Effect of nonuniform heat source/sink, and viscous and Joule dissipation on 3D Eyring–Powell nanofluid flow over a stretching sheet

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Abstract

The aim of this paper is to explore the effect of heat source/sink, and space- and temperature-dependent viscous and Joule dissipation on 3D magnetohydrodynamic radiating Eyring–Powell nanofluid streamline flow with convective conditions past a stretching sheet. The coupled nonlinear flow, thermal, and species phenomena equations are transformed into a system of coupled nonlinear ordinary differential equations through suitable similarity transformations with corresponding boundary conditions. The transformed dimensionless equations are then solved analytically with the Adomian decomposition method. A comprehensive study is conducted on the influence of sundry physical dimensionless parameters governing the flow velocity, temperature, and concentration distributions. For parameters of engineering interest, the computed numerical results are presented with the aid of tables. Furthermore, the present solutions agree with the earlier reported results in specific cases, and an excellent correlation is witnessed. The present analysis is of great interest germane to cooling of metallic plates, polishing of artificial heart valves, oil pipeline friction reduction in the oil industry, flow tracers, enhanced oil recovery, and separation processes in chemical industries and petroleum extraction.

Keywords: Eyring–Powell nanofluid; viscous dissipation; Joule heating; zero mass flux; non-uniform heat source/sink

Nomenclature

\[ a, b: \] Positive constants
\[ x, y, z: \] Coordinates (m)
\[ u, v, w: \] Velocities along the x, y, z directions (m s\(^{-1}\))
\[ f, g: \] Dimensionless velocity components
\[ U_\infty, V_\infty: \] Velocities along the x, y directions (m s\(^{-1}\))
\[ T: \] Fluid temperature (K)
\[ T_f: \] Surface temperature (K)
\[ T_\infty: \] Ambient temperature (K)
\[ C: \] Concentration of the fluid
\[ C_w: \] Concentration at wall (kg m\(^{-3}\))
\[ C_\infty: \] Ambient concentration (kg m\(^{-3}\))
\[ D_b: \] Brownian diffusion coefficient
\[ D_T: \] Thermophoretic diffusion coefficient
\[ h: \] Heat transfer coefficient
\[ \kappa: \] Thermal conductivity (W m\(^{-1}\) K\(^{-1}\))
\[ (c_p)_f: \] Specific heat of the fluid (J kg\(^{-1}\) K\(^{-1}\))
\[ (c_p)_p: \] Specific heat of the solid (J kg\(^{-1}\) K\(^{-1}\))
\[ q_r: \] Radiative heat flux (W m\(^{-2}\))
\[ k_1: \] Mean absorption coefficient (m\(^{-1}\))
\[ R: \] Radiation parameter
\[ N_b: \] Brownian motion parameter
\[ N_t: \] Thermophoresis parameter
\[ M: \] Magnetic field parameter

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Effect of nonuniform heat source/sink on 3D Eyring–Powell dissipative nanofluid flow

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Greek symbols

\[ \tau_{ij} : \text{Stress tensor of the Eyring–Powell fluid} \]
\[ \sigma^* : \text{Stefan–Boltzmann constant (W m}^{-2} \text{K}^{-4}) \]
\[ \sigma : \text{Electrical conductivity} \]
\[ \alpha_m : \text{Thermal diffusivity} \]
\[ \varepsilon, \delta_1, \delta_2 : \text{Eyring–Powell fluid parameters} \]
\[ \lambda_1, \lambda_2 : \text{Dimensionless velocity slip parameters} \]
\[ \nu : \text{Kinematic viscosity (m}^2 \text{s}^{-1}) \]
\[ \eta : \text{Similarity variable} \]
\[ \mu : \text{Dynamic viscosity (kg m}^{-1} \text{s}^{-1}) \]
\[ \tau : \text{Ratio of effective capacities of particle and fluid} \]
\[ \beta, \gamma : \text{Characteristics of the Eyring–Powell fluid} \]
\[ \theta : \text{Dimensionless temperature} \]
\[ \phi : \text{Dimensionless concentration} \]
\[ \rho_f : \text{Fluid density (kg m}^{-3}) \]
\[ \rho_p : \text{Density of the particle (kg m}^{-3}) \]

Subscripts

\[ f : \text{Fluid} \]
\[ \infty : \text{Condition at the free stream} \]
\[ w : \text{Condition at the wall} \]

Superscript

\[ () : \text{Differentiation with respect to } \eta \]

