ABSTRACT
The motive of this paper is to explore the influence of unsteady flow near a stagnation-point comprising Eyring-Powell nanoliquid over a convectively-heated stretched surface. The highly non-linear PDEs are transmuted into ODEs through similarity transformation before being settled numerically via the shooting technique. The numerical outcomes of prominent parameters are examined by a graphical representation and in tabular form. It is investigated that velocity profile shows an increasing behaviour due to the stretched parameter, while the conflicting effect is examined on temperature distribution and concentration of nanoparticle. Finally, we compare our results with the available literature and found this to be in excellent agreement.

1. Introduction
In recent times, much consideration has been paid to study of the viscous flow of non-linear (non-Newtonian) fluid because of its numerous industrial and engineering uses. Plastic polymers, foods, drilling muds, coated sheets, optical fibres and many more are examples of non-Newtonian liquid. The linear relationship between the shear stress and shear strain cannot be described by all rheological properties of non-linear (non-Newtonian) fluid. To overcome these challenges, many non-linear fluid models (Bird et al., 1987; Dorier & Tichy, 1992; Harris, 1977; Rajagopal, 1980; Rajgopal, Na, & Gupta, 1984; Wilkinson, 1970) have been discussed in the past. Powell–Eyring fluid is one of the non-Newtonian fluids. The Powell–Eyring fluid model has a positive favourable position over other non-Newtonian fluids in the sense that it is deduced from the kinetic theory of gases rather than from empirical relations. More significantly, it progresses like viscous fluid at high shear rates (Powell & Eyring, 1944). Malik, Khan, Hussain, and Salahuuddin (2015) investigated MHD mixed convective flow containing Eyring-Powell nanoparticle past a stretched surface. They demonstrated that the fluids were accelerated by expanding the Eyring-Powell parameter as well as mixed convection parameter. Hayat, Asad, Mustafa, and Alsaedi (2014) scrutinised the influence of unsteady Powell-Eyring fluid over an inclined stretched sheet in the presence of thermal radiation with uniform source/sink. Jalil, Asghar, and Imran (2013) studied the flow of Powell-Eyring fluid over a moving porous surface. Shafiq, Nawaz, Hayat, and Alsaedi (2013) investigated MHD axisymmetric flow of an electrically conducting third grade fluid between two permeable discs. Akbar, Abdelhalima, and Khan (2015) explored the influence of MHD flow of Eyring-Powell liquid towards a linear stretched sheet. Rosca and Pop (2014) analysed the flow with heat transfer holding Eyring-Powell liquid from a moving stretched/shrinking sheet. Recently, Khan, Khan, Malik, Salahuuddin, and Shafquatullah (2017) discussed the impact of mixed convective flow involving Eyring-Powell nanoliquid through a plate and cone with chemical reaction.

New challenges of modern technology include the cooling of electronic devices. The present regular heat transport liquid cannot produce the best possible cooling effects in the structures of industries. These situations influenced the advancement of the most present-day innovation, known as nanotechnology. Nanotechnology is discovered during the suspensions of ultrafine nanoparticles (< 100 nm) in oil, water or ethylene glycol. Such suspensions are nominated as nanoliquids. There are several features of chemical and physical aspects where these nanoparticles are tremendously reliable in the manufacturing of several products of engineering industries, involving a system of drug delivery, ceramics, coatings and paints, etc. Choi (1995) initiated a novel
technique to enhance the liquid thermal conductivity by dispersing the tiny particles in liquids which called nanofluids. Buongiorno (2006) noted that the Brownian motion and thermophoresis diffusion of nanoparticles produce massive improvement in the thermal conductivity of the fluid. Makinde and Aziz (2011) explored the influence of convective conditions on flow comprising a nanoliquid towards a stretched sheet. The influences of heat and mass transfer holding nanoliquid along an impulsively stretching surface were investigated by Haroun et al. (2015). Abolbashiari, Freidoonimehr, Nazari, and Rashidi (2015) discussed the influence of entropy generation on flow with heat and mass transfer containing Casson nanofluid past a convectively heated stretched sheet with slip effect. Dalir, Dehsara, and Salman (2015) discussed the influence of entropy generation on magnetic flow along with heat transfer characteristic involving Jeffrey nanofluid from a linearly stretched sheet. The impact of entropy generation on MHD mixed convective flow containing water based carbon nanotubes along an inclined stretching surface was examined by Feroz, Haq, Khan, and Zhang (2017). Recently, Jusoh, Nazar, and Pop (2018) reformed the three-dimensional flow comprising nanoliquid past a stretched/shrinking sheet with partial slip effect and zero mass flux.

