
*Research article***Thermocapillary convection of chemically reacting hybrid nanofluid with catalytic, cross diffusion, and activation energy in a porous medium application to crystal growth****Turki J. Alqurashi***

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Abstract: Chemical and food processes rely on thermocapillary-induced convection in the presence of catalytic and cross diffusion (Soret/Dufour effect). This study's goal was to investigate the effects of thermocapillary-induced convection of chemically reacting hybridized nanofluids over a surface in a non-Darcy porous domain with viscous dissipation, activation energy, and cross diffusion. The mathematical model for the Marangoni fluid flow, heat, and mass transport was derived based on the Navier–Stokes equation. The governing mathematical model, derived through a set of partial differential equations, was changed into a set of ordinary differential equations using suitable transformations. The bvp4c function (MATLAB software) was used to find the model's solutions. Skin friction, amount of mass, and heat transport were calculated. Entropy generation was also examined. The results for different combinations of relevant parameters are shown in graphical form. It was found that the Marangoni number enhances thermal transport and suppresses solutal mixing. It was observed that the velocity and temperature increase with increased Marangoni ratio parameter (r); the opposite occurs with concentration. Thermal and solute boundary layer thicknesses increase with increased values of Darcy number. Concentration also increases with increased Fr , with no considerable change in temperature. The outcomes of the thermocapillary convection effect can be applied in crystal growth in microgravity, materials processing, and microfluidic thermal management.

Keywords: Marangoni convection; chemical reaction; hybrid nanofluid; Soret/Dufour effect; activation energy; entropy generation; porous matrix

1. Introduction

Since heat transfer is vital to several areas, enhancing it has been the focus of significant research work. Heat sinks, electronic apparatuses, and diverse mechanical units can all gain from the thermal movement of conventional liquids, such as water, ethylene glycol, and oil. However, the thermal conduction of these basic fluids remains low, despite attempts by several researchers to boost heat conduction by adding a specific kind of nanoparticles, forming new fluids, termed nanofluids. Previous studies examined thermophoretic and thermocapillary effects [1,2], and entropy generation, activation energy, and cross-diffusion in nanofluid flows [3,4]. Numerous modern applications involve the flow and heat transfer of different liquids across an extended surface. In exothermic processes, particle separation, blood flow properties, and movement via dense matrix settling, the use of liquid movement through expanding surfaces is vital. Recently, some energy-efficient techniques have been suggested for power usage reduction. Microchannels, fuel cell gas turbines, curved conduits, heat exchangers, reactors, natural circulation, and evaporative cooling mechanisms all gain from entropy generation [5,6].

The flow driven by surface-related motion is termed Marangoni or thermocapillary-induced convection [7,8]. Thermocapillary convection has been applied in crystal growth in microgravity, materials processing, and microfluidic thermal management. Park et al. [9] explored the management of concentration-driven vertical Marangoni flows and introduced a capillary tube comprising a volatile liquid adjacent to the water droplet to examine the vapor-driven (solutal) Marangoni movement. They formulated a theoretical framework relying on scaling examinations to forecast the internal stream speed and oscillation rate, which showed good correspondence with the observed results. Agrawal et al. [10] evaluated the influence of thermal emission and warmth on the magnetic Marangoni flow of nanoparticles and discovered an increasing tendency in the temperature profile with additional variables. Ganesh et al. examined the flow of water and ethylene glycol across a magneto-Marangoni nano-boundary layer [11]. Results showed how water and ethylene glycol flow is impacted by the interaction of the magnetic factor with other relevant physical factors; also, the ethylene glycol nano-momentum boundary layer is deeper than the water nano-momentum layer. Mahanthesh et al. [12] revealed the effects of heat source and coupled diffusion through research on Marangoni convection in Casson fluid movement. The effects of induced magnetic and electric fields were ignored. They found that the thickness of the thermal layer is increased by erratic heat source actions.

Khan et al. [13] examined the Marangoni convective flow of a hybrid nanoliquid over a plate in a porous medium, with the Darcy-Forchheimer model replicating the porous media and incorporating the activation energy and viscous dissipation. They found that temperature and velocity gradients improve with increasing nanoparticle volume fractions. Al-Mdallal et al. [14] studied the radiative Marangoni effects of hybridized nanofluid flow in a non-straight magnetic field. They considered a continuous, laminar, incompressible, nonlinear boundary layer current at the interface of different hybrid nanofluids based on water. They found that the temperature distribution reduces as the Prandtl number and mass transfer parameter values rise. A numerical simulation of artificial Marangoni flow-driven micro-swimmers was conducted by Stricker [15],

being comprised of microdroplets that flowed in accordance with the Marangoni flow and were propelled by Belousov-Zhabotinsky (BZ) reactions. Burmasheva et al. [16] investigated how the Soret effect influenced Marangoni (shear) convective movements of inhomogeneous fluids by taking a mixture of two components and assuming that the mixture was in a zero-gravity setting. Alhendala et al. [17] used a volume of fluid (VOF) simulation to study Marangoni flow and concluded that, in the absence of gravity, VOF is a dependable numerical method for simulating high density gas-liquid two-phase flows.

In some fluid mixtures, a concentration gradient can produce a temperature alteration that is not negligible (i.e., Dufour effect) [18]. On the other hand, the temperature gradient in a fluid mixture causes a mass flux (i.e., Soret effect) [19]. These effects have relevance in fields like hydrology, petrology, and isotope separation. They have also been examined in double-diffusive and thin-needle nanofluid flows [20,21], and in flows over stretching cylinders [22,23]. Through the use of Marangoni convection, Jawad et al. [24] investigated the Dufour/Soret effects (SDE) on a magnetohydrodynamic (MHD) radiative boundary layer stream in a Darcy-Forchheimer porous domain. They took into account the flow system's electrical conductivity, viscosity, and incompressibility. They discovered that an increase in the Dufour number with a decrease in the Soret number causes an increase in thermal distributions while decreasing concentration distributions. As a result of Dufour and Soret effects, chemical reactions in MHD peristaltic motion were examined by Hayat et al. [25]. The magneto-convective stream of an incompressible couple-stress liquid in an inclined asymmetric-type channel was considered. They discovered that the fluid velocity is reduced at the channel's center line by the Hartman number and coupling stress fluid parameter. In an enclosure, coupled temperature, moisture, and entropy creation were explored by Hua and Mei [26]. They found that, while a stronger Soret effect increases moisture transportation by more than 100%, the Soret number has no discernible effect on the amount of heat transport, as shown by a meager 5% fall in average Nusselt number with growing Soret number. Shehzad et al. [27] investigated fluid flow dynamics using Soret/Dufour effects. They considered an incompressible Newtonian fluid flow that results from the rotation of an endlessly permeable disk. They found that Dufour and (thermal) Biot numbers have comparable effects on the temperature field. When both parameters increase, temperature profiles improve.

Mahabaleshwar et al. [28] explored the mixed magneto-radiative stream of non-Newtonian (Walters' liquid B and second-grade fluid) liquids and thermal transfer when affected by Dufour/Soret mechanisms, in a tilted magnetic field in a porous sheet. They discovered that an increase in the magnetic field's tilting angle results in thicker velocity, concentration, and temperature boundary layers. The effects of Hall current and Soret/Dufour number on the MHD natural convective current over a rotating vertical plate in a uniform porous medium were inspected by Kumar et al. [29]. They found that increasing the Hall current parameter tends to raise the secondary velocity across the boundary layer region. Yinusa et al. [30] investigated 3D transient squeeze flow and heat transfer between two parallel plates with associated Dufour and Soret impacts. They found that an increase in Dufour number results in a decrease in Soret number and an increase in the temperature profile. The impact of the double diffusion Christov-Cattaneo heat flux model on the 3D MHD rotational viscous flow of the Oldroyd-B nanofluid was investigated by Ali et al. [31]. They found that the Nusselt number decreases with increasing levels of Brownian, thermophoresis, magnetic, spinning, and Dufour number; however, the Nusselt number shows the opposite tendency as the Prandtl number.

Maiti et al. [32] investigated a fractional order model in a magnetic and vibrational environment for the thermo-chemical flow of blood with Soret/Dufour effects. They simulated blood flow via an artery under the influence of thermal radiation and a magnetic field using a straight circular tube that vibrates periodically. They found that the chemical reaction and thermal radiation parameters affected the heat and mass transfer of blood through a straight artery with a porous media. Shojaei et al. [33] conducted an hydrothermal study of non-Newtonian second-grade liquid stream with SDE effects. They discovered an inverse relationship between simultaneous fluctuations in Dufour/Soret number and the rate of mass and heat transfer. In this scenario, raising the Dufour number while lowering the Soret number results in an increase in mass transfer rate, as well as a decrease in heat transfer rate. A power-law-type fluid and magnetic field were explored by Hussain et al. [34] in relation to mixed diffusion convection with Dufour and Soret effects. They discovered that the increase in convective heat and mass transport is correlated with increases in the power law index, Darcy number, and Dufour number. Salleh et al. [35] inspected the outcome of SDE on forced convection flow over a thin needle while taking a Buongiorno's nanofluid model into consideration. By increasing the Soret value or lowering the Dufour value, the amount of heat and mass transmission in a particular area can be increased. Bekezhanova and Goncharovac investigated the effects of Dufour/Soret number on the characteristics of evaporating liquid flows [36]. They suggested using solid, impermeable walls composed of a volatile liquid and a gas-vapor mixture to fill an endless tube. They found that for the method to represent evaporative convection to be effective, the system's divergence from the thermodynamic equilibrium state must be negligible.