1. Introduction

In practice, a simple Newtonian constitutive relation cannot explain the complex nature of every real-world fluid. When dealing with industrial and engineering applications, the non-Newtonian models have been used. The non-Newtonian fluids have vast applications and hence gained much attention in bubble columns, plastic foam processing, boiling, bubble absorption, oil pipeline friction reduction in the oil industry, and flow tracers. One of the most important non-Newtonian constitutive models, say the Eyring–Powell model, which is derived from the molecular theory of gases, gained potential interest among researchers: Samuel, Hammed, and Srinivas (2018) reported Eyring–Powell squeezing radiative flow through an infinite channel by using the Adomian decomposition method (ADM) and the results were validated with the results obtained through the homotopy analysis method (HAM) and the shooting technique. Agbaje, Mondal, Motsa, and Sibanda (2017) adopted the multidomain bivariate spectral quasi-linearization method to report on the heat generation influence of Eyring–Powell nanofluid stream through a stretched sheet subject to zero mass flux. In this work, bivariate Lagrange interpolation with quasi-linearization techniques was coupled and the solutions for boundary layer equations were obtained with the Chebyshev spectral collocation method. A horizontal surface of a paraboloid revolution was considered by Abegunrin, Animasun, and Sandeep (2018) to study the catalytic surface reaction-based Powell–Eyring fluid with the classical Runge–Kutta method coupled with the shooting technique. Abdul Gaffar, Ramachandra Prasad, and Keshava Reddy (2016) reported on ion slip/Hall currents with viscous and Joule dissipation effects. In this article, the authors used KBM (Keller-Box Method) for the Powell–Eyring flow model from the vertical surface in a permeable environment and the results so obtained were validated with the Nakamura tridiagonal finite-difference scheme. Hayat, Bilal Ashraf, Shehzad, and Abouelmagd (2015) reported on 3D Eyring–Powell nanofluid flow above an exponentially elongating sheet and produced series solutions with the HAM subject to uniform flow constraints. When a surface with convective temperature is moving toward the direction of uniform free stream, HAM solutions are delivered by Hayat, Iqbal, Qasim, and Obaidat (2012) for a steady stream. In the year 2018, OHAM (Optimal Homotopy Analysis Method) was used by Hayat and Nadeem (2018a) to study the 3D stream with the Cattaneo–Christov heat flux model and homogeneous– heterogeneous reactions. Later, the work of Hayat et al. (2012) was extended by Hayat and Nadeem (2018b) and it was concluded that Fourier’s model temperature is higher than the Cattaneo–Christov heat flux model temperature. In the incompressible Ree–Eyring magnetohydrodynamic (MHD) peristaltic fluid stream, Hayat, Akram, Alsaedi, and Zahir (2018) reported on endoscopy and chemical reaction effects subject to velocity and temperature slips on the outer tube. Jafarnomghaddam (2019) investigated the Powell–Eyring MHD flow problem solved by the numerical scheme with (Homotopy Perturbation Method) HPM. In this investigation, the author introduced a novel topology technique, namely the contraction mapping homotopy technique (CMHT), to avoid the h-curve analysis and ensure the natural convergence with CMHT. Animasun, Mahanthesh, and Koriko (2018) studied the flow past a slanted paraboloid of revolution surface with tiny gold nanoparticles subject to surface velocity slip and buoyancy effects. Farooq, Hayat, Ahmad, and Alsaedi (2018) reported on the effects of radial magnetic field on the non-Newtonian flow in a curved channel with respect to convective temperature conditions by adopting a perturbation technique. Gireesha, Gorla, and Mahanthesh (2015) analyzed the 3D MHD flow of radiating Eyring–Powell fluid over an elongating sheet with the RKF45 method coupled with the shooting technique. Bhatti, Abbas, and Rashidi (2017) reported entropy generation analysis of Eyring–Powell nanofluid past a permeable sheet by employing the successive linearization method. Hamid, Zubair, Usman, Khan, and Wang (2019) modeled heat and mass transfer impacts on time-dependent Prandtl fluid on a flat plate. Nadeem, Khan, Noor, and Shafiq (2019) reported on bioconvective nanofluid past a stretching sheet. Statistical computations of Casson nanofluid flow with heat and mass conditions were analyzed by Mackoli and Mahanthesh (2019).

Potential applications of non-Newtonian Eyring–Powell fluid motivated the different investigators to look for many possibilities under several flow geometries such as double stratification flow of Eyring–Powell fluid in an inclined stretching cylinder by Khalil-Ur-Rehman, Malik, Bilal, Bibi, and Ali (2017). The influence of chemical reaction on magneto-nanofluid flow over a stretched cylinder has been studied by Ramzan, Bilal, and Chung (2017). For the solution of the complex system, they have used the HAM. Moreover, Hayat, Awais, and Asghar (2013) presented their work on 3D MHD fluid flow past a stretching sheet. Hina, Mustafa, Hayat, and Alsaedi (2016) studied peristaltic flow from
a curved channel with a regular perturbation method. A parallel channel filled with fluid subject to isothermal boundary conditions for temperature was proposed by Khan, Sultan, and Rubbab (2015) using OHAM. Nadeem and Saleem (2014) have used a rotating cone to investigate time-dependent boundary layer flow using a similar concept of OHAM. Recently, Parand and Hajimohammadi (2018) introduced Laguerre’s generalized functions with a (Quasi Linearization) QL based collocation method for solving boundary layer equations in an unbounded domain. Rehman, Malik, Tahir, and Zehra (2018) reported on scaling group transformation for Eyring–Powell stream past a porous stretching sheet with a numerical scheme. Hayat, Nadeem, and Khan (in press) explored 3D hybrid CNT (Carbon Nanotubes) nanofluid rotating flow over an exponentially stretching surface with the Lobatto IIIA formula and the same work was extended for well-posed boundary layer ODEs are produced with the ADM.