Convective heat transfer plays a valuable role due its environmental technology and industrial process containing immersion water heating, solar panel, boiler turbine and many more. Much consideration has been paid to analysis of the characteristics of convective boundary condition. The focus on thermal boundary layer flow under physically applicable convective type boundary conditions is reported by Aziz (2009) and Magyari (2011). Ishak (2010) extended the study of Aziz by considering the consequence of suction/injection. Further, Aziz (2010) inspected hydrodynamic and thermal slip flows with an isoflux thermal boundary condition. The impact of buoyancy flow past a vertical plate with a convective boundary condition was investigated by Makinde and Olanrewaju (2010). Makinde and Aziz (2011) explored the influence of convective boundary condition on boundary layer flow comprising nanoliquid from a stretched surface. They found that the rate of heat transfer reduces due to Brownian motion. Gupta, Kumar, Beg, and Singh (2014) studied the thermal radiation effect on mixed convective flow of micropolar fluid over a shrinking sheet using the variational finite element technique. Swapna, Kumar, Bég, and Singh (2015) investigated hydromagnetic flow of a micropolar fluid in the presence of convective wall heating. Bég, Uddin, Rashidi, and Kavyani (2014) pursued the buoyancy effect on mixed convective flow over a vertical surface with magnetic field and thermal radiation. Recently, Ibrahim (2017) discussed the impact of thermal radiation on the tangent hyperbolic fluid with nanomaterial in the presence of second order slip with convective boundary condition.

The intention of the current article is to analyse the impact of unsteady flow of an Eyring-Powell nanofluid near stagnation point past a convectively heated stretched sheet. A set of suitable transformations showed modifications of the non-linear PDEs to ODEs and these transmuted equations are solved through a shooting technique. The influences of the substantial parameters are demonstrated in detail with the help of tables and graphical results.

2. Description and formulation of the governing equations

We examine an unsteady flow of an incompressible Eyring-Powell model from a convectively heated stretched sheet involving nanofluid as shown in Figure 1 (Zaib, Bhattacharyya, Urooj, & Shafie, 2018). The surface is stretched in two lateral x-direction and y-direction with the velocities, respectively, in the form of $U_w(x, t) = \frac{a}{1 - ct^3}$ for Eyring-Powell, the governing equations can be

$$
\rho_l \frac{\partial u}{\partial x} + \frac{1}{\sigma} \sinh^{-1} \left( \frac{1}{E} \frac{\partial u}{\partial x} \right),
$$

where $\mu$ is the dynamic viscosity of base fluid

$$
\sinh^{-1} \left( \frac{1}{E} \frac{\partial u}{\partial x} \right) \leq \frac{1}{E} \frac{\partial u}{\partial x} \leq \frac{1}{6} \left( \frac{\partial u}{\partial x} \right)^3 \leq \left( \frac{\partial u}{\partial x} \right) \ll 1.
$$

$\sigma$ and $E$ are Eyring-Powell and rheological fluid parameters. Using the boundary layer approximation for Eyring-Powell, the governing equations can be

![Figure 1. Physical model of the problem.](Image)
rendered as
\[
\frac{\partial u}{\partial t} + \frac{u}{x} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \left( \nu + \frac{1}{\rho \sigma E} \right) \frac{\partial^2 u}{\partial y^2} - \frac{1}{2 \rho \sigma E^2} \left( \frac{\partial^2 u}{\partial y^2} \right)^2 + \frac{\partial u}{\partial t} + U_e \frac{\partial u}{\partial x}
\]
Equation (3)

\[
\frac{\partial T}{\partial t} + \frac{u}{x} \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \Lambda D_B \left[ \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} + \left( \frac{D_r}{T_\infty} \right) \left( \frac{T^2}{T^2} \right) \right]
\]
Equation (5)

