RESEARCH ARTICLE

Homotopic Computations for Non-Darcian Modified EyringPowell Incompressible Liquid Configured by Varying Thickened Surface

Muhammad Zubair[1,*], **Muhammad Waqas**[2], **Muhammad Zeshan**[2] **and Sami Ullah Khan**[3]

[1] School of Qilu Transportation, Shandong University, Jinan 250061, China
[2] NUTECH School of Applied Sciences and Humanities, National University of Technology, Islamabad 44000, Pakistan
[3] Department of Mathematics, Namal University, Mianwali 42250, Pakistan

Abstract

The simulations for the non-Fourier heat transfer model have been performed for modified Eyring-Powell fluid, comprising the variable viscosity. The inertia outcomes for thermal problem are evaluated by incorporating the Darcy-Forchheimer features. The investigation for visualizing the heat transfer aspects is subject to variable thermal conductivity. The flow is induced by a nonlinear moving surface. After developing the governing expressions, an analytical treatment of the problem is presented. The results are graphically presented to endorse physical aspects of current model.

Keywords: variable sheet thickness, non-linear stretching sheet, non-Fourier heat flux, modified eyring powell liquid, variable thermal conductivity.

1 Introduction

Fourier heat conduction model is the basic key for thermoelectric transport models [1]. However, a fundamental drawback of the widely used Fourier's law is that it describes a parabolic energy equation, which is valid for instantaneous propagation of thermal disturbances and consequently, the energy transport is anisotropic and leads to the unrealistic assumption of infinite heat propagation speed. To address this deficiency, a general structure known as Fourier's law with thermal relaxation was developed by Cattaneo [2] where a thermal relaxation time, representing the finite thermal conduction speed, was assigned. Exploiting this idea, Christov [3] goes a step further and improves the model by framing it in a frame-indifferent way using Oldroyd's theory of upper-convected derivatives, so that compatibility with the tenets of rational thermodynamics is achieved. The earlier work of Christov [3] initiated a series of studies of heat transfer with non-Fourier effects. Straughan [4] deduced the variation in thermal results subject to natural convective flow by imposing the non-traditional Fourier's approach.

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***Corresponding author:**
✉ Muhammad Zubair
mzubair@sdu.edu.cn

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At the same time, there is a great interest in investigating different types of non-Newtonian fluids, ranging from everyday products to industrial liquids such as blood, ketchup, cheese, drilling mud, and colloidal suspensions. Of a variety of constitutive models, the 1944 Eyring–Powell fluid, originally proposed by Powell and Eyring, has been recognized for its ability to replicate Newtonian-like behavior at both low and high shear rates. Its empirical nature provides a more realistic description of complex rheological behavior, particularly for shear thickening and thinning phenomena. Several studies, including those by [5–7], have validated the versatility of the Eyring–Powell model in diverse flow configurations. Zubair et al. [8] further advanced this field by incorporating ferromagnetic effects into the Eyring–Powell model while utilizing the Cattaneo-Christov (CC) heat flux theory. Their work highlights the necessity of coupling advanced heat conduction models with non-Newtonian flow theory to achieve accurate predictions of coupled heat and momentum transport. Recent progress in non-Newtonian fluid mechanics has expanded these insights: Reddy et al. [9] investigated MHD Eyring–Powell hybrid nanofluid transport with the non-Fourier heat flux model in solar pump applications, while Hayat et al. [10] examined Powell-Eyring nanofluid flow over a non-linear stretching sheet with variable thickness under MHD effects. For Darcy–Forchheimer configurations involving Cattaneo-Christov heat flux, [11] investigated the impact of the Darcy–Forchheimer–Brinkman model on generalized Eyring–Powell liquid subject to Cattaneo–Christov double diffusion aspects, [12] analyzed Prandtl-Eyring nanofluid flow with entropy generation and variable heat transfer, and [13] conducted a numerical investigation of viscoelastic Darcy-Forchheimer flow with non-Fourier heat flux and nonlinear thermal radiation. Additionally, [14, 15] addressed the Cattaneo-Christov heat flux model in flows over surfaces of variable thickness and in non-Newtonian Darcy-Forchheimer porous media, respectively.