Numerous authors explored the behavior of flow characteristics with dissimilar geometries subject to diverse boundary environments on Newtonian and non-Newtonian flow models that include 2D Marangoni MHD convection over a flat surface (Al-Mudhaf & Chamkha, 2015), viscoelastic fluid flow through a spongy plate with variable viscosity model (Hussain, Akbar, Sarwar, Nadeem, & Iqbal, 2019), nanofluid mixed convection about a cone (Chamkha, Abbabbandy, Rashad, & Vajravelu, 2013), Casson non-Newtonian flow model with shooting technique between two concentric cylinders (Hussain, Javed, & Nadeem, 2019), FEA (Finite Element Analysis) of MHD over a disk (Sudarsana Reddy, Sreedevi, & Chamkha, 2017), dual solutions of oblique stagnation point flow over a shrinking and stretching sheet (Nadeem, Khan, & Khan, 2019), micropolar fluid streams above a porous stretched surface (Damesh, Al-Odat, Chamkha, & Shannak, 2009; Magyari & Chamkha, 2010), inclined magnetic field effect on Jeffrey nanofluid flow in an asymmetric channel (Akrak, Zafar, & Nadeem, 2018), magnetic Jeffrey fluid stream in a rotating cone (Saleem, Al-Qarni, Nadeem, & Sandeep, 2018), upright porous plate embedded in micropolar liquid (Chamkha, Mohamed, & Ahmed, 2011), shape factor and sphericity effect of nanofluid flow over a stretching surface (Subhani & Nadeem, 2019), Das, Sharma, and Sarkar (2016) adopted the Nachtsheim–Swigert shooting iteration technique along with the sixth-order Runge–Kutta method to study second-grade electrically conducting MHD flow past a vertical expanding sheet subject to convective heat flux condition.

In all previously mentioned investigations, to the best of our knowledge, no attempt is made on the collective effects of all the aforementioned parameters. Our paramount interest and novelty in this article are to investigate how the 3D Eyring–Powell fluid system arises in the field of fluid dynamics with the influence of nonuniform heat source/sink, and Joule and viscous dissipation subject to velocity slip, convective surface temperature, and zero mass flux conditions. The widely accepted similarity transformation is exploited for the reduction of the fluidic PDE (Partial Differential Equations) model to a system of nonlinear ordinary differential equations (ODEs). Convergent solutions for well-posed boundary layer ODEs are produced with the ADM.

The different governing parameter contributions are portrayed by plots and in tabular form. Finally, the ADM series solutions so obtained are validated with numerical solutions in the literature. The current problem considered is relevant to food processing, crystal growth, fiber and wire coating, friction reduction in the oil industry, flow tracers, production of glass fibers, and many other areas.

2. Mathematical Analysis of the Problem

The 3D flow of steady, incompressible, and electrically conducting non-Newtonian Eyring–Powell fluid past a linearly varying stretching sheet with dispersed nanoparticles is investigated in the present problem. The Cartesian coordinates are chosen with the origin “O” and the sheet is placed along the plane z = 0 where the flow occurs toward the region z > 0. Keeping the origin as fixed, the sheet velocity along the x-direction is \( u_\infty(x) = ax \) and toward the y-direction is \( V_\infty(x) = by \). Here, a and b are positive constants, as shown in Fig. 1. The sheet surface temperature and concentration of nanofluids are \( T_1 \) and \( C_\infty \), respectively, and \( T_\infty \) and \( C_\infty \) represent ambient fluid temperature and concentration, respectively. The magnetic Reynolds number is assumed to be small in comparison with the imposed external magnetic field applied to the flow. It is also assumed that the Hall current effect is neglected.

Furthermore, in the Eyring–Powell fluid model, the Cauchy stress tensor \( T \) can be given as

\[
T = -p I + \tau,
\]

\[
\nabla \cdot \tau = -\nabla p + \nabla \cdot (\eta \nabla \tau) + \sigma (J \times B).
\]

Here, \( p \) is the pressure, \( l \) is the identity tensor, \( \sigma \) is the electrical conductivity of the fluid, and \( \eta \) is extra stress tensor of the Eyring–Powell fluid model and is defined as

\[
\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + (1/\beta) \sinh^{-1} \left[ \left( 1/\gamma \right) \left( \frac{\partial u_i}{\partial x_j} \right) \right],
\]

where \( \mu \) is the viscosity coefficient, and \( \beta \) and \( \gamma \) are characteristics of the Eyring–Powell fluid such that

\[
\sinh^{-1} \left( \frac{1}{\gamma} \frac{\partial u_i}{\partial x_j} \right) \approx \frac{1}{6} \frac{\partial u_i}{\partial x_j} \quad \text{and} \quad \frac{1}{\gamma} \frac{\partial u_i}{\partial x_j} < 1.
\]

Under the above assumptions, the equations of conservation of mass, momentum, energy, and nanoparticle volume fraction for Eyring–Powell nanofluid are given as (Gireesha et al., 2015; Mahanthesh, Gireesha, & Gorla, 2017)

\[
\frac{\partial u_i}{\partial x_j} + \frac{\partial v_i}{\partial y} + \frac{\partial w_i}{\partial z} = 0.
\]
for the flow problem are
\[ u = U_w(x) + K_1 \frac{∂u}{∂z}, \quad v = V_w(y) + K_2 \frac{∂v}{∂z}, \quad w = 0, \]
\[ -k \frac{∂T}{∂z} = h_l(T - T_i), \quad \frac{∂C}{∂y} + D_T \frac{∂T}{∂z} = 0. \]

at \( z = 0, \ u = 0, \ v = 0, \ T \rightarrow T_0, \ C \rightarrow C_0 \) as \( z \rightarrow \infty \). (10)