The relative boundary conditions are
\[
\hat{u} = U_w(x, t), \quad \hat{T} = 0, \quad -k \frac{\partial T}{\partial y} = h(t)(\tilde{T}_f - \tilde{T}),
\]
Equation (6)

We start with the following similarity transformation
\[
\eta = \sqrt{\frac{a}{\nu(1 - ct)}}, \quad \hat{u} = \frac{ax}{1 - ct} f' (\eta), \quad \hat{v} = -\sqrt{\frac{va}{1 - ct}} f'' (\eta),
\]
\[
\theta(\eta) = \frac{T - T_\infty}{T_f - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \quad h(t) = d/\sqrt{1 - ct}.
\]
Equation (7)

In view of relation (8), Equations (4–6) are transmuted to
\[
(1 + \epsilon) \frac{d^2 f}{d \eta^2} + \left( \frac{df}{d \eta} \right)^2 f'' (\eta) \frac{d^2 f}{d \eta^2} + \gamma f'' (\eta) \frac{d^2 f}{d \eta^2} \frac{d f}{d \eta} = \tilde{\lambda} \left( \frac{df}{d \eta} \right)^2 + \tilde{\lambda} A + A^2 = 0
\]
Equation (8)
Hence $s_w''$ is the shear stress at the sheet, $q_w''$ is the heat flux, $q_m''$ is the mass flux of nanoparticle are written as

$$
s_w'' = \left( \mu + \frac{1}{E_s} \right) \frac{\partial u}{\partial y} - \frac{1}{6} \left( \frac{1}{E_s} \frac{\partial u}{\partial y} \right)^3,
$$

$$
q_w'' = -k \frac{\partial T}{\partial y}, \quad q_m'' = -k \frac{\partial C}{\partial y}.
$$

That is

$$
C_r Re_s^{1/2} = (1 + \varepsilon)f''(0) - \frac{6}{3} \theta f''(0) = 0,
$$

$$
Nu_x = -\theta'(0), \quad Sh_x = -\phi'(0),
$$

where $Re_s = (xU_w/\nu)$ is the Reynolds number.

3. Method of solution

The non-linear transmuted Equations (9–11) along relevant boundary condition (12) is solved using a shooting technique. In this technique, we first convert Equations (9–11) into an initial value problem. Then we pick a right finite value of $\eta$, say $\eta_0 (\approx 10)$. First, we transmute the Equations (9–11) which are eased to a first order system by establishing new variables as

$$
f' = p, \quad p' = q,
$$

$$
q' = \left( \frac{p^2 - fq + \lambda \left( \frac{\eta}{2} q + p - A \right) - A^2}{1 + \varepsilon - \omega q^2} \right),
$$

$$
\theta' = r, \quad r' = -Pr rs - Pr r - Pr Ntr^2 + Pr \frac{\eta}{2} \lambda r,
$$

$$
\phi' = s, \quad s' = Sc \left( \frac{\eta}{2} \lambda - f \right) s - \frac{Nt}{Nb} \phi',
$$

with the boundary conditions

$$
f(0) = 0, \quad p(0) = 1, \quad r(0) = -\gamma (1 - \theta(0)), \quad \phi(0) = 1, \quad p(\infty) = A, \quad \theta(\eta_0) = 0, \quad \phi(\eta_0) = 0.
$$

To solve the above system of equations as an initial value problem, we need the values for $q(0)$ i.e. $f''(0)$, $\theta(0)$ and $s(0)$ i.e. $\phi'(0)$ but there is no such value.
given. As an appropriate guess, values for $f''(0)$, $\theta(0)$ and $\phi'(0)$ are suggested and integration is performed. Next, we compare our calculated values for $f'(g)$, $\theta(g)$ and $\phi(g)$ at $g = 1$ through the boundary conditions $f'(\infty) = A$, $\theta(\infty) = 0$ and $\phi(\infty) = 0$, respectively, and regulate the estimated values of $f''(0)$, $\theta(0)$ and $\phi'(0)$ for better approximation. The step size is considered as $\Delta \eta = 0.01$. The procedure is reiterated until we get outcomes correct up to the required accuracy level of $10^{-5}$.