Recent developments in fluid dynamics have emphasized the importance of varying sheet thickness on the behaviour of non-Newtonian fluids especially in industrial processes involving calendering and coating. Khalil et al. [16] examined the impact of variable fluid properties and the double diffusive Cattaneo–Christov model on dissipative non-Newtonian fluid flow due to a stretching sheet, demonstrating that temperature-dependent viscosity and variable thermal conductivity significantly influence the heat and mass transfer characteristics. Similarly, Anwar et al. [17] studied non-Newtonian flow of fluids over stretching sheets in porous space and stressed on the effect of thermal conductivity and magnetic fields in changing the pattern of flow and heat transfer rates. Aziz et al. [18] conducted an entropy analysis for Powell–Eyring nanofluid flow over a stretching surface incorporating the Cattaneo–Christov heat flux model, revealing the role of thermal relaxation and fluid rheology in governing entropy production. Nonlinear stretching surfaces play an important impact in transport phenomenon, especially for complex materials. It is reported through some investigative studies that magnetic field, buoyancy and convective boundary conditions play a vital role in flow features and heat transfer characteristics in such systems [19, 20, 22]. The combined influence of Darcy–Forchheimer porous resistance, variable thermal conductivity and Cattaneo-Christov heat flux in boundary layer flows has also been demonstrated [21]. These observations are also useful for the industrial processes regarding the nonlinear stretching surface. The Modified Eyring–Powell model is particularly useful in replicating shear-thinning behaviour without developing singularities at zero shear rate as seen in models such as power-law or Bingham. Modified Eyring–Powell model has recently been utilized to consider many engineering problems, such as temperature dependent viscosity in web coating process, non-similar boundary layer flow and heat transfer over a wedge, and chemically reacting nanofluid flow over wedges. These applications demonstrate the model's practical applicability and accuracy in describing the rheological response of the non-Newtonian fluid in various engineering and biomedical practices (see [23–25]).

Motivated by the above scenario, the present research is pursued to address the impacts of non-Fourier heat flux in Darcy–Forchheimer flow of a Modified Eyring–Powell fluid towards a nonlinear stretching surface with variable thickness. Thermal results are claimed under the assumptions of temperature dependent thermal conductivity. The problem is simplified into dimensionless forms. The homotopy analysis scheme, with excellent accuracy is followed to entertain the simulations.

2 Mathematical Modeling

We investigate a two-dimensional Darcy–Forchheimer flow of a modified Eyring–Powell fluid on a non-linear stretching sheet with variable thickness. The stretching surface starts with a slit placed at the origin with x-axis placed along the sheet and y-axis perpendicular to it. The thermal conductivity is considered as temperature-dependent, and heat diffusion is described using a non-Fourier (Cattaneo–Christov) heat flux model. The surface profile is $y = A(x+b)^{\frac{1-n}{2}}$. The boundary layer assumptions are introduced and the equations of continuity, momentum, and energy written out in the boundary layer coordinate system.

$$\partial_x u + \partial_y v = 0 \tag{1}$$

$$u\partial_x u + v\partial_y u = \frac{\mu}{\rho}\partial_{yy}u + \frac{q}{\rho}\left(\frac{1}{\rho BC}\right)^q \left(1+\frac{q+2}{6c^2}(\partial_y u)^2\right) \times (\partial_y u)^{q-1}\partial_{yy}u - \frac{\mu}{\rho k^*}u - \frac{C_b}{\sqrt{k^*}}u^2 \tag{2}$$

$$\begin{aligned} &u\partial_x T + v\partial_y T + \lambda\{(u(\partial_x u)(\partial_x T) + v(\partial_y u)(\partial_y T)) \\ &+v\partial_y u(\partial_x T) + 2uv\partial_{xy}T + u^2\partial_{xx}T + v^2\partial_{yy}T\} \\ &= -\frac{1}{\rho c_p}k(T)\partial_{yy}T \end{aligned} \tag{3}$$

with conditions

$$\begin{aligned} &u = U_w(x) = U_0(x+b)^n, \quad v = 0, \\ &T = T_w \text{ at } y = A(x+b)^{\frac{1-n}{2}}, \\ &u \to 0, \quad T \to T_\infty \text{ as } y \to \infty \end{aligned} \tag{4}$$