Here, \( h_l \) is the heat transfer coefficient. Now with an introduction of the following similarity transformations (Chamkha & Khaled, 2000), the partial differential equations are converted to ODEs:

\[ u = \alpha f'(η), \quad v = β g'(η), \quad w = -\sqrt{\text{Re}_f}(f(η) + g(η)), \]
\[ θ(η) = \frac{T - T_0}{T_r - T_0}, \quad φ(η) = \frac{C - C_0}{C_r - C_0}, \quad η = \frac{L}{\sqrt{\text{Re}_f} \, z}. \]

where prime (‘) represents the differentiation with respect to the independent similarity variable \( η \). Upon substituting the above similarity variables in equations (4) to (6), (8), and (9), the resultant set of self-similar nonlinear coupled ODEs is

\[ (1 + 4 \frac{1}{3} \, R) \frac{θ'''}{θ} + Pr(f(1 - f)θ' + Pr N_0 φ' + Pr N_1 φ^2) \]
\[ + A_1 f' + B_1 \theta + E c_r Pr \left((f')^2 + M(f)^2\right) \]
\[ + E c_r Pr \left((g')^2 + M(g)^2\right) = 0. \]
\[ φ'' + Le Pr(f(1 - f)φ' + \frac{N_1}{N_0} φ'') = 0. \]

The corresponding boundary conditions will take the following form:

\[ \text{at } η = 0, f(0) = 0, g(0) = 0, φ(0) = B i (θ(0) - 1). \]
\[ N_0 φ'(0) + N_1 φ''(0) = 0. \]
\[ f'(0) = 1 + λ_1 f''(0) = 1 + λ_2 g''(0). \]
\[ \text{and as } η → \infty, f'(η) → 0, g'(η) → 0, φ''(η) → 0, φ(η) → 0. \]

The relevant boundary conditions (Dhamini, Kameswaran, Sibanda, Motsa, & Mondal, 2019; Nayak, Shaw, Pandey, & Chamkha, 2018; Reddy, Murthy, Chamkha, & Rashad, 2013; Sreedevi, Sudarsana Reddy, & Chamkha, 2018; Umar et al., 2019)
3. Semi-Analytical Solution and Validation of the Results

3.1. Adomian decomposition method

The coupled ODEs (11)–(14) associated with boundary conditions (15) are solved using a semi-analytical technique called the ADM and the mathematical procedure is as follows:

\[
\begin{align*}
    f'' &= \frac{1}{1 + \epsilon} \left((-f + g)^{f'' + f'^2 + \epsilon \delta f f'' + Mf'}\right), \\
    g'' &= \frac{1}{1 + \epsilon} \left((-f + g)^{g'' + g'^2 + \epsilon \delta g g'' + Mg'}\right), \\
    \phi'' &= \frac{3 \pi r}{2 + 4 \beta} \left((-f + g)^{\phi'' - N_{k} \phi' - N_{0} \phi'' - E \epsilon_{k} \left(f^{2'' + Mf^{2''}}\right)}\right), \\
    \phi' &= -Le Pr \left((f + g) \phi' - \frac{N_{k}}{N_{0}} \eta\right). \quad (19)
\end{align*}
\]

Let us introduce \( L_{1} = \frac{d^{2}}{d \lambda d \eta} \) with the inverse operator \( L_{1}^{-1} = \int \int \int \frac{1}{\lambda} d \lambda d \eta \) and \( L_{2} = \frac{d^{2}}{d \eta d \phi} \) with the inverse operator \( L_{2}^{-1} = \int \int \frac{1}{\phi} d \phi d \eta \). Thus, equations (16)–(19) become

\[
\begin{align*}
    f(\eta) &= L_{1}^{-1} \left(\frac{1}{1 + \epsilon} \left((-f + g)^{f'' + f'^2 + \epsilon \delta f f'' + Mf'}\right)\right), \\
    g(\eta) &= L_{1}^{-1} \left(\frac{1}{1 + \epsilon} \left((-f + g)^{g'' + g'^2 + \epsilon \delta g g'' + Mg'}\right)\right), \\
    \phi(\eta) &= L_{2}^{-1} \left(\frac{3 \pi r}{2 + 4 \beta} \left((-f + g)^{\phi'' - N_{k} \phi' - N_{0} \phi'' - E \epsilon_{k} \left(f^{2'' + Mf^{2''}}\right)}\right)\right).
\end{align*}
\]

The unknown functions \( f(\eta), g(\eta), \phi(\eta) \), and \( \phi(\eta) \) can be expressed as an infinite series of the form

\[
\begin{align*}
    f(\eta) &= \sum_{m=0}^{\infty} f_m(\eta), \quad g(\eta) = \sum_{m=0}^{\infty} g_m(\eta), \\
    \phi(\eta) &= \sum_{m=0}^{\infty} \phi_m(\eta), \quad \phi(\eta) = \sum_{m=0}^{\infty} \phi_m(\eta). \quad (24)
\end{align*}
\]