4. Results and discussion

In this paper, the following values are fixed during the computation $Nb = 0.5$, $Nt = 0.5$, $\lambda = 1$, $A = 0.2$, $Pr = 1.0$, $Sc = 1$, $Nb = 0.5$, $\epsilon = 0.3$, and $\delta = 0.3$. The influences of pertinent parameters concerned in the fluid flow problem are argued via tables and graphs. In addition, a comparison of $f''(0)$, $-\theta'(0)$ and $-\phi'(0)$ with available outcomes in limiting cases is elaborated through Tables 1 and 2 and found to be an excellent agreement. Table 3 explores the numerical data of surface drag friction, heat and mass transfer rate with respect to stretching parameter $A$ and fluid parameter $\epsilon$. It is evident from this Table,
that an enhancement in the value of $A$ and $\varepsilon$ reduces $C_{f0}$, with increments in $Nu_{x}Re_{x}^{1/2}$ and $Sh_{x}Re_{x}^{1/2}$ observed.

Figures 2–4 represent the effect of fluid parameter $\varepsilon$ on velocity of liquid, temperature distribution and concentration of nanoparticles. Figure 2 illustrates that fluid velocity elevates due to the rising value of $\varepsilon$. Physically, it can be seen that for larger values of fluid parameter, the viscosity declines and as a result liquid velocity is augmented. However, Figures 3 and 4 portray that the temperature distribution and concentration of nanoparticle tend to decrease due to increasing values of $\varepsilon$.

Fluid velocity, temperature distribution and concentration of nanoparticle for different values of $\varepsilon$ are presented in Figures 5–7, respectively. Figure 5 specifies that the boundary layer thickness is enhanced due to greater values of $A (A > 1)$ and shrinks with declining values of $A (A < 1)$. However, when $A = 1$, no boundary layer structure is observed, which agrees well with the physical behaviour of the flow. Physically, when the stretched velocity is below the free stream velocity, the velocity ratio of free stream to stretched velocity is greater than 1 and consequently a delaying force is moderated, which increases the fluid velocity. From Figures 6 and 7, it can be seen that the temperature distribution and concentration of nanoparticle decrease with the larger values of $\varepsilon$.

Figures 8–10 illustrate the influence of unsteady parameter $\lambda$ on velocity profile, temperature distribution and concentration of nanoparticle. It can be seen from Figure 8 that the liquid velocity and momentum boundary layer decline with greater
values of $\lambda$. Figures 9 and 10 show that the temperature distribution and concentration of nanoparticle significantly escalates due to larger values of $\lambda$. Physically, this shows that more heat and mass is moved from the fluid to the surface and therefore the temperature is enhanced with concentration.

Figures 11 and 12 are constructed to show the influence of $Nb$ on the temperature distribution and concentration of nanoparticle. Figure 11 depicts that the temperature of the liquid shows an increasing trend for enhancing values of Brownian motion. Physically, this is the reason why the irregular motion of fluid molecules enhances Brownian motion, thus producing the movement of nanoparticle away from the surface. In contrast, the opposite trend is detected on concentration of nanoparticle as portrayed in Figure 12. Figure 13 shows that the temperature distribution climbs as the thermophoretic parameter is enhanced. The task of thermophoretic strength at the ambient is that the nanoparticles are being pushed near the warm boundary towards the cold fluid. Therefore, we
expect that the thermal boundary layer will become thicker due to a thermophoresis effect. Figure 14 confirms that the concentration of nanoparticle and concentration boundary thickness grow with larger values of the thermophoretic parameter.