The mixed convection current of a Carreau nanoliquid under the influence of Soret and Dufour numbers was studied by Sardar et al. [37]. They considered the issue of SDE on steady 2D Carreau nanofluid flows in mixed convection boundary layers across wedges. They discovered that an increase in the thermophoresis parameter (N_t) and the Soret number increased the boundary layer thickness of nanoparticle volume fractions. By using the finite difference method, Khan et al. [38] examined the irreversibility of Darcy-Forchheimer flow under the influence of SDE, considering the unsteady magnetohydrodynamic flow of an incompressible viscous fluid. They discovered that the porosity variable has a reverse trend for velocity and the skin friction coefficient. For MHD convective flow with Soret and Dufour numbers, Aly [39] discovered that the intensity and concentration distributions of flow are reduced as the Soret number declines and the Dufour number increases.

The thermal and stream exchange of several fluids over an expanding or moving surface is a common feature of many modern innovations and applications. Thermocapillary-induced convection of hybrid nanoliquids over a stretchable surface with activation energy, catalytic, and cross diffusion effects has not been studied. Therefore, in the current work, the activation energy, catalytic and cross diffusion effects, and viscous dissipation occur in a thermocapillary-induced convective stream of hybrid nanoliquids over a movable surface encircled by porous media. Additionally, we compute the Bejan number and system entropy production.

2. Mathematical model and numerical methodology

2.1. Physical model

The steady, laminar, incompressible, hybrid nanoliquid Marangoni convective flow and heat transfer over a surface is inspected as shown in Figure 1. The x-axis is taken along the surface, and

the y -axis in the vertical direction. (u, v) are velocities in (x, y) directions. The surface is embedded in an isotropic porous medium, which is modeled by the extended Darcy-Forchheimer model. A hybridized nanofluid contains a base fluid and two types of nanoparticles. Here, we have water (H_2O) as the base fluid and manganese-zinc ferrite ($MnZnFe_2O_4$) and nickel-zinc ferrite ($NiZnFe_2O_4$) as the nanoparticles. The nanoparticles are in thermal equilibrium with the local fluid. The effects of activation energy, viscous dissipation, (internal) heat generation, chemical reaction, and Soret/Dufour effects are analyzed. The entropy generation and Bejan number in the current flow system are computed and thoroughly analyzed.

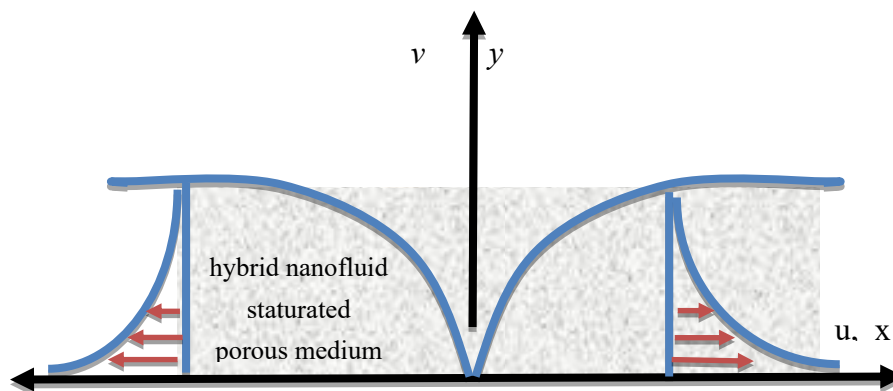


Figure 1. Physical model.

2.2. Mathematical formulation

Using the Boussinesq approximation, the mathematical model for the fluid flow, heat, and mass transport is derived based on the Navier-Stokes equation as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (2.1)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} - \frac{\mu_{hnf}}{(\rho)_{hnf}} \left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\nu_{hnf}}{K^*} \right) u + \frac{F}{\sqrt{k}} u^2 = 0, \quad (2.2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k_{hnf}}{(\rho c_p)_{hnf}} \frac{\partial^2 T}{\partial y^2} + \frac{\mu_{hnf}}{(\rho c_p)_{hnf}} \left(\frac{\partial u}{\partial y} \right)^2 + \frac{\partial^2 C}{\partial y^2} \left(\frac{D_e k_T}{c_s c_p} \right) + \frac{Q}{(\rho c_p)_{hnf}} (T - T_\infty), \quad (2.3)$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - k_o^2 (C - C_\infty) \left(\frac{T}{T_\infty} \right)^{n^*} \exp \left[\frac{-E_a}{kT} \right] + \frac{\partial^2 T}{\partial y^2} \left(\frac{D_e k_T}{T_m} \right). \quad (2.4)$$

The boundary conditions are derived according to the physical model of the geometry proposed in the study. The values at surface are

$$\mu_{hnf} \frac{\partial u}{\partial y} = \frac{\partial \sigma}{\partial x} = \sigma_0 \left(\gamma_c \frac{\partial C}{\partial x} \Big|_{y=0} + \gamma_T \frac{\partial T}{\partial x} \Big|_{y=0} \right), \quad v = 0, \quad T = (T_0 X^2 + T_\infty) \quad \text{at } y = 0, \\ u \rightarrow 0, \quad T \rightarrow T_\infty, \quad C \rightarrow C_\infty \quad \text{as } y \rightarrow \infty, \quad (2.5)$$

where

$$\sigma = \sigma_0(1 - \gamma_T(T - T_\infty) - \gamma_C(C - C_\infty)), \quad (2.6)$$

$$\gamma_T = \left(-\frac{1}{\sigma_0} \frac{\partial \sigma}{\partial T}\right) \Big|_{T=T_\infty} \text{ and } \gamma_C = \left(-\frac{1}{\sigma_0} \frac{\partial \sigma}{\partial C}\right) \Big|_{C=C_\infty}.$$

Here, C , C_p , D , K^* , k_0^2 , T , k_{hnf} , $(\rho c_p)_{hnf}$, E_a , k , μ_{hnf} , ρ_{hnf} , and σ denote solute concentration, specific heat, mass diffusivity, porous medium permeability, chemical reaction rate, temperature, thermal conductivity, heat capacitance, activation energy coefficient, Boltzmann Constant, dynamic viscosity, density, and surface tension, respectively. The subscripts m, 0, ∞ , and hnf denote the mean, reference condition, ambient values, and hybrid nanoliquid, respectively.

The following transformation is utilized to convert the governing model:

$$u = \frac{v_f}{L} X f'(\xi), \quad v = -\frac{v_f}{L} f(\xi), \quad \theta(\xi) = \frac{T - T_\infty}{T_0 X^2}, \quad \phi(\xi) = \frac{C - C_\infty}{C_0 X^2}, \quad \xi = \frac{y}{L}, \quad X = \frac{x}{L}.$$

Substituting the above in Eqs (2.1)–(2.4), we get the following ODEs:

$$\frac{f'''}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}A_1} - f f'' - (f')^2 - \frac{\beta f'}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}A_1} - F_r (f')^2 = 0, \quad (2.7)$$

$$\frac{A_3}{P_r A_2} \theta'' + \frac{E_c (f')^2}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}A_2} + D_u \phi'' + H_g \theta - 2\theta f' - \theta' f = 0, \quad (2.8)$$

$$\frac{1}{Sc} \phi'' - 2f' \phi - f \phi' - k_1 \phi (1 - \delta \theta)^{n^*} \exp\left[\frac{-E_1}{1 + \delta \theta}\right] + S_r \theta'' = 0. \quad (2.9)$$

The values at boundary in dimensionless form are

$$f(0) = 0, \quad \frac{f''(0)}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}} = -2(1+r),$$

$$\theta(0) = 1, \quad \phi(0) = 1, \quad f'(\infty) \rightarrow 0, \quad \theta(\infty) \rightarrow 0, \quad \phi(\infty) \rightarrow 0. \quad (2.10)$$

2.3. Physical quantities

The drag coefficient and amount of heat/mass transfer along the surface are key factors in the study. Therefore, the skin friction, (local) Nusselt number, and (local) Sherwood number are derived along the surface as follows:

$$C_{fx} = \frac{2}{\rho_f u_w^2} (\mu_{hnf} \frac{\partial u}{\partial y} \Big|_{y=0}), \quad Nu_x = \frac{x}{k_f T_0 X^2} (-k_{hnf} \frac{\partial \theta}{\partial y} \Big|_{y=0}) \text{ and } Sh_x = \frac{x}{C_0 X^2} (-D \frac{\partial \phi}{\partial y} \Big|_{y=0}).$$

The dimensionless form of C_{fx} and Nu_x is

$$C_{fx}(Re^{0.5}) = \frac{f''(0)}{(1-\phi_2)^{2.5}(1-\phi_1)^{2.5}} Nu_x / (Re^{0.5}) = -\left(\frac{k_{hnf}}{k_f}\right) \theta'(0) \text{ and } Sh_x / (Re^{0.5}) = -\phi'(0).$$