The linear and nonlinear terms of equations (20)–(23) can now be decomposed by an infinite series of polynomials as

\[
\begin{align*}
    f_m &= \sum_{n=0}^{\infty} A_m f_n, \quad g_m &= \sum_{n=0}^{\infty} B_m g_n, \quad \phi_m &= \sum_{n=0}^{\infty} C_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} D_m \phi_n, \quad f_m &= \sum_{n=0}^{\infty} E_m f_n, \\
    f_m &= \sum_{n=0}^{\infty} F_m g_n, \quad g_m &= \sum_{n=0}^{\infty} G_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} H_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} I_m \phi_n, \\
    \phi_m &= \sum_{n=0}^{\infty} J_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} K_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} L_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} M_m \phi_n, \\
    g_m &= \sum_{n=0}^{\infty} N_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} O_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} P_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} Q_m \phi_n, \quad \phi_m &= \sum_{n=0}^{\infty} R_m \phi_n. \quad (25)
\end{align*}
\]

The exact solutions of equations (20)–(23) are as follows:

\[
\begin{align*}
    f(\eta) &= \lim_{m \to \infty} f_m(\eta), \quad g(\eta) = \lim_{m \to \infty} g_m(\eta), \\
    \phi(\eta) &= \lim_{m \to \infty} \phi_m(\eta), \quad \phi(\eta) = \lim_{m \to \infty} \phi_m(\eta). \quad (26)
\end{align*}
\]

Therefore, the right-hand side of equations (20)–(23) can be written as

\[
\begin{align*}
    L_{1}^{-1}(L_{1} f) &= f(\eta) - \eta f'(\eta) - \frac{1}{21} \eta^{2} f''(\eta), \\
    L_{1}^{-1}(L_{1} g) &= g(\eta) - \eta g'(\eta) - \frac{1}{21} \eta^{2} g''(\eta). \quad (27)
\end{align*}
\]

From equation (15), invoke the boundary conditions

\[
\begin{align*}
    f(0) &= 0, \quad f'(0) = p, \quad g(0) = 0, \quad g'(0) = q, \quad \phi(0) = r, \quad \phi'(0) = s.
\end{align*}
\]

The solutions of equations (20)–(23) may therefore be written as

\[
\begin{align*}
    f(\eta) &= (1 + \lambda_{1} \eta) \eta + \frac{1}{21} \eta^{2} p, \\
    g(\eta) &= (1 + \lambda_{2} \eta) \eta + \frac{1}{21} \eta^{2} q, \\
    \phi(\eta) &= \eta \left(-\frac{N_{k}}{N_{0}}\right) + \frac{1}{21} \eta^{2} \phi(0). \quad (31)
\end{align*}
\]

Here, the unknown values of \( p, q, r, \) and \( s \) are to be determined. Utilizing equations (32)–(35), the initial guess solutions and the successive order solutions are expressed as follows:

\[
\begin{align*}
    f_{0}(\eta) &= (1 + \lambda_{1} p) \eta + \frac{1}{21} \eta^{2} p, \quad (36) \\
    g_{0}(\eta) &= (1 + \lambda_{2} q) \eta + \frac{1}{21} \eta^{2} q, \quad (37) \\
    \phi_{0}(\eta) &= \frac{Bi + r}{Bi} r + \eta \eta, \quad (38) \\
    \phi_{0}(\eta) &= \eta \left(-\frac{N_{k}}{N_{0}}\right) + \frac{1}{21} \eta^{2} \phi(0) + s. \quad (39)
\end{align*}
\]

Using \( m = 0 \) and 1 in equations (40)–(43), the solutions of equations (20)–(23) are expressed as follows:

\[
\begin{align*}
    f(\eta) &= \sum_{i=0}^{2} f_{i}(\eta) = f_{0}(\eta) + f_{1}(\eta) + f_{2}(\eta) + O(f_{3}(\eta)) \\
    &= (1 + \lambda_{1} p) \eta + \frac{1}{21} \eta^{2} p + (T_{1} + T_{2}) \eta^{3} + (T_{2} + T_{3}) \eta^{4} \\
    &\quad + (T_{3} + T_{13}) \eta^{5} + T_{15} \eta^{6} + T_{16} \eta^{7} + T_{17} \eta^{8}. \quad (44)
\end{align*}
\]
Table 1: Computational results of all the unknowns using the shooting technique.

| M  | p   | q   | r   | s   | Ec_b | p   | q   | r   | s   |
|----|-----|-----|-----|-----|------|-----|-----|-----|-----|
| 0  | -0.96455 | -0.96456 | -0.30242 | 0.302415 | 0   | -1.10089 | -1.10089 | -0.2073 | 0.207302 |
| 1  | -1.27005 | -1.27005 | -0.29848 | 0.298484 | 0.2 | -1.10089 | -1.10089 | -0.13562 | 0.13562 |
| 2  | -1.94895 | -1.94895 | -0.28822 | 0.288217 | 0.3 | -1.10089 | -1.10089 | -0.09801 | 0.098012 |
| 5  | -5.78107 | -5.78107 | -0.24333 | 0.243333 | 0.5 | -1.10089 | -1.10089 | -0.01876 | 0.018765 |

