfer coefficients $\theta'(0)$ rise as well, signifying greater thermal diffusion and thinner thermal boundary layers. The heat transfer rate is also increased by increasing the mixed convection parameter λ since buoyancy-driven flow occurs. Higher heat transfer coefficients $\theta'(0)$ are also influenced by the presence of heat generation parameter Q with the becoming more noticeable at higher Prandtl number Pr values. These results show how responsive the area of stagnation variation flow and thermal factors to provide important details to improve thermal management in systems that have significant volumetric and convectional heat sources.

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1. INTRODUCTION

The heat transfer mechanism in mixed convection is affected by both forced and natural flows. Internal heat generation from chemical processes, electrical heating or other sources complicates the thermal boundary layer and temperature distribution. The rates of heat transmission are significantly influenced by the unique flow behaviour that occurs when fluid velocity is zero at a stagnation point on a vertical plate.

Recent study has focused on the difficulties of mixed convection flows at stagnation sites. Irshad et al. [1], conducted a computational study examining the application of nanofluids to enhance heat transfer in mixed convection flow over a vertical plate with a heat source/ sink, highlighting the significant role of nanoparticle concentration in improving thermal performance. Fenuga et al. [2] and Azeman and Ishak [3] studied focuses on the mixed convection flow of a fluid near a stagnation point on a non-linearly stretching vertical sheet in the presence of a magnetic field (MHD). The study utilised similarity transformations and computational methods to analyse the impact of various flow parameters on velocity, temperature and heat transfer rate. The results indicated that the heat transfer rate at the surface increases with mixed convection. Meanwhile, Ajay et al. [4] conducted a numerical analysis to investigate the impact of internal heat generation on mixed convection boundary layer flow and heat transfer from a vertical flat plate. The study employed an implicit finite difference scheme alongside the quasilinearization method (QLM) to clarify the impact of varying internal heat generation parameters on local shear stress, heat transfer, temperature, and velocity profiles. The internal heat generation of the fluid can significantly alter heat transfer rates and temperature distribution. A study by Jha BK et al. [5] indicates that internal heat generation leads to thicker thermal boundary layers and elevated surface temperatures in mixed convection flow from a convectively heated vertical porous plate, influenced by nonlinear thermal radiation and suction/injection effects. These results underscore the necessity of incorporating interior heat sources in thermal studies to ensure accurate predictions and efficient thermal management.

Various technical applications, including energy systems, electronic cooling devices, and thermal management systems, significantly rely on the comprehension of heat transfer in mixed convection flows at stagnation points on vertical plates. Islam MA and Akter R [6] conducted a numerical investigation on the effects of MHD, thermal absorption, and internal heat generation on stagnation point flow over a declining surface. The research, utilising finite difference methods, revealed that elevated temperatures and reduced thermal boundary layers resulted from heightened magnetic field intensity and heat-generating factors. Kamal et al. [7] found that needle-shaped nanoparticles made of copper, alumina, and titania in a water-based nanofluid significantly improved heat transfer, attaining an improvement of up to 14% relative to alternative configurations.

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Nomenclature

a, b	constants
C_f	skin friction coefficient
f	dimensionless stream function
f_0	suction/injection parameter
g	acceleration due to gravity…………….…$\mathrm{ms^{-2}}$
Gr_x	local Grashof number
k	thermal conductivity……………...$\mathrm{Wm^{-1}K^{-1}}$
Nu_x	local Nusselt number
P	fluid pressure……………………….… $\mathrm{Nm^{-2}}$
P_r	Prandtl number
q_w	heat transfer from the plate………….. $\mathrm{Wm^{-2}}$
Re_x	local Reynolds number
T	fluid temperature…………………………...K
T_w	plate temperature…………………………...K
T_∞	ambient temperature…………..…………….K
u, v	velocity components along the x and y directions, respectively……………...… $\mathrm{ms^{-1}}$
$U(x)$	free stream velocity…………………....$\mathrm{ms^{-1}}$
V_w	uniform surface mass flux
x, y	Cartesian coordinates along the surface and normal to it, respectively………..……….. m
Greek symbols	
α	thermal diffusivity…………….......….$\mathrm{m^2s^{-1}}$
β	thermal expansion coefficient…..……….$\mathrm{K^{-1}}$
η	similarity variable
θ	dimensionless temperature
λ	buoyancy or mixed convection parameter
μ	dynamic viscosity……….………..$\mathrm{kg\ m^{-1}s^{-1}}$
ν	kinematic viscosity…….………….…. $\mathrm{m^2s^{-1}}$
ρ	fluid density……..…………..……..….$\mathrm{kg\ m^{-3}}$
τ_w	skin friction
ψ	stream function
Subscripts	
w	condition at the wall
∞	ambient condition
Superscripts	
$'$	differentiation with respect to η