2.4. Entropy analysis

The entropy production for the designated flow is derived by irreversibility due to fluid flow,

thermal, and solute processes:

$$S_G = \frac{k_{hnf}}{T_\infty^2} \cdot \left(\frac{\partial T}{\partial y} \right)^2 + \frac{\mu_{hnf}}{T_\infty} \cdot \left(\frac{\partial u}{\partial y} \right)^2 + \frac{R^* D}{T_\infty} \cdot \left(\frac{\partial T}{\partial y} \right) \left(\frac{\partial C}{\partial y} \right) + \frac{R^* D}{C_\infty} \cdot \left(\frac{\partial C}{\partial y} \right)^2. \quad (2.11)$$

The non-dimensional form of entropy generation is

$$N_G = A_3 \delta \theta'^2 + \frac{BrRe}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}} (f'')^2 + L^* \theta' \phi' + L^* \frac{\delta_1}{\delta} \phi'^2. \quad (2.12)$$

The Bejan number (Be) is defined as the proportion of mass and heat transfer irreversibility over total entropy:

$$Be = \frac{A_3 \delta \theta'^2 + L^* \theta' \phi' + L^* \frac{\delta_1}{\delta} \phi'^2}{A_3 \delta \theta'^2 + \frac{BrRe}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}} (f'')^2 + L^* \theta' \phi' + L^* \frac{\delta_1}{\delta} \phi'^2}, \quad (2.13)$$

where

$$\begin{aligned} \frac{\rho_{hnf}}{\rho_f} &= (1-\phi_2) \left[(1-\phi_1) + \phi_1 \frac{\rho_{s1}}{\rho_s} \right] + \phi_2 \frac{\rho_{s2}}{\rho_f}, \\ \mu_{hnf} &= \frac{\mu_f}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}}, \\ \frac{(\rho C_p)_{hnf}}{(\rho C_p)_f} &= (1-\phi_2) \left[(1-\phi_1) + \phi_1 \left(\frac{(\rho C_p)_{s1}}{(\rho C_p)_f} \right) \right] + \phi_2 \frac{(\rho C_p)_{s2}}{(\rho C_p)_f}, \\ A_1 &= (1-\phi_2) \left[(1-\phi_1) + \phi_1 \frac{\rho_{s1}}{\rho_s} \right] + \phi_2 \frac{\rho_{s2}}{\rho_f}, \\ A_2 &= \frac{(\rho C_p)_{hnf}}{(\rho C_p)_f} = (1-\phi_2) \left[(1-\phi_1) + \phi_1 \left(\frac{(\rho C_p)_{s1}}{(\rho C_p)_f} \right) \right] + \phi_2 \frac{(\rho C_p)_{s2}}{(\rho C_p)_f}, \\ A_3 &= \frac{k_{hnf}}{k_f} = \frac{k_{s2} + 2k_{bf} - 2\phi_2(k_{bf} - k_{s2})}{k_{s2} + 2k_{bf} + \phi_2(k_{bf} - k_{s2})}, \\ \frac{k_{bf}}{k_f} &= \frac{k_{s1} + 2k_f - 2\phi_1(k_f - k_{s1})}{k_{s1} + 2k_f + \phi_2(k_f - k_{s1})}. \end{aligned}$$

The thermophysical properties of the nanoparticles and the base fluid are presented in Table 1.

Table 1. Thermo-physical values of nanoparticles and the base liquid.

Materials	Density (ρ)	Specific heat (c_p)	Thermal conductivity (k)
NiZnFe ₂ O ₄	4800.0	710.0	6.30
MnZiFe ₂ O ₄	4700.0	1050.0	3.90
Water (H ₂ O)	997.10	4179.0	0.613

The non-dimensional factors considered in the model above are as follows:

$\beta = \frac{\nu_f L^2}{K^* \nu_f}$ is the inverse Darcy number; $F_r = \frac{C_p}{\sqrt{K^*}}$ is the Forchheimer factor; $Pr = \frac{\nu_f}{\alpha_f}$ is the Prandtl number; $Sc = \frac{\nu_f}{D_f}$ is the Schmidt number; $k_1 = \frac{k_0^2 L^2}{\nu_f}$ denotes the chemical reaction rate; $E_1 = \frac{E_a}{kT_\infty}$

is the activation energy; $\delta = \frac{T_0 X^2}{T_\infty}$ denotes the temperature difference; $Br = \frac{\mu v_f^2}{k T_0 L^2 X^2}$ is the Brinkman number; $L^* = \frac{R^* D C_0}{k_f}$ is the diffusion parameter; $Ec = \frac{v_f^2}{c_p T_0 L^2}$ is the Eckert number; $\delta_1 = \frac{C_0 X^2}{C_\infty}$ is the concentration difference; and $r = \frac{C_0 \gamma C}{T_0 \gamma_r}$ is the Marangoni ratio parameter.

2.5. Numerical method

The governing equations are a system of partial differential equations that are strongly nonlinearly coupled. Finding the closed form solution for this system is very challenging. Using a transformation based on similarity variables, the controlling partial differential equations are converted into a set of ordinary differential equations. The boundary value equations are then solved numerically over a range of pertinent investigation-related factors.

$$f = S_1, \quad f' = S_2, \quad f'' = S_3, \quad f''' = S'_3,$$

$$S'_3 = (1 - \phi_1)^{2.5} (1 - \phi_2)^{2.5} A_1 \left(S_1 S_3 + (S_2)^2 + \frac{\beta z_2}{(1 - \phi_1)^{2.5} (1 - \phi_2)^{2.5} A_1} + F_r (S_2)^2 \right),$$

$$\theta = S_4, \quad \theta' = S_5, \quad \theta'' = S'_5,$$

$$S'_5 = \frac{Pr A_2}{A_3} \left(2 S_2 S_4 + S_1 S_5 - \frac{Ec (S_3)^2}{(1 - \phi_1)^{2.5} (1 - \phi_2)^{2.5} A_2} - Du S'_7 - H_g S_4 \right),$$

$$\phi = S_6, \quad \phi' = S_7, \quad \phi'' = S'_7,$$

$$S'_7 = \frac{1}{Du} \left(2 S_2 S_4 + S_1 S_5 - \frac{Ec (S_3)^2}{(1 - \phi_1)^{2.5} (1 - \phi_2)^{2.5} A_2} - H_g S_4 - \frac{A_3}{A_2 Pr} S'_5 \right).$$

The in-built function *bvp4c* in MATLAB software is utilized to solve the above system to obtain a numerical solution. The function implements a fourth-order collocation formula grounded on the three-stage Lobatto IIIa method. It provides a continuous smooth solution across the mesh. The solver adjusts the grid size automatically, and the error tolerance is taken as 10^{-6} on calculations.

3. Results and discussion

Results are shown regarding velocity, temperature, and concentration for constant values of $Pr = 6.2$, $Sc = 1$, $\phi_1 = 0.05$, and $\phi_2 = 0.05$. The skin friction (drag), Nusselt number, and Sherwood number are also calculated and graphed/tabulated against various relevant parameters. The numerical values of Cf , Sh , and Nu ($-f''(0)$, $-\theta'(0)$, and $-\phi'(0)$) are given in Tables 2–4.

From Table 2, it can be seen that both mass and heat transfer rates decrease with increased Darcy and Forchheimer numbers. The internal heat generation parameter enhances the mass transfer rate but negatively impacts the amount of heat transfer. Local heat transfer increases (decreases) with increasing values of the Soret (Dufour) parameter. Conversely, the local mass transfer increases (decreases) with increasing values of the Dufour (Soret) parameter.

It is clear from Table 3 that the amount of mass transfer improves with increased Eckert, Cr , and δ values.

Table 2. Numerical data of $-\theta'(0)$, $-\phi'(0)$ for diverse β , Fr, Hg, Sr, and Du, with $n = \delta = E1 = 1.0$, $Cr = Ec = 0.5$, $\varphi_1 = 0.05$, and $\varphi_2 = 0.05$.

β	Fr	Hg	Sr	Du	$-\theta'(0)$	$-\phi'(0)$
0.0	0.5	0.1	0.2	0.2	1.540459	1.617782
0.2					1.412061	1.588512
0.5					1.236155	1.547416
0.7					1.128633	1.521925
0.9					1.027898	1.497966
0.2	0	0.1	0.2	0.2	1.536493	1.661887
	1				1.412061	1.588512
	2				1.306328	1.532861
	3				1.215429	1.488588
	4				1.136123	1.452197
0.2	0.5	-0.8	0.2	0.2	2.686101	1.394138
		-0.4			2.167554	1.473740
		0			1.575705	1.563793
		0.4			0.866273	1.670243
		0.8			-0.104632	1.811693
0.2	0.5	0.1	0.0	0.2	1.387232	1.685787
			0.1		1.399875	1.637672
			0.2		1.412061	1.588512
			0.3		1.423176	1.538648
			0.4		1.432104	1.488795
0.2	0.5	0.1	0.2	0.0	2.233952	1.464054
				0.1	1.853018	1.521574
				0.2	1.412061	1.588512
				0.3	0.891299	1.668023
				0.4	0.260039	1.765018

Table 3. $-\theta'(0)$ and $-\phi'(0)$ values for different E1, δ , Ec, and Cr with $\beta = 0.2$, $Fr = 0.5$, $n = 1.0$, $Sr = Du = 0.2$, $Hg = 0.1$, $\varphi_1 = 0.05$, and $\varphi_2 = 0.05$.