The thermal conductivity is assumed to be $k(T) = k_\infty(1+\epsilon\Theta)$, where k_∞ is the thermal conductivity of the ambient fluid, ϵ symbolizes a small coefficient for thermal conductivity, and Θ is dimensionless temperature. The constants (b, c, d) have no dimension, and μ is the dynamic viscosity and ρ the fluid density. The factors B, C, and q are related to the Modified Eyring–Powell (MEP) fluid model. Where c_p is the specific heat, T is the fluid temperature, T_∞ the ambient temperature, and u, v are the velocity components in the x, y direction, respectively. Following quantities are adopted for simplification:

$$\begin{aligned} &\chi = \sqrt{\frac{2\nu U_0}{n+1}}(x+b)^{\frac{n+1}{2}}F(\xi), \\ &\xi = y\sqrt{\frac{(n+1)U_0}{2\nu}}(x+b)^{\frac{n-1}{2}}, \\ &u = U_0(x+b)^n F'(\xi), \\ &v = -\sqrt{\frac{n+1}{2}}U_0\nu(x+b)^{n-1}\left(F(\xi)+\frac{n-1}{n+1}\xi F'(\xi)\right), \\ &\Theta(\xi) = \frac{T-T_\infty}{T_w-T_\infty} \end{aligned} \tag{5}$$

By substituting Eq. (5) into Eqs. (2)–(4) and introducing the coordinate shift $\eta = \xi - \alpha$ to map the wall boundary to $\eta = 0$, the governing equations reduce to

$$\left(1+Kq\sqrt{\frac{n+1}{2}}\delta f''\right)^{q-1}\left(1-\frac{q+2}{3}\delta(f'')^2\right)f''' + ff'' - \frac{2n}{n+1}(f'')^2 - \frac{2}{n+1}\beta f' - \frac{2}{n+1}fr(f')^2 = 0 \tag{6}$$

$$(1+\epsilon\Theta)\Theta'' + \epsilon\Theta'^2 + Pr(f\Theta' + \gamma\left(\frac{n-3}{2}f\Theta'f' - \frac{n+1}{2}f^2\Theta''\right)) = 0 \tag{7}$$

with

$$\begin{aligned} &f'(0) = 1, \quad f(0) = \frac{1-n}{1+n}, \\ &\Theta(0) = 1, \quad f'(\infty) = 0, \quad \Theta(\infty) = 0 \end{aligned} \tag{8}$$

Here $K\left(=\frac{1}{\mu BC}\right)$ and $\delta\left(=\frac{U_0^3(x+b)^{3n-1}}{2\nu c^2}\right)$ illustrating the fluid parameters, $fr\left(=\frac{2c_b(x+b)}{\sqrt{k^*(n+1)}}\right)$, $\beta\left(=\frac{2\nu}{k^*(n+1)U_0(x+b)^{n-1}}\right)$, γ the thermal relaxation parameter and $Pr\left(=\frac{\nu}{\alpha}\right)$. The wall drag force is:

$$C_f = \frac{2\tau_w}{\rho U_w^2} \tag{9}$$

In which

$$\tau_w = \mu\partial_y u + \frac{1}{BC}\partial_y u - \frac{1}{6BC^3}(\partial_y u)^3 \quad \text{at} \quad y = A(x+b)^{\frac{1-n}{2}} \tag{10}$$

The dimensionless form is

$$\frac{\sqrt{Re_x}C_f}{2} = \sqrt{\frac{n+1}{2}}\left(1+K-\frac{n+1}{2}\frac{K\delta}{3}f''(0)\right)f''(0) \tag{11}$$

where $Re_x = \frac{U_w(x+b)}{\nu}$ the local Reynolds number.