These findings highlight the importance of nanoparticle characteristics in improving thermal performance in complex flow environments. The interplay of induced and natural convection leads to mixed convection, resulting in complex flow and thermal behaviours, especially near stagnation zones where pressure peaks and fluid velocity is null. The creation of internal heat complicates the thermal field, necessitating comprehensive analysis to predict and enhance heat transfer efficiency. Recent research by Jusoh et al. [8] on Ag-Cu hybrid nanofluids has demonstrated their considerable potential to enhance heat transfer in cooling systems, particularly under convective boundary conditions. The research demonstrates that increasing the Biot number and the concentration of silver nanoparticles significantly improves the heat transfer rate.

Mixed convection flow near a stagnation point on a vertical surface is a fundamental problem in fluid dynamics and heat transfer, with applications in thermal insulation, energy systems, and the cooling of electronic devices. The stagnation point, at which the fluid velocity at the surface nears zero, significantly influences the development of the boundary layer and subsequently affects the thermal performance of the system. Ghalambaz et al. [9] investigated the heat transmission of hybrid nanofluids over a vertical plate using mixed convection and analysed the stability of stagnation-point boundary layer flow. The nanoparticle composition greatly influences the boundary layer flow and heat transmission characteristics, according to their findings. They discovered two solutions for opposing flow conditions, with stability analysis indicating that only the upper branch solutions are stable. Wahid et al. [10] also studied the hybrid nanofluid radiative mixed convection stagnation point flow on a vertical flat plate, incorporating the Dufour and Soret effects. Their research provided a comprehensive understanding of the heat and mass transfer mechanisms in these flows by emphasising the significance of radiation and cross-diffusion effects on the thermal and concentration boundary layers. Khashi'ie et al. [11] investigate the mixed convective stagnation point flow towards a vertical Riga plate in a hybrid Cu-Al_2O_3/water nanofluid, revealing that the electromagnetohydrodynamic (EMHD) force generated by the Riga plate significantly influences heat transfer efficiency and can delay boundary layer separation. Moreover, research by Azeman et al. [12] studied on the flow and thermal transfer of Powell–Eyring nanofluid at a stagnation point on a vertically stretched sheet has shown that non-Newtonian fluid properties and nanoparticle interactions are crucial in affecting thermal efficiency. Recent numerical studies reveal that the behaviour of nanofluids around a three-dimensional stagnation point is significantly influenced by factors such as nanoparticle type, shape, and volume fraction, especially under microgravity conditions with g-jitter effects.

Furthermore, considering the synergistic effects of suction/injection, internal heat generation, and nonlinear thermal radiation, Zainal et al. [13] investigated mixed convection flow from a convectively heated vertical porous plate. Their research emphasised the impact of internal heat generation and nonlinear radiation on temperature and velocity fields, demonstrating how these factors can significantly alter the characteristics of the boundary layer. The present analysis introduces an additional layer of complexity by incorporating a volumetric heat source, unlike the prior research conducted by Pantokratoras A. [14] which analysed the interplay between buoyancy and forced convection without accounting for internal heat generation.

This paper offers novel insights into heat transfer behaviour influenced by coupled convection and internal heating, significantly affecting temperature gradients, boundary layer thickness, and local Nusselt number. This paper also enhances research by Ishak and Nazar [15] which examined the effect of mass transfer in suction or injection on the mixed convection boundary layer flow near a stagnation point on a vertical porous plate. This inquiry primarily examines the heat transfer characteristics of a steady, two-dimensional mixed convection flow with internal heat generation flow near a stagnation point on a vertical porous plate. Meanwhile, the effect of internal heat generation on the velocity and temperature fields is meticulously examined, emphasising its alteration of the thermal boundary layer structure and overall heat transfer performance. The dimensionless governing equations are solved numerically using the BVP4C function within the MATLAB. The findings are shown for various physical parameters to demonstrate their effects.