Ec	Cr	E1	δ	$-\theta'(0)$	$-\phi'(0)$
0	0.5	1.0	1.0	4.186321	1.160768
0.5				2.521607	1.417656
1				1.412061	1.588512
1.5				0.302746	1.759012
2				-0.806325	1.929132
0.5	-1.0	1.0	1.0	1.876669	0.883443
	-0.5			1.709896	1.159586
	0			1.556751	1.386705
	0.5			1.412061	1.588512
	1.0			1.273753	1.773467

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Ec	Cr	E1	δ	$-\theta'(0)$	$-\phi'(0)$
0.5	0.5	0	1.0	1.308118	1.743490
		1		1.412061	1.588512
		2		1.473486	1.498410
		3		1.508977	1.448297
		5		1.540948	1.405743
0.5	0.5	1.0	1	1.412061	1.588512
			2	1.313860	1.708357
			3	1.213681	1.829831
			4	1.113424	1.950600
			5	1.013847	2.069725

Table 4 shows the $-f''(0)$, $-\theta'(0)$, and $-\phi'(0)$ for various values of Marangoni ratio parameter (r). It is clear that $-f''(0)$ and $-\phi'(0)$ increase and $-\theta'(0)$ decreases with increasing r values. Also, heat transfer decreases with increasing values of Eckert number, chemical reaction, and temperature difference parameters. However, the activation energy parameter supports the local heat transfer rate while adversely affecting the mass transfer rate.

Table 4. $-f''(0)$, $-\theta'(0)$, and $-\phi'(0)$ for various r with $Cr = Fr = 0.5$, $\beta = 0.2$, $Hg = 0.1$, $Ec = \sigma = \delta = E1 = n = 1.0$, $Sr = Du = 0.2$, $\phi_1 = 0.05$, and $\phi_2 = 0.0$.

r	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	2.000000163	1.840920	1.430418
0.2	2.399999679	1.412061	1.588511
0.5	2.999998953	0.553634	1.840564
0.7	3.399999761	-0.145574	2.018726
1	4.000000326	-1.365533	2.301232

Figure 2 demonstrates the velocity, solute concentration, and temperature for several values of the Marangoni ratio parameter (r) with $\beta=0.2$, $E1=1$, $n1=1$, $Fr=0.5$, $Cr=0.5$, $Ec=0.5$, $Hg=0.1$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Sr=0.2$, and $Du=0.2$. The temperature and velocity increase with increasing Marangoni ratio factor (r). On the other hand, the opposite behavior is noted with the solute concentration. For a greater r , an overshoot of temperature is witnessed near the boundary.

Figure 3 provides the influence of (inverse) Darcy number (β) on velocity, thermal, and solute fields for fixed values of $r=0.2$, $E1=1$, $n1=1$, $Fr=0.5$, $Cr=0.5$, $Ec=0.5$, $Hg=0.1$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Sr=0.2$, and $Du=0.2$. The thermal and solute boundary layer thicknesses increase with increased values of (inverse) Darcy number. However, the momentum boundary layer thickness decreases with increased β values. This is due to flow resistance and results in a reduction in fluid speed.

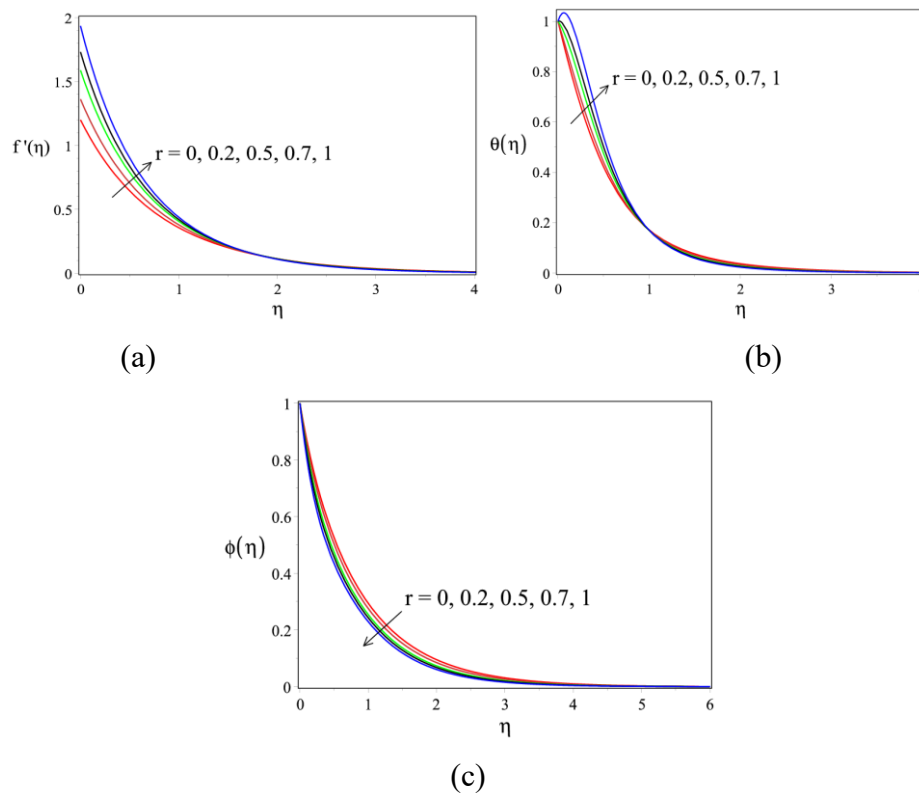


Figure 2. Velocity, temperature, and concentration profiles for different values of Marangoni ratio parameter (r).

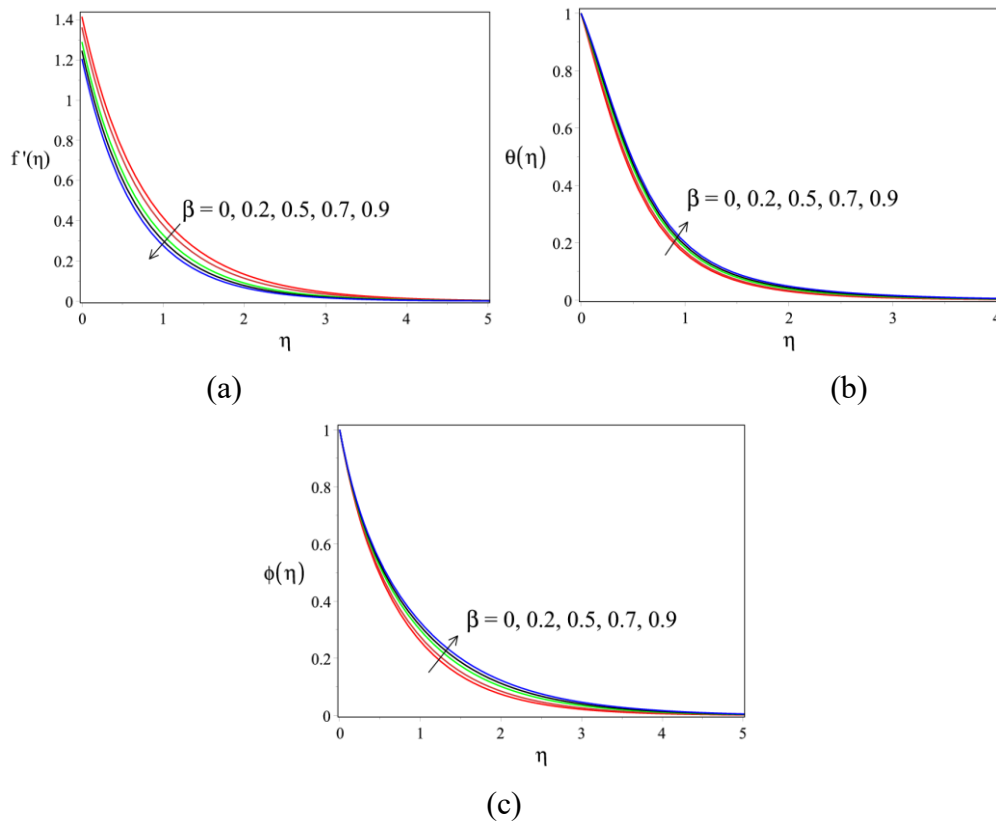


Figure 3. Velocity, temperature, and concentration profiles for different values of (inverse) Darcy number (β).

Figure 4 shows the influence of Forchheimer number (Fr) for fixed values of $r=0.2$, $E1=1$, $n1=1$, $\beta=0.2$, $Cr=0.5$, $Ec=0.5$, $Hg=0.1$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Sr=0.2$, and $Du=0.2$. With increasing values of Fr , the resistance inside the porous matrix rises, and the velocity (speed) of the fluid is reduced. There is no considerable change in temperature. However, the concentration increases with increased Fr values.

The effect of Eckert number (Ec) on thermal and solute fields is shown in Figure 5 with $r=0.2$, $E1=1$, $n1=1$, $\beta=0.2$, $Cr=0.5$, $Fr=0.5$, $Hg=0.1$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Sr=0.2$, and $Du=0.2$. The effect of Ec on temperature is clearly seen in Figure 5(a); the thermal (boundary) layer increases with increased values of Ec . Viscous dissipation converts the kinetic energy into thermal energy inside the system, boosting the fluid temperature. However, no significant effect is observed on the concentration field. There is a temperature overshoot near the boundary for higher values of Ec .