Figure 15 depicts the influence of Biot number $\gamma$ on temperature distribution. Physically, amplification of Biot number $\gamma$ produces a robust outcome which gives clues to a sophisticated temperature profile at the surface. As the surface convection is enhanced, the temperature of fluid at the sheet is enhanced. It is observed from Figure 16 that the thickness of the thermal boundary layer becomes thinner as Prenhances. Physically, a fluid in the presence of larger Pr has a small thermal dispersion compared to viscous dispersion and consequently the coefficient of heat transfer declines and thickness of the thermal boundary diminishes. From Figure 17, we can observe that due to growing values of Scthat communicates to a weak coefficient of Browninan diffusion, guides to small depth of penetration for concentration of nanomaterial. Consequently, the concentration of nanoparticles at the sheet declines with rising Sc.

Figures 18–20 have been prepared to show the impact of $\varepsilon$ on the skin friction coefficient, the Nusselt number and the Sherwood number versus stretching parameter $A$. These outcomes show that the values of skin friction decline due to larger values of $\varepsilon$, whereas the values of the Nusselt number and the Sherwood number are enhanced.

5. Conclusion

Unsteady flow of Eyring-Powell fluid comprising nanomaterial towards a stretched sheet with the convective boundary condition has been analysed. Shooting techniques have been used to solve the transmuted PDEs to ODEs. It is found that velocity of fluid is enhanced due to greater values of the fluid parameter, whereas the temperature distribution and concentration of nanoparticle decrease with enhancing fluid parameter. The Brownian motion $Nb$ and thermophoresis mechanisms $Nt$ escalate the thermal behaviour of the fluid, while the concentration of nanoparticle increases due to $Nt$ and decreases due to $Nb$. Further, both Prandtl number $Pr$ and Schmidt number $Sc$ have similar behaviour effect on temperature and concentration of nanoparticle. Also, the temperature of the fluid shows a decreasing function of $\gamma$. It has been observed from Table 3 that the skin friction coefficient diminishes with increase of fluid parameter $\varepsilon$, while the Nusselt number and Sherwood number show an escalating trend.

Nomenclature

| Symbol | Description |
|--------|-------------|
| $A$    | Free stream velocity |
| $a$, $b$, $c$ | Constants |
| $C_{fr}$ | Skin friction coefficient |
| $C$    | Nanoparticle volume friction |
| $C_w$  | Nanoparticle volume friction at the sheet surface (wall) |
| $C_{\infty}$ | Ambient nanoparticle volume friction |
| $D_B$  | Brownian diffusion coefficient |
| $D_T$  | Thermophoresis diffusion coefficient |
| $f'(\eta)$ | Dimensional velocity |
| $h$    | Convective heat transfer coefficient |
| $k$    | Thermal conductivity |
| $Sc$   | Schmidt number |
| $Nb$   | Brownian motion parameter |
| $Nt$   | Thermophoresis parameter |
| $Nu_A$ | Nusselt number |
| $Pr$   | Prandtl number |
| $q_{\infty}$ | Wall heat flux |
| $q_m$  | Mass flux |
| $Re_x$ | Local Reynolds number |
| $Sh_x$ | Sherwood number |
| $T$    | Local fluid temperature |
| $T_f$  | Temperature of the hot fluid |
| $T_w$  | Sheet surface (wall) temperature |
| $T_\infty$ | Ambient temperature |
| $u$, $v$ | Velocity components |
| $x, y$ | Coordinates along the sheet |

Greek Symbol

| Symbol | Description |
|--------|-------------|
| $\alpha$ | Thermal diffusivity |
| $\delta$, $\varepsilon$ | Fluid constants |
| $\theta$ | Dimensionless temperature |
| $\phi$ | Dimensionless nanoparticle volume friction |
| $\gamma$ | Biot number |
| $\eta$ | Similarity variable |
| $\mu$ | Absolute viscosity |
| $\nu$ | Kinematic viscosity |
| $\rho$ | Density |
| $\rho_p$ | Nanoparticle mass density |
| $(\rho C)_f$ | Heat capacity of fluid |
| $(\rho C)_p$ | Effective heat capacity |
| $\Psi$ | Stream function |
| $\Lambda$ | Parameter defined by $(\rho C)_p/(\rho C)_f$ |
Disclosure statement

No potential conflict of interest was reported by the authors.

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