2. METHODOLOGY

A viscous and incompressible two-dimensional stagnation point laminar flow is measured normal to the vertical plate with uniform surface mass flux. It is assumed that T_w is the temperature at the boundary while T_∞ and U is denoted as ambient temperature and velocity at the free stream respectively with $U = ax$ vary linearly with the distance x from the stagnation point. Presence of internal heat generation leads to an additional energy input in the fluid domain, which affects the temperature distribution. At the boundary, the surface was heated with constant temperature, or this boundary condition is also known as constant wall temperature. By inducing boundary layer and Boussinesq approximations, the fluid system is derived as [15-16],

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + U\frac{dU}{dx} + g\beta(T - T_\infty) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p}(T - T_\infty) \tag{3}$$

subjected to

$$\begin{gathered} u = 0, \quad v = V_w, \quad T = T_w \quad at \quad y = 0 \\ u \to U, \quad T \to T_\infty \quad as \quad y \to \infty \end{gathered} \tag{4}$$

To reduce the complexity of the system of partial differential equations, similarity transformation is conducted where the system is reduced into dimensionless form. By introducing similarity variables such that,

$$\eta = (U/\nu x)^{1/2} y, \qquad \psi = (U\nu x)^{1/2} f(\eta), \qquad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \tag{5}$$

where ψ is the stream function defined as $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$. By using these information and similarity variables in (5) the system of partial differential equation in (1) – (3) together with boundary condition in (4) is reduced into dimensionless ordinary differential equation such that

$$f''' + ff'' + 1 - f'^2 + \lambda\theta = 0, \tag{6}$$

$$\frac{1}{Pr}\theta'' + f\theta' + Q\theta = 0, \tag{7}$$

subjected to

$$\begin{gathered} f(0) = f_0, \qquad f'(0) = 0, \qquad \theta(0) = 1, \\ f'(\infty) \to 1, \qquad \theta(\infty) \to 0. \end{gathered} \tag{8}$$

where f_0 denoted as the suction/ injection parameter and for this study, impermeable plate was chosen with $f_0 = 0$. The prime notation denoted the differentiation respected to η, the mixed convection parameter defined as $\lambda = Gr_x/Re_x^{5/2}$, heat generation parameter $Q = \frac{Q_0}{\rho C_p a x}$ and Pr is Prandtl number $Pr = \frac{\nu}{\alpha}$. The local Grashof number and the local Reynolds number denoted as$Gr_x = g\beta(T_w - T_\infty)x^3/\nu^2$ and $Re_x = Ux/\nu$. The system of ordinary differential equations is then solved numerically so that the effects considered are analysed graphically in the next section.

3. RESULTS AND DISCUSSION

In this study, the MATLAB program was used to numerically solve the nonlinear ordinary differential equations (6) and (7) that were subject to boundary conditions (8). We observed that the findings in this study are only applicable in the small region near the stagnation line and are not valid outside the region. We have compared our findings with the results by Ishak and Nazar [15] for the heat transfer coefficient $\theta'(0)$ values for mixed convection parameter $\lambda = 1.0$ and heat generation $Q = 0$ with various values of Prandtl Number Pr to verify the numerical approach that was employed in this study. This comparison is presented in Table 1. However, only some of them are shown in the tables due to the space constraint. The findings show that there is a significant amount of agreement. Therefore, it can be considered that the code that has been written may be used to analyse the issue that is covered in this work with great confidence.