3 Homotopic Procedure

The convergent solutions of Eqs. (6) and (7) are solved using the HAM, in the presence of the boundary conditions (8). The solutions are given in series, consistent with the nature of the problem. The initial guesses and associated linear operators are given by:

$$\begin{aligned} f_0(\eta) = 1 - e^{-\eta}, \quad \theta_0(\eta) = e^{-\eta}, \\ L_f = f''' - f', \quad L_\theta = \theta'' - \theta' \end{aligned} \tag{12}$$

Such that

$$\begin{aligned} L_f \left[C_1 + C_2 e^{\eta} + C_3 e^{-\eta}\right] = 0, \\ L_\theta \left[C_4 e^{\eta} + C_5 e^{-\eta}\right] = 0. \end{aligned} \tag{13}$$

in which C_i $(i = 1-5)$ elucidate the arbitrary constants. An important part of the HAM method is the H-curve, which presents the convergence of the Eqs. (6) and (7) subject to Eq. (8). The optimal ranges for the convergence-control parameters are $-1.85 \leq h_f \leq -0.15$ and $-1.6 \leq h_\theta \leq -0.4$. The H-curve derived is shown in Figure 1. Table 1 presents accuracy of HAM simulations. The illustration of residual error for HAM has been plotted in Figure 2.

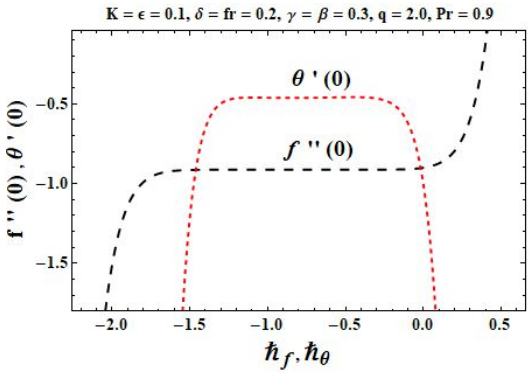

Figure 1. H-Curve for h_f and h_θ.

Table 1. The Homotopic solutions for convergence when $K = \epsilon = 0.1, \delta = fr = 0.2, \gamma = \beta = 0.3, q = 2.0$ and $Pr = 0.9$.

Approximation Order	$-f''(0)$	$-\theta(0)$
1	0.7182	0.7264
6	0.7223	0.5678
12	0.7223	0.5691
18	0.7223	0.5710
24	0.7223	0.5705
30	0.7223	0.5705

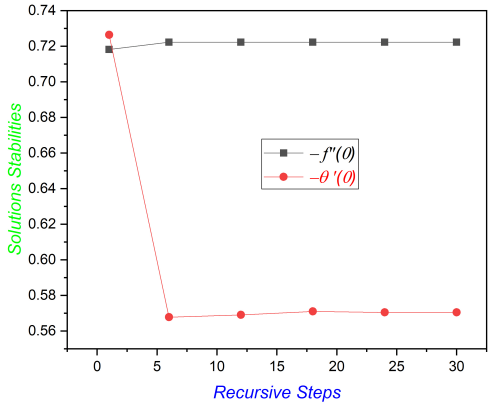

Figure 2. Residual error for HAM.

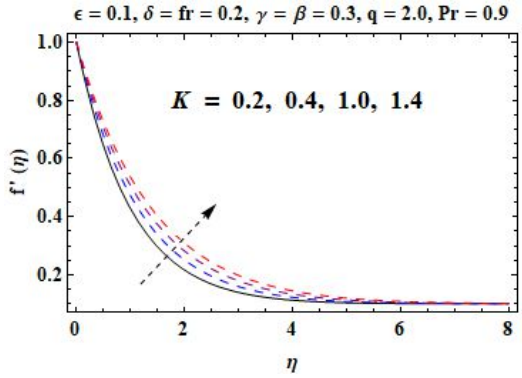

Figure 3. K via f'.