The heat generation/absorption effect on thermal fields is depicted in Figure 6 with $r=0.2$, $E1=1$, $n1=1$, $\beta=0.2$, $Cr=0.5$, $Fr=0.5$, $Ec=0.5$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Sr=0.2$, and $Du=0.2$. It is clear from the profiles that the thickness of the thermal boundary layer increases with increased values of Hg , as the internal thermal energy rises due to heat generation.

Figure 7 shows the impact of Dufour parameter on temperature with $r=0.2$, $E1=1$, $n1=1$, $\beta=0.2$, $Cr=0.5$, $Fr=0.5$, $Ec=0.5$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Sr=0.2$, and $Hg=0.1$. The temperature increases with increased values of Dufour parameter.

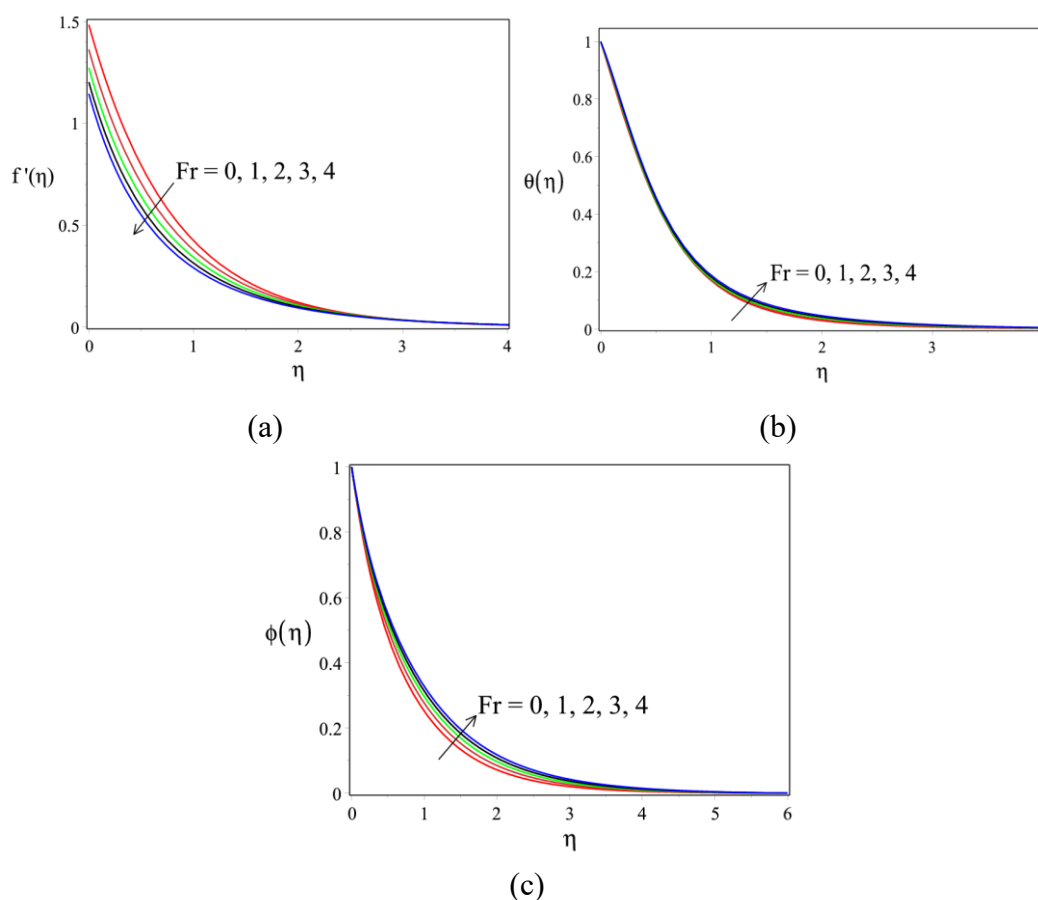


Figure 4. Velocity, temperature, and concentration profiles for different values of Forchheimer number (Fr).

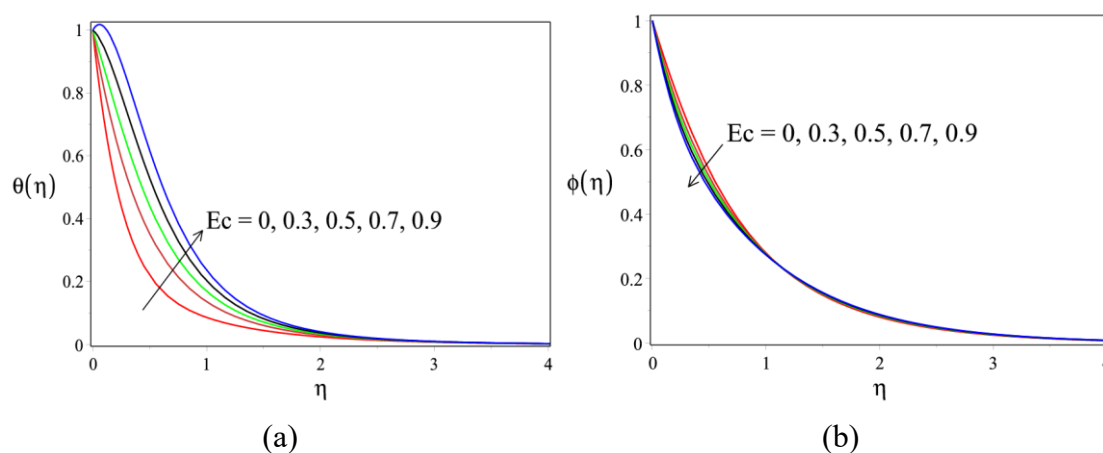


Figure 5. Temperature and concentration for different values of Eckert number.

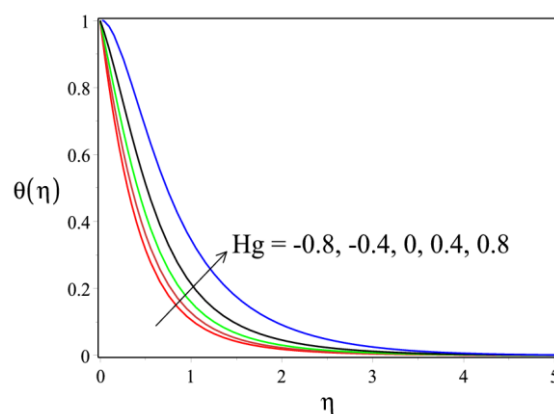


Figure 6. Temperature for different values of heat generation parameter (Hg).

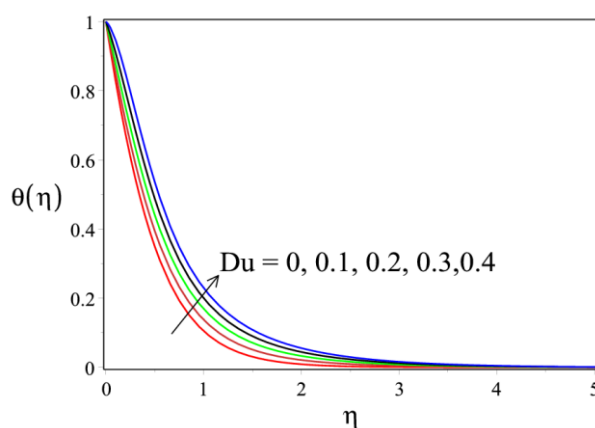


Figure 7. Temperature profiles for different values of Dufour number (Du).

Figure 8 shows the Soret effect on the concentration field for fixed values of $r=0.2$, $E1=1$, $n1=1$, $\beta=0.2$, $Cr=0.5$, $Fr=0.5$, $Ec=0.5$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Du=0.2$, and $Hg=0.1$. The solute concentration increases with increased value of Soret number.

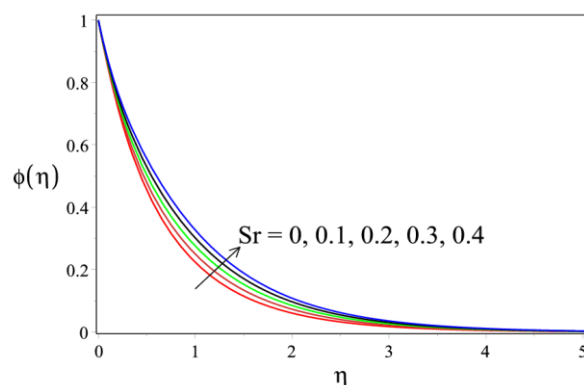


Figure 8. Concentration profiles for different values of Soret number (Sr).

Figure 9 demonstrates the chemical reaction effect on the concentration field for fixed values of $r=0.2$, $E_1=1$, $n_1=1$, $\beta=0.2$, $H_g=0.1$, $Fr=0.5$, $Ec=0.5$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Du=0.2$, and $Sr=0.2$. The solute boundary layer thickness decreases with increased chemical reaction parameter values.