Table 1. Values of rate heat transfer coefficient $\theta'(0)$ for mixed convection parameter $\lambda = 1.0$ with various values of Prandtl number Pr when heat generation $Q = 0$

λ	Q	Pr	Ishak and Nazar [15]	Present results
1.0	0	0.70	0.7641	0.7640
		1.00	0.8708	0.8706
		2.50	-	1.1581
		7.00	1.7224	1.7223
		10.0	1.9446	1.9445

Table 2 presents the variation of the heat transfer coefficient $\theta'(0)$ with respect to different values of Prandtl number Pr when heat generation $Q = 0.05$ and mixed convection parameter $\lambda = 0.05$ for the first row. While second row shows variation of the heat transfer coefficient $\theta'(0)$ values with respect to different values of heat generation parameter Q when the mixed convection parameter $\lambda = 0.05$ and Prandtl number $Pr = 0.07$. It is observed that for a fixed mixed convection parameter λ and heat generation Q, the heat transfer coefficient $\theta'(0)$ increases with increasing Prandtl number Pr.This behavior is expected since a greater Prandtl number Pr corresponds to lower thermal diffusivity, which leads to a thinner thermal boundary layer and steeper temperature gradients at the surface, thereby improves heat transmission. Similarly, for a fixed mixed convection parameter λ and Prandtl number Pr, increasing the value of Q also results in a higher heat transfer coefficient $\theta'(0)$. This can be explained by the fact that greater internal heat generation raises the local temperature gradient near the surface, further promoting heat transfer. Furthermore, contrasting outcomes for various λ, increasing the mixed convection parameter causes increase the value of heat transfer coefficient $\theta'(0)$. A higher mixed convection parameter λ has greater buoyancy effects than forced convection, which increases the rate of heat transfer from the surface and intensifies convective currents. Overall, the results demonstrate that increasing any of the parameters Q and Pr leads to enhanced heat transfer efficiency due to their impacts on temperature gradients and thermal boundary layer behavior and temperature gradients.

Table 2. Values of rate heat transfer coefficient $\theta'(0)$ for mixed convection parameter $\lambda = 0.05$ with various values of Prandtl number Pr and heat generation Q

λ	Q	Pr	Heat Transfer Coefficient $\theta'(0)$
0.05	0.05	0.70	0.7400
		1.00	0.8389
		2.50	1.1581
		7.00	1.6585
0.05	0.05	0.70	0.7400
	0.50		0.9650
	1.20		1.2518
	2.00		1.5234

Figure 1 and 2 illustrates the temperature profile $\theta(0)$ for different values of the Prandtl number Pr with the mixed convection parameter $\lambda = 0.05$ and heat generation $Q = 0.05$ and $Q = 1.7$. The profiles show how the temperature changes across the boundary layer (denoted by η). As observed, as the Prandtl number Pr increases, the temperature profile $\theta(0)$ decreases more quickly showing that the thermal boundary layer is thinner. However, when comparing the two figures, the profiles in Figure 2 (with higher heat generation $Q = 1.7$) are thicker and greater in height than those in Figure 1 (with $Q = 0.05$). This is due to the fact that more heat generation raises the boundary layer's average temperature. In summary, Pr controls how fast the temperature drops, while Q affects how much heat is present in the system.

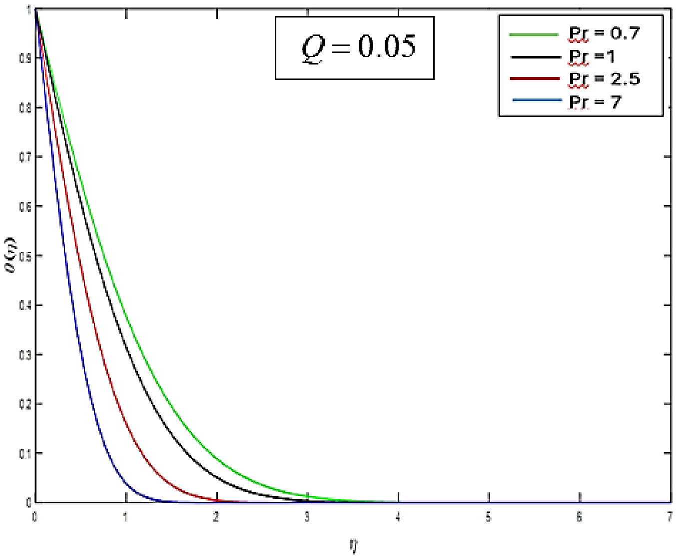

Figure 1. Temperature profile $\theta(0)$ for different values of Prandtl Number Pr with mixed convection parameter $\lambda = 0.05$ and heat generation $Q = 0.05$