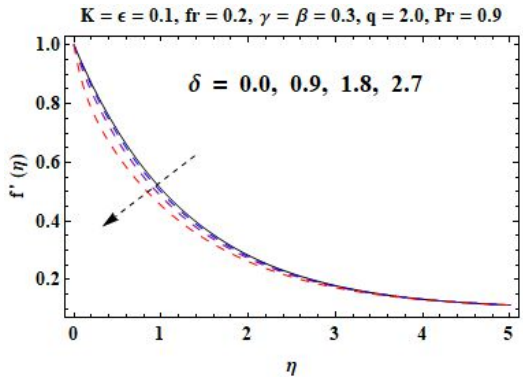

Figure 4. θ via f'.

4 Analysis of results

In this section an investigation is made regarding the effects of various parameters on skin friction, velocity and temperature in Figures 3, 4, 5, 6, 7, 8, 9 and 10. Figure 3 shows that when the material parameter K becomes larger, the velocity f' gets increased and the momentum boundary layer thickness becomes thick due to reduction in effective viscosity. In contrast, Figure 4, an increase in the sheet thickness parameter δ causes a decrease in velocity and the boundary layer thickness. From Figure 5, it can be observed that, with

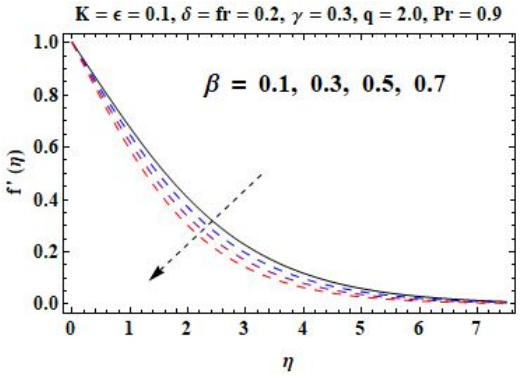

Figure 5. β via f'.

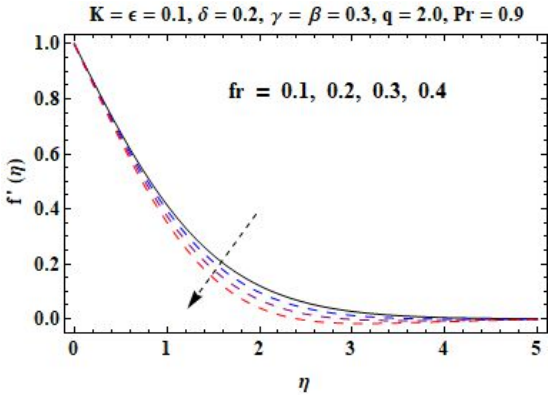

Figure 6. fr via f'.

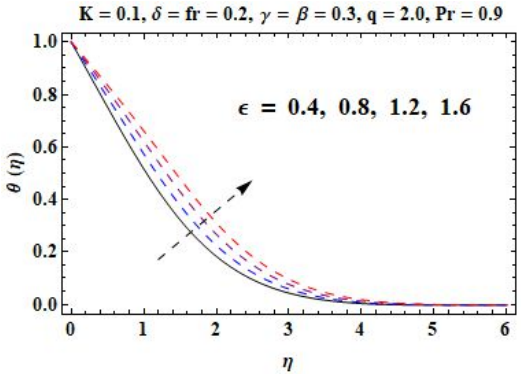

Figure 7. ϵ via θ.

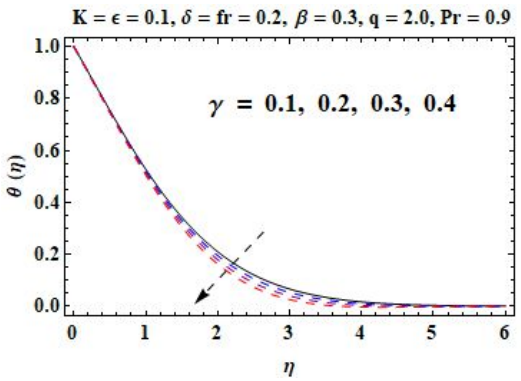

Figure 8. γ via θ.