The power of activation energy parameter E_1 on solute concentration is shown in Figure 10 with $r=0.2$, $Cr=0.5$, $n_1=1$, $\beta=0.2$, $H_g=0.1$, $Fr=0.5$, $Ec=0.5$, $\delta=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Du=0.2$, and $Sr=0.2$. With increasing values of E_1 , the concentration increases inside the boundary layer, that is, the activation energy improves the mass transfer inside the system.

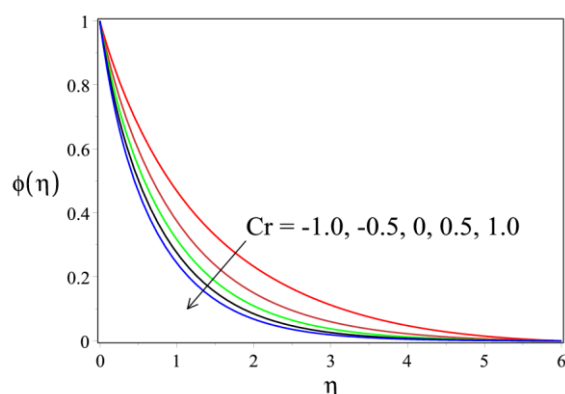


Figure 9. Concentration profiles for various values of the chemical reaction parameter (Cr).

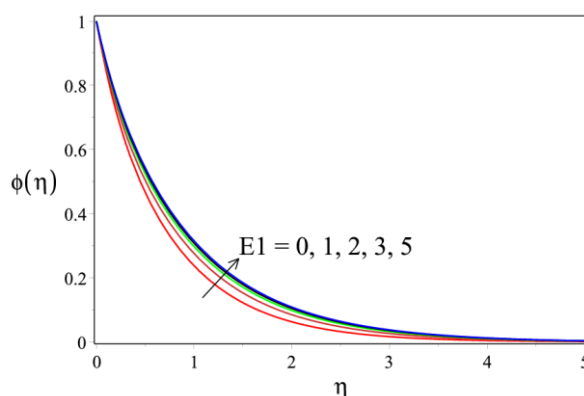


Figure 10. Concentration profiles for different values of the activation energy parameter (E_1).

Figure 11 shows the impact of δ on solute concentration ($\phi(\eta)$) with $r=0.2$, $Cr=0.5$, $n_1=1$, $\beta=0.2$, $Hg=0.1$, $Fr=0.5$, $Ec=0.5$, $E_1=1$, $\phi_1 = 0.05$, $\phi_2 = 0.05$, $Du=0.2$, and $Sr=0.2$. We found that there is a small change in the concentration field as a result of changing the values of δ .

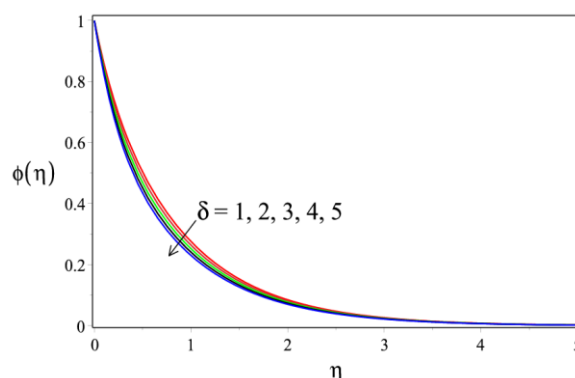


Figure 11. Concentration profiles for different values of the temperature difference parameter (δ).

The effect of drag coefficient (C_f), amount of heat transfer (Nu), and amount mass transfer (Sh) under various combination of parameters is calculated and depicted in Figures 12–22.

Figure 12 demonstrates the influence of β and r on cf , Nu , and sh values. It is clear that Nusselt and Sherwood numbers decrease with increasing values of β ; C_f does not vary. When increasing the values of r , the Nusselt number declines, and the Sherwood number increases.

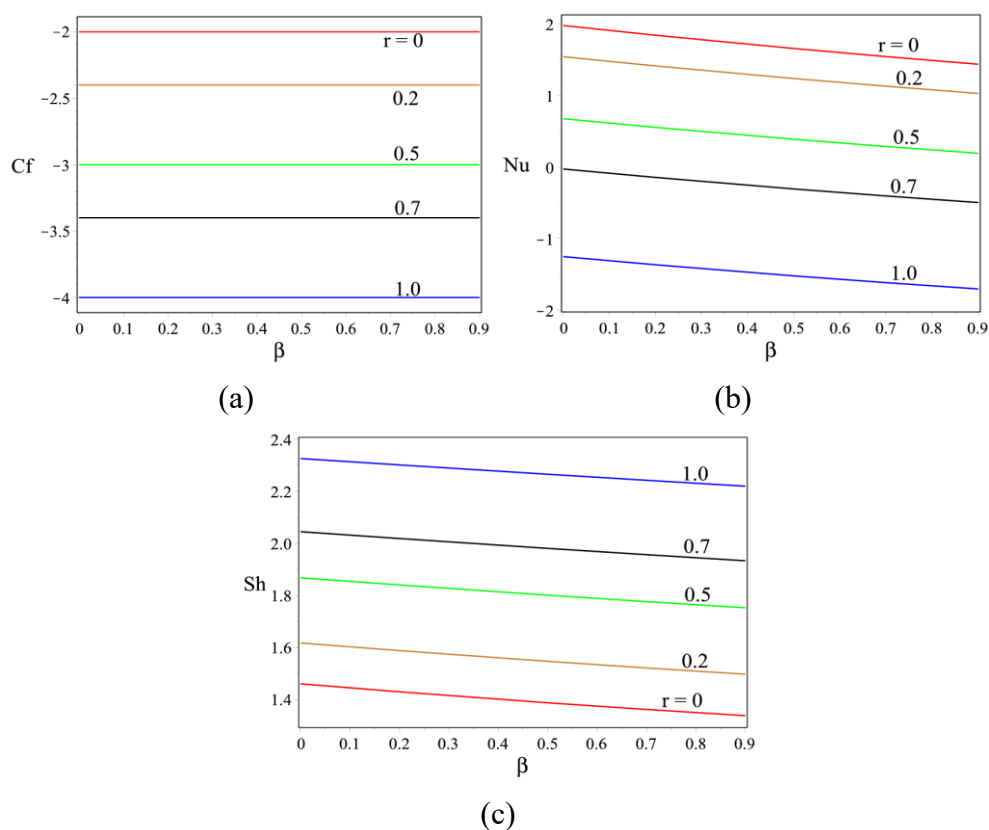


Figure 12. Effect of β and r on (a) skin friction (C_f), (b) Nusselt number (Nu), and (c) Sherwood number (Sh).

Figure 13 shows the influence of Soret (Sr) and chemical reaction (Cr) parameters on mass and heat transfer rates. It is clear that the Nusselt number declines and Sherwood number increases with increasing Cr values. However, Nu increases and Sherwood number decreases by strengthening the Soret number.

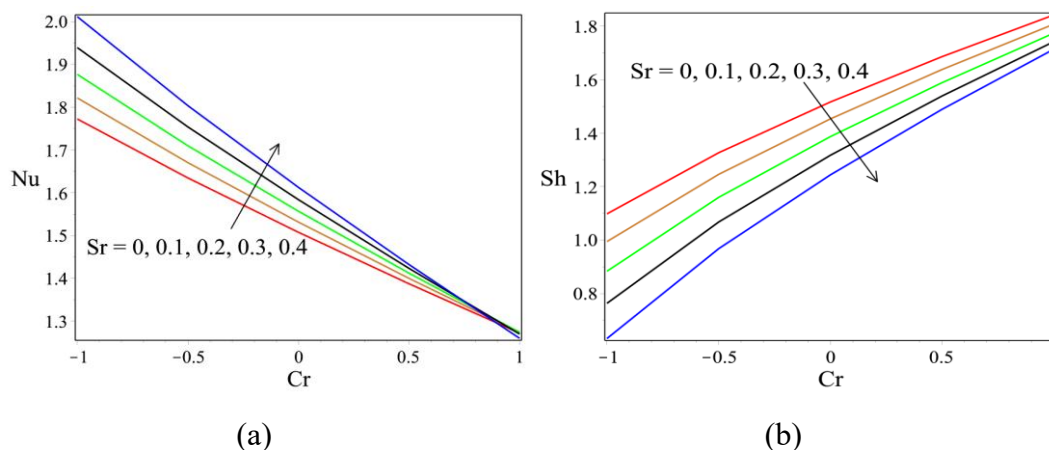


Figure 13. Effect of chemical reaction (Cr) and Soret number (Sr) on (a) Nusselt number (Nu), and (b) Sherwood number (Sh).

Figure 14 shows the impact of $E1$ and δ on heat and mass transfer values. Heat transfer increases with increasing values of $E1$ and decreases with increased δ . The Sherwood number shows the opposite trend: Sh increases with δ and decreases with increasing $E1$.