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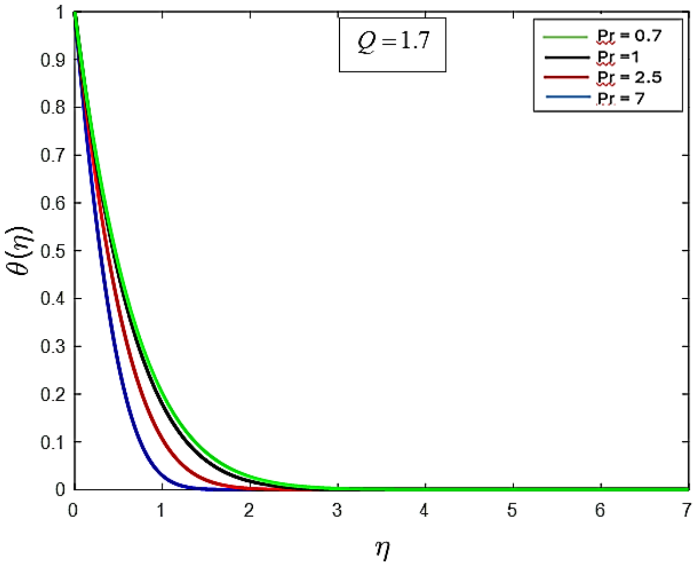

Figure 2. Temperature profile $\theta(0)$ for different values of Prandtl Number Pr with mixed convection parameter $\lambda = 0.05$ and $Q = 1.7$

Figure 3 displays the temperature profile $\theta(0)$ for different values of the heat generation parameter Q with Prandtl number $Pr = 0.7$ and mixed convection parameter $\lambda = 0.05$. The surface temperature gradient is also impacted since higher Q often results in a little decrease in the surface gradient but an increase in the system's total thermal energy. The temperature profile $\theta(0)$ becomes higher and decays more slowly, indicating enhanced internal heating and a thicker thermal boundary layer. This occurs because more heat is generated within the fluid, raising the overall temperature across the domain, even though the thermal diffusivity (set by Prandtl number Pr) remains unchanged.

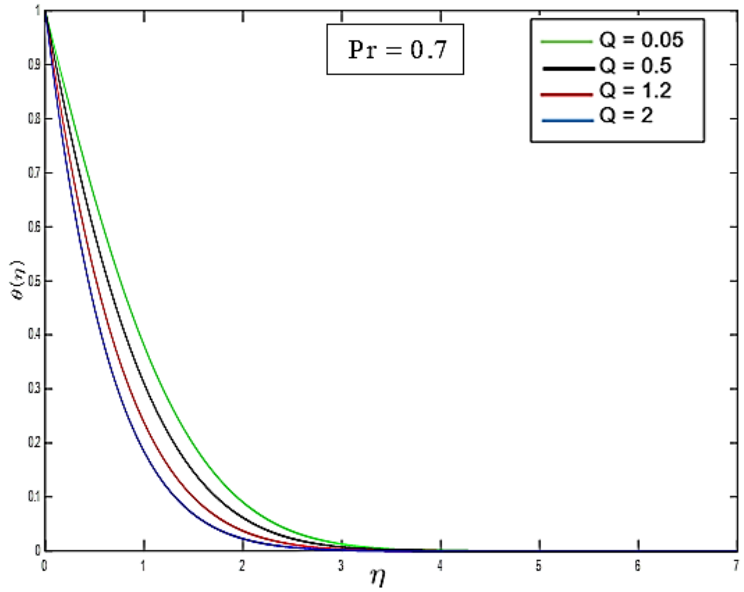

Figure 3. Temperature profile $\theta(0)$ for different values of heat generation Q with mixed convection parameters $\lambda = 0.05$ and Prandtl number $Pr = 0.7$

Figure 4 shows temperature profile $\theta(0)$ against the similarity variable η for various values of the mixed convection parameter λ, at a fixed Prandtl number $Pr = 0.5$ and heat generation $Q = 0.05$.The graph shows that increasing the mixed convection parameter λ increases the fluid's rate of cooling, as shown by the temperature profile $\theta(0)$ greater drop. This is due to the fact that particularly in fluids with low Prandtl number Pr, where heat spreads more quickly than momentum, higher buoyancy effects encourage quicker thermal diffusion.