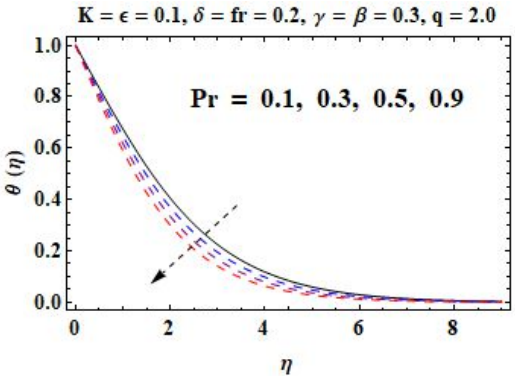

Figure 9. Pr via θ.

decreases because of higher resistance in the porous medium. Similarly, Figure 6 demonstrates that at a higher Forchheimer number fr, inertial effects become more pronounced, which leads to slower flow velocity. Notice from Figure 7 that, temperature θ increases with increasing thermal conductivity parameter ϵ because the higher the value of the thermal conductivity, the more heat is moved from the sheet to the fluid. In Figure 8, the temperature θ decreases as ν increases with the maximum heat transfer performance when $\gamma = 0$. It is evident from Figure 9 that, Pr inhibits the thermal boundary layer and temperature profile considerably because of smaller thermal diffusivity. Finally, Figure 10 indicates that skin friction gets enhanced with respect to both K and δ showing stronger shearing effect with the surface as compared to the high value of both these parameters. The homotopic solutions for exhibiting convergence can be seen in Table 1 and the stability of these solutions is shown in Figure 2. A comparison of the skin friction coefficient is given in Table 2, which shows good agreement with available data.

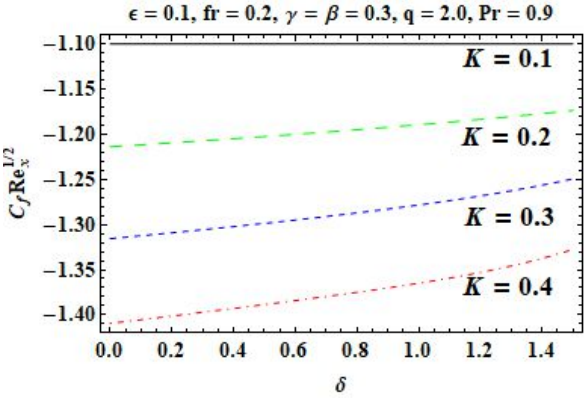

Figure 10. Skin Friction on K and δ.

an ascent rate of the porosity parameter β, the velocity

Table 2. The comparative analysis of skin friction coefficient.

	$-f''(0)$	$-f''(0)$
β	Turkyilmazoglu [26]	Present
0.0	1.00000	1.00000
0.5	1.22474487	1.01980
1.0	1.41421356	1.11803

5 Conclusion

This work aims to provide a comprehensive analysis of the Darcy–Forchheimer flow of a Modified Eyring–Powell material. Updated heat flux approach is followed to model the problem. The noteworthy observations are:

- The velocity decreases as the porosity parameter and Forchheimer number are increased.
- A larger material parameter leads to increasing the fluid velocity.
- The velocity and corresponding layer thickness decrease with increasing δ.
- Peak variation in temperature rate is assessed due to variable thermal conductivity.
- A decrement in wall shear force is observed due to sheet thickness parameter.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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Dr. Muhammad Zubair is working as a Postdoc fellow in School of Qilu Transportation, Shandong University, Jinan, 250061, China. He is working mainly in the field of Newtonian, non-Newtonian fluid mechanics, Porous Media, Heat and mass transfer, stretching sheet, stretching cylinders, curved surfaces etc. (Email: mzubair@sdu.edu.cn)