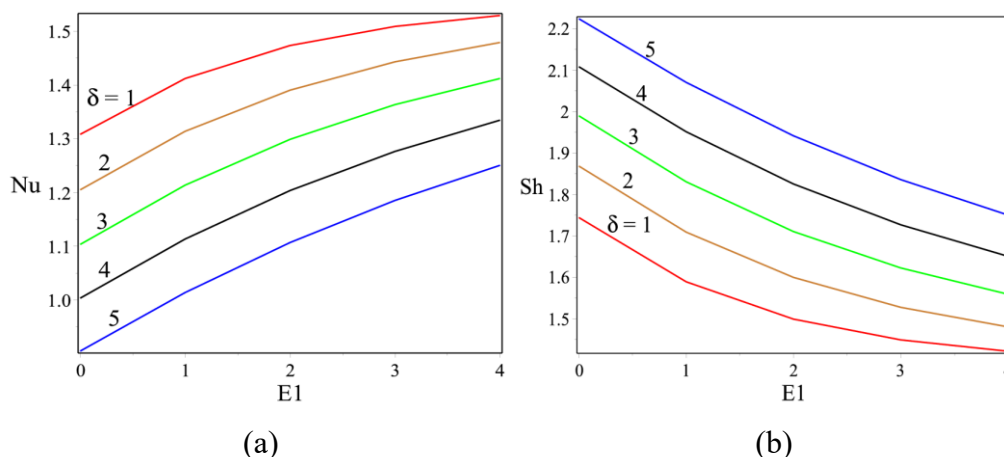


Figure 14. Effect of $E1$ and δ on (a) Nusselt number (Nu) and (b) Sherwood number (Sh).

Figure 15 explores the effects of Fr and β on the amount of heat and mass transfer. Both rates decrease with increased values of Fr and β .

Figure 16 demonstrates the impact of Dufour parameter and heat generation parameter on heat and mass transfer. With increased Du and Hg values, Nu decreases, and Sh increases.

Figure 17 demonstrates the effects of Soret parameter and heat generation parameter on Nu and Sh . Nu decreases with increasing Hg ; the opposite behavior is found with Sh . The heat and mass transfer rate respond nonlinearly to the Soret parameter.

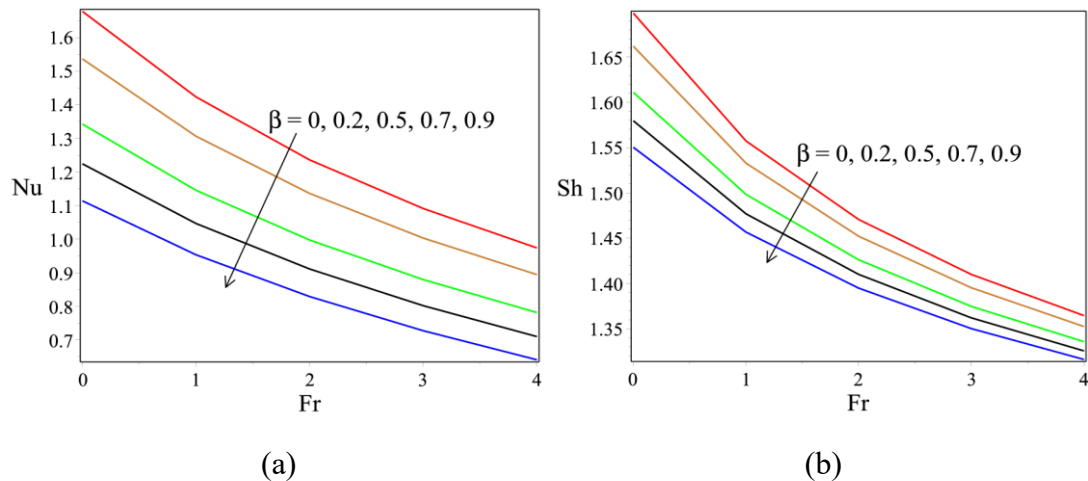


Figure 15. Effect of Fr and β on (a) Nusselt number (Nu) and (b) Sherwood number (Sh).

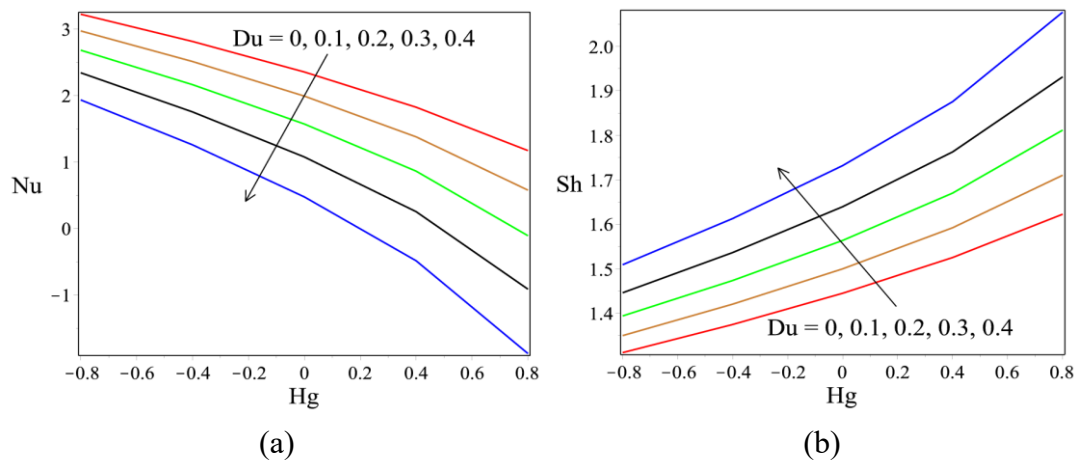


Figure 16. Effect of heat generation (Hg) and Dufour number (Du) on (a) Nusselt number (Nu) and (b) Sherwood number (Sh).

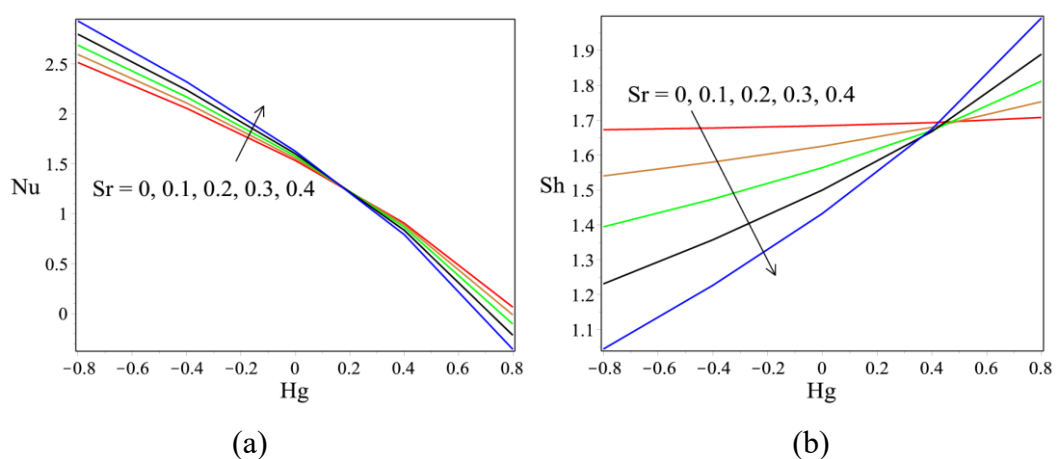


Figure 17. Effect of heat generation (Hg) and Soret number (Sr) on (a) Nusselt number (Nu) and (b) Sherwood number (Sh).

Figure 18 explores the influence of Du and Sr on Nu and Sh . Sherwood number decreases with Sr and increases with Du . Nu decreases with Du and increases with Sr .

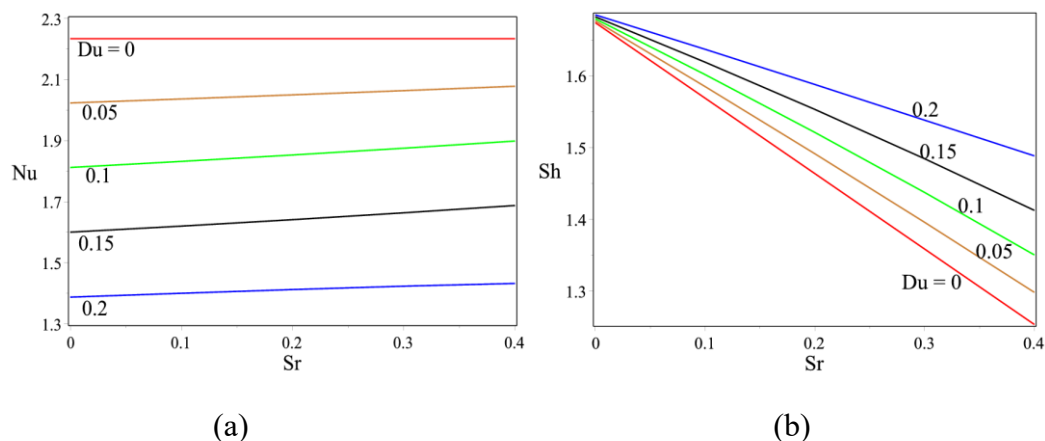


Figure 18. Effect of Soret number (Sr) and Dufour number (Du) on (a) Nusselt number (Nu) and (b) Sherwood number (Sh).

Figure 19 shows the impact of $E1$ with Sr on heat and mass transfer rate. Nu increases with both $E1$ and Sr .

Figure 20 demonstrates the entropy generation ($Ng(\eta)$) and the Bejan number ($Be(\eta)$) for diverse Br values. The Bejan number decreases and entropy profile increases with increasing values of Br .