Table 2: Comparison of $-\theta'(0)$ among numerical and semi-analytical results for $\lambda_1 = 0, \lambda_2 = 0, E_{c_x} = 0$, and $E_{c_y} = 0$.

| Bi  | M   | Pr | Previous results (RK45) (Gireesha et al., 2015) | Present results (ADM) |
|-----|-----|----|-----------------------------------------------|-----------------------|
| 0.3 | 0   | 0.72 | 0.17800                                      | 0.178091             |
|    | 1   | 1.5 | 0.34900                                      | 0.349119             |

\[
g(q) = \sum_{i=0}^{2} g_{i}(q) = g_{0}(q) + g_{1}(q) + g_{2}(q) + O(g_{3}(q))
\]
\[
g(q) = \frac{1}{2} \left( a^{2} + b^{2} \right) + \frac{1}{2} \left( c^{2} + d^{2} \right) + \frac{1}{2} \left( e^{2} + f^{2} \right) + \frac{1}{2} \left( g^{2} + h^{2} \right)
\]
\[
\theta(q) = \sum_{i=0}^{2} \theta_{i}(q) = \theta_{0}(q) + \theta_{1}(q) + \theta_{2}(q) + O(\theta_{3}(q))
\]
\[
\eta(q) = \frac{B_{i} + r}{B_{i}} + r q + T_{i} q^{2} + (T_{i} + T_{23}) q^{3} + (T_{i} + T_{24}) q^{4} + (T_{25}) q^{5} + (T_{26}) q^{6} + T_{27} q^{7}.
\]
\[
C(q) = \sum_{i=0}^{2} C_{i}(q) = C_{0}(q) + C_{1}(q) + C_{2}(q) + O(C_{3}(q))
\]
\[
C(q) = \eta \left( -\frac{N}{N_{0}} r \right) + s + T_{28} q^{2} + (T_{29} + T_{30}) q^{3} + (T_{11} + T_{39}) q^{4} + (T_{31}) q^{5} + T_{32} q^{6}.
\]
Table 3: Comparison of $-\theta'(0)$ and $-\phi'(0)$ among numerical and semi-analytical results for $Pr = 3$, $\lambda_1 = 0$, $\lambda_2 = 0$, $A_1 = 0$, and $B_1 = 0$.

| $M$ | $E_{cx}$ | $E_{cy}$ | Previous results (RKF45) | Present results (ADM) |
|-----|---------|---------|--------------------------|-----------------------|
|     |         |         | $Re_{x}^{-1/2} Nu$ | $Re_{x}^{-1/2} Sh$ | $Re_{x}^{-1/2} Nu$ | $Re_{x}^{-1/2} Sh$ |
| 0.5 | 0.3     | 0.2     | 0.278471 | 0.54910  | 0.2784723 | 0.549136 |
| 1.0 | 0.6     | 0.3     | 0.152099 | 0.55200  | 0.1520912 | 0.552189 |

Here, the unknowns $p$, $q$, $r$, and $s$ are obtained using the shooting technique for various characterizing parameters and presented in Table 1. The semi-analytical ADM results obtained through equations (44)–(47) are validated with the numerical results obtained with the RKF45 method integrated with the shooting technique, which are tabulated in Tables 2 and 3. In the absence of uniform source/sink, velocity slip conditions, and identical concentration conditions, computed results are in good agreement with the results of Gireesha et al. (2015), which are presented in Table 2. Furthermore, in the absence of nonuniform heat source/sink and slip with uniform concentration conditions, the computed results are in agreement with the results of Mahanthesh et al. (2017), which are presented in Table 3.

4. Results and Discussion

Meticulous mathematical calculations have been accomplished to analyze the effect of nonuniform heat source/sink, and viscous and Joule dissipation on 3D MHD radiating Eyring–Powell nanofluid current over an elongating sheet under convective circumstances. The prevailing coupled nonlinear boundary layer equations are rendered into a system of coupled nonlinear ODEs, which are well posed. The dimensionless boundary value problem is then solved analytically through the ADM. Graphical dispersions of the impact of magnetic field ($M$), parameter $\varepsilon$, slip parameter $\lambda_1$, slip parameter $\lambda_2$, heat source/sink parameters ($A_1$, $B_2$), Eckert numbers ($E_{cx}$ and $E_{cy}$), Lewis number ($Le$), Biot number ($Bi$), thermophoresis parameter ($N_t$), and Brownian motion parameter ($N_b$) on momentum, energy, and concentration contours are exhibited in Figs 2–27. The mathematical results are calculated for the above physical factors by setting $\lambda_1 = 0.1$, $\lambda_2 = 0.1$, $A_1 = 0.2$, $A_2 = 0.1$, $\varepsilon = 0.5$, $M = 1$, $Pr = 3.2$, $N_t = 0.5$, $N_b = 0.5$, $Le = 2$, $E_{cx} = 0.2$, $E_{cy} = 0.2$, $R = 0.5$, $\delta_1 = 0.1$, $\delta_2 = 0.1$, and $Bi = 0.4$. Moreover, the CPU took 3.26 s to calculate the velocity shapes, 3.91 s to compute the temperature outlines, and
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Figure 5: Impact of $M$ on $\phi$.

Figure 6: Impact of $\epsilon$ on $f'$.

Figure 7: Impact of $\epsilon$ on $g'$.