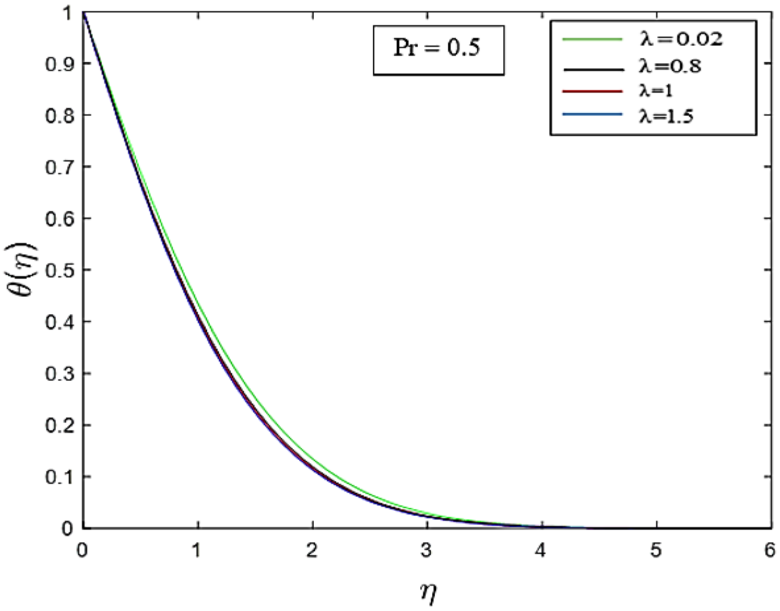

Figure 4. Temperature profile $\theta(0)$ with variations of the mixed convection parameters λ with heat generation $Q = 0.05$

In Figure 5, for fixed value $Q = 0.05$ when the mixed convection parameters $\lambda = 0.05$, variations in the Prandtl number Pr do not significantly affect the velocity profile $f'(\eta)$. This is because the flow is low internal heat generation Q values make it little connected to heat and Prandtl number Pr mainly influences thermal not momentum diffusivity. As a result, the velocity profiles certainly happen indicating that the velocity field remains constant across a range of Prandtl number Pr values.

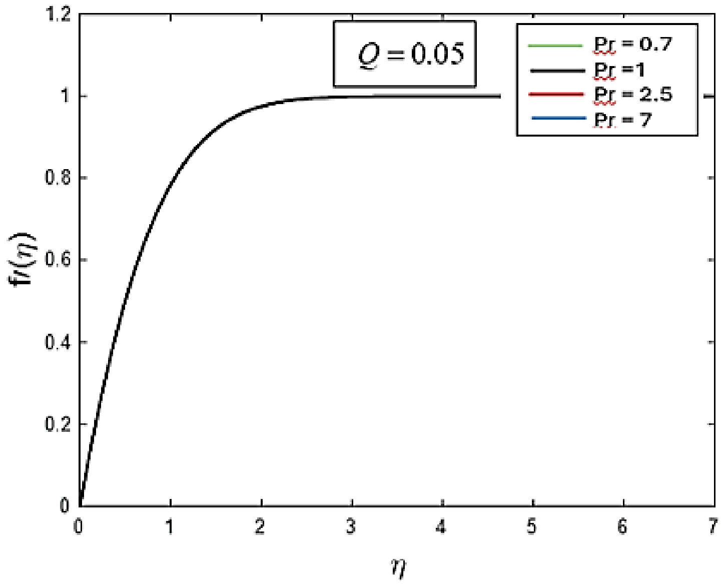

Figure 5. Velocity profile, $f'(\eta)$ for different values of Prandtl number Pr with and heat generation parameter $Q = 0.05$ and mixed convection parameters $\lambda = 0.05$