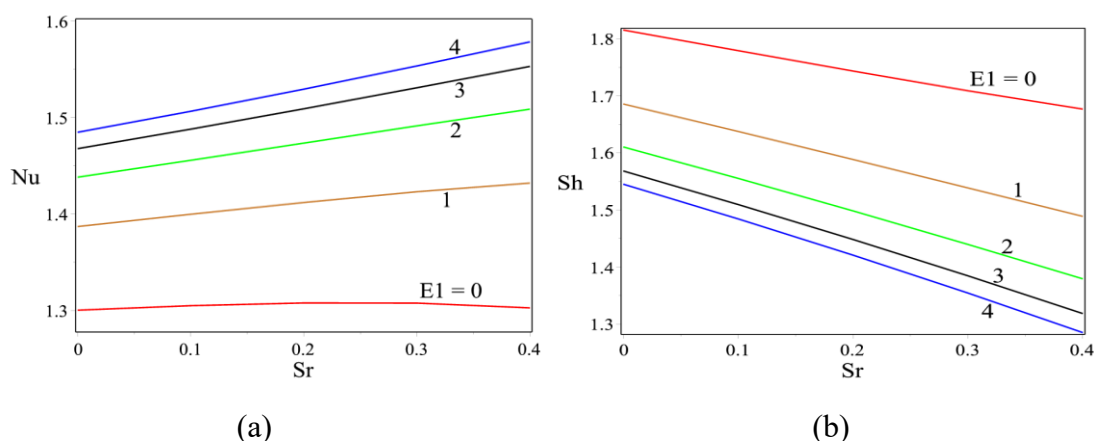


Figure 19. Effect of Sr and $E1$ on (a) Nusselt number (Nu) and (b) Sherwood number (Sh).

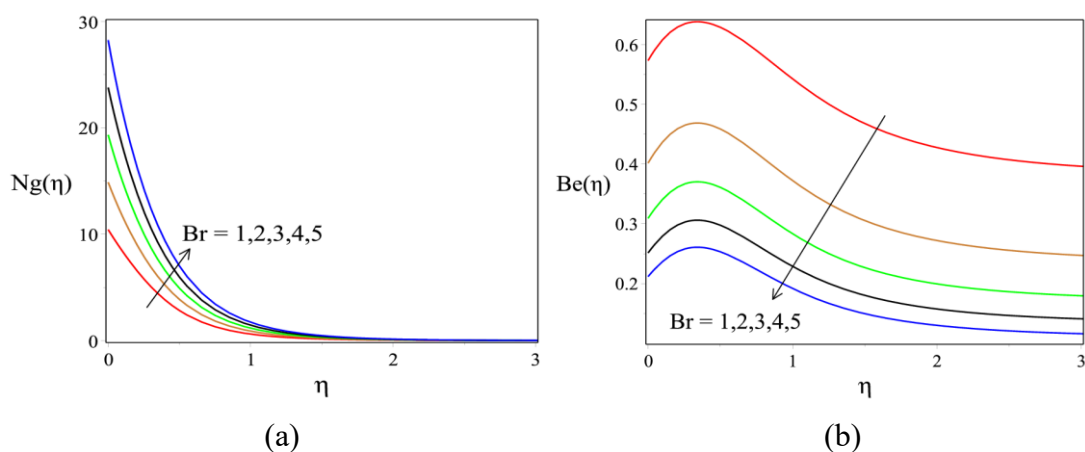


Figure 20. Entropy generation (a) and Bejan number (b) for different Brinkman number values.

Figure 21 explores the effect of entropy generation and Bejan number for different L values. Both $Ng(\eta)$ and $Be(\eta)$ increase with increasing values of L .

Figure 22 illustrates the impact of r on entropy generation and Bejan number. It is evident that the Bejan number decreases with increased r values. No significant impact on entropy generation profiles was observed when altering the r values. The Bejan number decreases by half in most cases, which indicates that fluid friction irreversibility is dominant here.

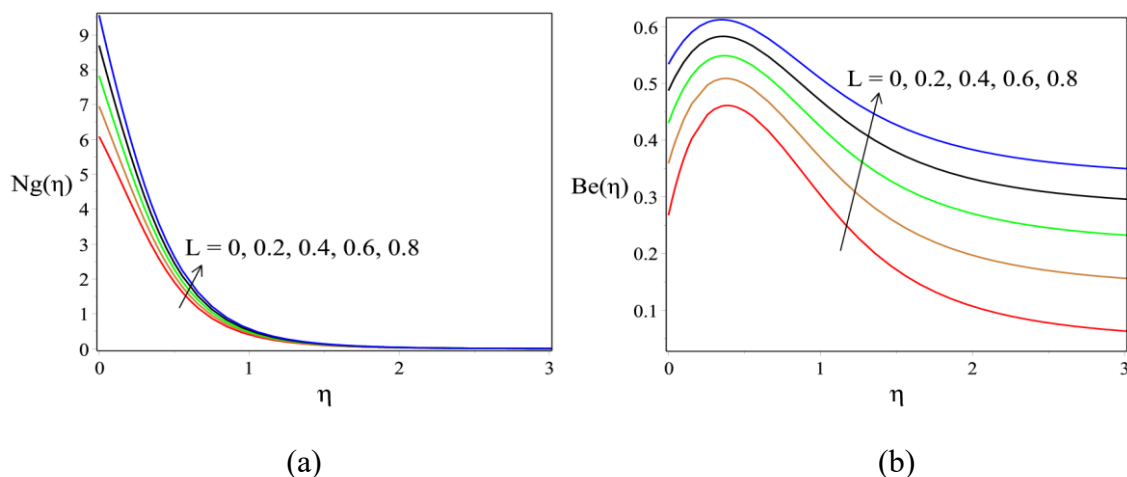


Figure 21. Entropy generation (a) and Bejan number (b) for different L values.

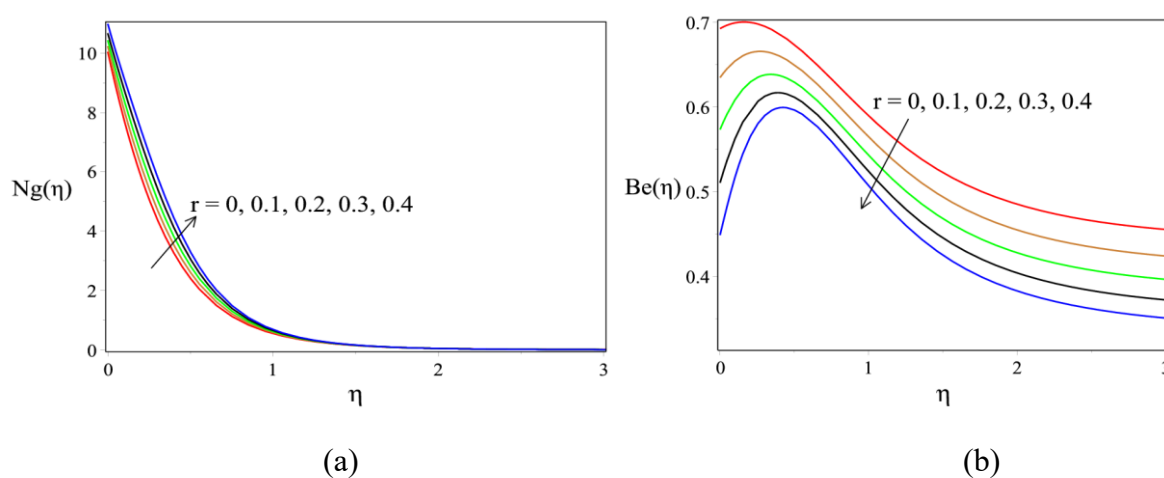


Figure 22. Entropy generation (a) and Bejan number (b) for different r values.

4. Conclusions

The heat generation, activation energy, cross diffusion, chemical reactions, and viscous dissipation are all caused by thermocapillary-induced convection of hybrid nanofluids over a surface embedded in a non-Darcy porous matrix. The study produced the following findings:

- Temperature and velocity increase in opposition to concentration and the Marangoni ratio parameter.
- As the Forchheimer number (Fr) increases, the momentum boundary layer thickness decreases, and the solutal boundary layer thickness increases.

- Temperature increases with increasing Dufour, Eckert number, and heat generating parameter values. Additionally, at higher Eckert number values, the temperature overshoots close to the border.
- With increasing Eckert number, Dufour, and heat generation parameter values, temperature increases. It is also observed that temperature overshoots near the boundary for higher Eckert number values.
- As the Soret and activation energy parameters increase, concentration increases. However, as the chemical reaction parameter increases, it decreases.
- The amount of heat transfer increases with Sr and E_1 and declines with increasing r , β , Cr , δ , Fr , Du , and Hg .
- Mass transfer rate increases with r , Cr , δ , Du , and Hg and decreases with β , Sr , E_1 , and Fr .
- Entropy generation increases with increasing diffusion parameter, Brinkman number, and Marangoni ratio parameter.
- BZ reactions increases with increasing diffusion parameter and decreases with increasing Marangoni ratio parameter and Brinkman number.

Use of Generative-AI tools declaration

The author declares he has not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The author declares no competing interests.

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