Figure 8: Impact of $\epsilon$ on $\theta$.

Figure 9: Impact of $\epsilon$ on $\phi$.

Figure 10: Impact of $\lambda_1$ on $f'$. 
Figure 11: Impact of $\lambda_1$ on $\theta$.

Figure 12: Impact of $\lambda_1$ on $\phi$.

Figure 13: Impact of $\lambda_2$ on $g'$.

Figure 14: Impact of $\lambda_2$ on $\theta$.

Figure 15: Impact of $\lambda_2$ on $\phi$.

Figure 16: Impact of $A_1$ on $\theta$. 
Figures 2–5 show velocity ($f'$, $g'$), temperature, and concentration ($\theta$, $\phi$) contours for the magnetic field (M). The influence of M on conducting fluid produces resistive force called a Lorentz force. Due to this, $f'$ and $g'$ decrease and consequently $\theta$ and $\phi$ increase. It is interesting to mark that, due to high magnetic intensity, it reduces the solutal concentration profile far from the sheet. The influence of the Eyring–Powell parameter ($\varepsilon$) on $f'$, $g'$, $\theta$, and $\phi$ distributions is portrayed in Figs 6–9. Figures 6 and 7 show that on improving values dispersals near the boundary layer diminish, while the opposite behavior is observed in Figs 8 and 9 for $\theta$ and $\phi$ values. Figures 10 and 13 show the profiles for slip arguments $\lambda_1$ and $\lambda_2$, respectively. For increasing values of $\lambda_1$ and $\lambda_2$, the $f'$ and $g'$ distributions decrease due to the fact that the Eyring–Powell fluid experienced the slip at sheet surface. Figures 11 and 14, and 12 and 15 depicts the temperature and concentration profiles for $\lambda_1$ and $\lambda_2$, respectively. These figures depict that profiles decrease near the surface and show...
the reverse effect for $1 \leq \eta \leq 1.5$, and then reach asymptotically to zero at the sufficiently large boundary conditions. Figures 16 and 17 illustrate the $\theta$ profiles for $A_t$ and $B_t$ values. From these figures, it is evident that the temperature profiles increase with an increase in $A_t$ and $B_t$ values.

Figures 18 and 20 show temperature distributions for different values of Eckert number ($E_{cx}$, $E_{cy}$) along the $x$ and $y$ directions. These figures reveal that the $\phi$ contours in the thermal boundary layer increase with improving $E_{cx}$ and $E_{cy}$. However, $\phi$ sketches decrease near the surface of the sheet in the range $0.5 \leq \eta \leq 0.6$ and then $\phi$ distributions are found to increase, as shown in Figs 19 and 21. The concentration profiles near the surface of the wall are increased for $Le$, and then they immediately show reverse effects and satisfy the far-field boundary conditions, as exemplified in Fig. 22. Figures 23 and 24 illustrate the $\theta$ and $\phi$ contours for $Bi = 0, 0.2, 0.4, 0.6$. In Fig. 23, shapes start with surface boundary values and increase near the surface and then diminish in the range $1 \leq \eta \leq 8$, whereas in Fig. 24 distributions are increased along with $Bi$ values. In Fig. 25, for $N_t = 0.1, 0.2, 0.3, 0.4$, the $\theta$ profiles are increased, whereas in Figs 26 and 27 the $\phi$ profiles are plotted for $N_t$ and $N_b$, respec-
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Figure 27: Impact of \( N_b \) on \( \phi \).

Figure 26 reveals that contours decrease at the sheet surface and then increase for \( \eta \geq 0 \). However, the opposite trend is observed in Fig. 27.

In Table 4, the values of local Nusselt number \( (Re^{1/2}_x Nu) \) and local skin friction values \( (Re^{1/2}_x C_f) \) are tabulated for different parameters. Table 4 reveals that \( Re^{1/2}_x Nu \) decreases for \( Ec_y \), \( A_1 \), \( B_1 \), \( N_t \), and \( N_b \), while the opposite trend is recorded for \( Bi \) and \( R \). However, the magnitude of \( Re^{1/2}_x C_f \) values increased for \( Bi \) and \( N_t \), while for an increase in \( Ec_x \), \( Ec_y \), \( A_1 \), \( B_1 \), \( R \), and \( N_b \), the magnitude of \( Re^{1/2}_x Sh \) is diminished. However, for increasing values of \( Le \), the values of \( Re^{1/2}_x Nu \) increased and then decreased for large values of \( Le \), whereas the opposite behavior is observed in case of \( Re^{1/2}_x C_f \).

5. Conclusions

The influence of nonuniform heat source/sink, and viscous and Joule dissipation on 3D MHD radiating Eyring–Powell nanofluid flow over an elongating sheet subject to velocity slip, convective temperature, and zero mass flux boundary conditions is explored numerically. The prevailing coupled nonlinear boundary layer equations are rendered into a system of coupled nonlinear ODEs by exploiting the similarity transformations. The well-posed, dimensionless boundary layer balances are then solved analytically with the semi-analytical ADM. For the corroboration of the current outcomes, an assessment is made using former outcomes in definite cases and it is found that both the results agree with each other. The potential key inferences are summarized as follows:

- Using the graphical and numerical explorations, the effect of proficient physical quantities on flow characteristics is analyzed to ascertain the strength of the ADM scheme.
- Velocity contours decline for growing values of magnetic field parameter and slip parameters, while the opposite behavior is noticed for Eyring–Powell fluid parameter. Powell–Eyring nanofluid heat rises for the magnetic field, nonuniform heat source/sink, Eckert number, Biot number, and thermophoresis parameter, whereas it is reduced for rising slip parameters and Eyring–Powell fluid parameter. Fluid concentration distributions diminish for Lewis number, Brownian motion parameter, and Eyring–Powell fluid parameter. However, concentration profiles decrease near the surface and then increase away.