Figure 6 displays velocity profile $f'(\eta)$ as a function of the similarity variable η for variations of the mixed convection parameters λ with a fixed Prandtl number $Pr = 0.5$ and heat generation parameter $Q = 0.05$. As λ increases, the velocity profile $f'(\eta)$ display a thinner boundary layer and faster growth because of increased buoyant pressures from free convection. This illustrates how the impact of thermal gradients on fluid flow is amplified as the mixed convection parameter is increased even when thermal diffusivity is high which means low value of Prandtl number Pr. As we can see from discussion, higher mixed convection parameter λ strengthens buoyancy effects to improve heat and momentum transfer, but changes in Prandtl number Pr largely impact thermal behavior and have little effect on velocity profiles when heat generation parameter Q is low.

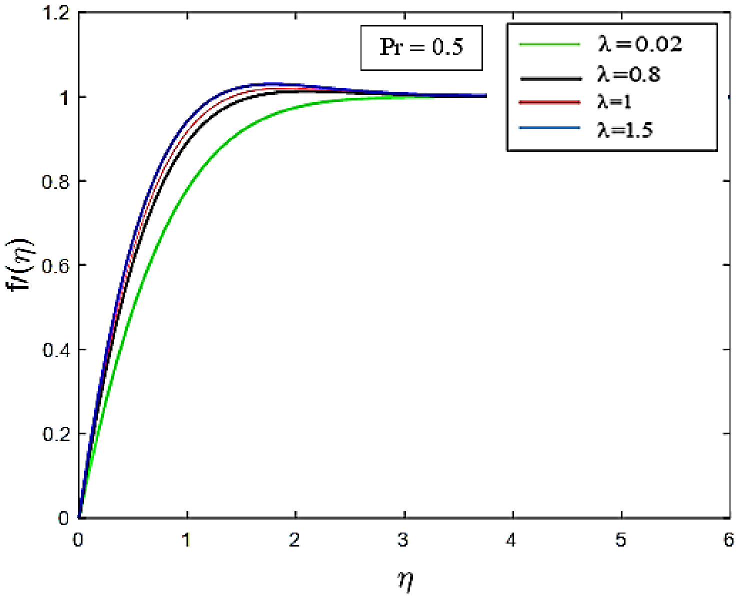

Figure 6. Velocity profile $f'(\eta)$ with variations of the mixed convection parameter λ with a fixed Prandtl number $Pr = 0.5$ and heat generation parameter $Q = 0.05$

4. CONCLUSIONS

Heat transmission in a mixed convection boundary layer flow with internal heat generation close to a stagnation point on a vertical plate was numerically analyzed in this work. The study showed how the Prandtl number Pr, the heat generation parameter Q and the mixed convection parameter λ critically affect the thermal and velocity boundary layer behavior by using MATLAB to solve the governing nonlinear ordinary differential equations.

The findings showed that raising the Prandtl number improves heat transfer by creating steeper temperature gradients and thinner thermal boundary layers. Similarly, heat generation in the fluid domain raises the temperature overall and thickens the thermal boundary layer. It was discovered that the mixed convection parameter greatly affected the velocity and thermal profiles, enhancing buoyancy-driven effects that encourage more effective convective heat transfer.

Notably, changes in the mixed convection parameter obviously affected both the temperature and velocity fields, highlighting its major role in flow-thermal interaction, whereas the Prandtl number had no effect on the velocity profile under low heat generation conditions. These findings contribute for future understanding of convective transport phenomena in thermally active fluid systems and provide a basis for optimizing thermal management strategies in relevant engineering applications and validating the numerical results with experimental or high-fidelity simulation data for practical implementation.

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AUTHOR CONTRIBUTIONS

Siti Nur Aisyah Azeman (Conceptualisation; Proving, Resources; Writing- original draft), Anis Zafirah Azmi (Conceptualisation; Proving; Writing- review & editing), Mohamad Hidayad Ahmad Kamal (Proving; Writing- review & editing), Nurul Hafizah Zainal Abidin (Conceptualisation; Writing- review & editing), Nor Alwani Omar (Resources; Writing- review & editing).

DECLARATION OF ORIGINALITY

The authors declare no conflict of interest to report regarding this study conducted.

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