### Table 4: Computation of \(-f''(0)\) and \(-\theta'(0)\) for different parameter values.

| \( Ec_x \) | \( Ec_y \) | \( A_1 \) | \( B_1 \) | \( Bi \) | \( R \) | \( Le \) | \( N_t \) | \( N_b \) | \( Re^{1/2}_x C_f \) | \( Re^{1/2}_x Nu \) |
|-----------|-----------|-------|-------|------|-----|------|------|------|----------------|----------------|
| 0.2       | 0.2       | 0     | 0     | 0.4  | 0.5 | 2    | 0.1  | 0.1  | 0.17472       | 0.295695       |
| 0.3       |           |       |       |      |     |      |      |      | 0.14731       | 0.24552        |
| 0.5       |           |       |       |      |     |      |      |      | 0.08666       | 0.144431       |
| 0.2       | 0.3       | 0     | 0     | 0.4  | 0.5 | 2    | 0.1  | 0.1  | 0.14731       | 0.24552        |
| 0.5       |           |       |       |      |     |      |      |      | 0.08666       | 0.144431       |
| 0.6       |           |       |       |      |     |      |      |      | 0.05611       | 0.093513       |
| 0.2       | −0.1      | 0     | 0     | −0.1 | 0   | 0.1  | 0    | 0.1  | 0.18480       | 0.308006       |
| 0.1       |           |       |       |      |     |      |      |      | 0.17499       | 0.291653       |
| 0.1       | −0.1      | 0     | 0     | −0.1 | 0   | 0.1  | 0    | 0.1  | 0.17003       | 0.283377       |
| 0.1       | 0.1       | 0     | 0     | 0.2  | 1   | 2    | 2    | 2    | 0.16402       | 0.273374       |
| 0.1       | 0.2       | 0     | 0     | 0.2  | 1   | 2    | 2    | 2    | 0.16403       | 0.382743       |
| 0.3       |           |       |       |      |     |      |      |      | 0.13139       | 0.218987       |
| 0.5       |           |       |       |      |     |      |      |      | 0.19236       | 0.320596       |
| 0.4       | 0.4       | 0.3   | 0.3   | 0.4  | 1   | 2    | 2    | 2    | 0.16403       | 0.382743       |
|           |           | 0.5   | 0.5   | 0.4  | 1   | 2    | 2    | 2    | 0.16403       | 0.382743       |
|           |           | 0.6   | 0.6   | 0.4  | 1   | 2    | 2    | 2    | 0.16344       | 0.381358       |
|           |           |       |       |      |     |      |      |      | 0.16396       | 0.382566       |
|           |           |       |       |      |     |      |      |      | 0.16403       | 0.382743       |
|           |           |       |       |      |     |      |      |      | 0.16344       | 0.381358       |
| 2         | 0.2       | 0.4   | 0.4   | 0.4  | 1   | 2    | 2    | 2    | 0.32955       | 0.384478       |
| 0.6       | 0.6       | 0.4   | 0.4   | 0.4  | 1   | 2    | 2    | 2    | 0.63685       | 0.371498       |
| 0.1       | 0.1       | 0.4   | 0.4   | 0.4  | 1   | 2    | 2    | 2    | 0.08167       | 0.381143       |
| 0.6       | 0.6       | 0.4   | 0.4   | 0.4  | 1   | 2    | 2    | 2    | 0.02720       | 0.380833       |
from the boundary layer, reaching asymptotically to far-field boundary condition.

- The magnitude of local skin friction values increased for Biot number and thermophoresis parameters, while for an increase in Eckert number, radiation, heat source/sink, and Brownian motion parameters, the magnitude of local skin friction is decelerated. However, for increasing values of Lewis number, the values of local Nusselt number increased and then decreased for large values of Lewis number, whereas the opposite behavior is observed in case of local skin friction at the surface.

- The values of local Nusselt number decrease for Eckert number, heat source/sink, thermophoresis, and Brownian motion parameters, while the opposite trend is recorded for Biot number and radiation parameter.

In the future, one may explore the generalized Buongiorno model with Corcione’s model (see Wakif, Boulahia, Ali, Eid, & Sehaqui, 2018; Wakif, Boulahia, Mishra, Rashidi, & Sehaqui, 2018), an improved numerical paradigm such as (Generalized Differential Quadrature Method) GDQM (see Wakif, Qasim, Afridi, Saleem, & Ai-Qarni, 2019; Wakif et al., 2019), and collocation-based SQLM (Spectral Quasi Linearization Method) (see Wakif, Boulahia, & Sehaqui, 2017) for the superior numerical treatment of the current fluidic model.

Conflicts of Interest Statement

Authors declare that they have no conflicts of interest to disclose.

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