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Heat and mass transfer analysis of radiative and chemical reactive effects on MHD nanofluid over an infinite moving vertical plate

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ABSTRACT

A comparative study of nanofluid ($Cu–H_2O$) and pure fluid (water) is investigated over a moving upright plate surrounded by a porous surface. The novelty of the study includes the unsteady laminar MHD natural transmission flow of an incompressible fluid, to get thermal conductivity of nanofluid is more than pure fluid. The chemical reaction of this nanofluid with respect to radiation absorption is observed by considering the nanoparticles to attain thermal equilibrium. The present work is validated with the previously published work. The upright plate travels with a constant velocity u_0, and the temperature and concentration are considered to be period harmonically independent with a constant mean at the plate. The most excellent appropriate solution to the oscillatory pattern of boundary layer equations for the governing flow is computed utilizing the Perturbation Technique. The impacts of factors on velocity, temperature, and concentration are visually depicted and thoroughly elucidated. The fluid features in the boundary layer regime are explored visually and qualitatively. This enhancement is notably significant for copper nanoparticles.

1. Introduction

Nanofluids combine solid nanoparticles and the base fluid, wherein the nanoparticle's principal dimension is less than 100 nm. Choi et al. [1], Eastman et al. [2] and Das et al. [3] were the first researches who coined the term 'nanofluid' for any "liquid that contains a dispersion of submicronic solid particles" with a length between 1 and 50 nm. Gupta et al. [4] and Jeevanandam et al. [5] summarized that Nanoparticles are characterized into several kinds based on their size, shape, physical, and chemical characteristics, and classified as polymeric nanoparticles, metallic nanoparticles, Carbides, ceramic & lipid-based Nps. These are suspended into the base fluids like water, ethanol, EG, and refrigerants. Many authors have observed that thermophysical characteristics of nanofluids show better results than their base fluids by Sarfraz et al. [6] and Tawfik et al. [8] summarized recent developments in the research of nanofluids, and stated its importance in industrial processes, permanency evaluation methodologies, constancy improvement procedures, thermophysical characteristics of nanofluids, and commercialization of products. Harry Williams et al. [9] analyzed magnetic nanoparticles involved the cancer treatment and infectious diseases. Magnetic nanoparticles expend added energy than a micro-particulate in resisting present magnetic strengths that are likely in cancer treatment (see Tables 1 and 2).

Magnetohydrodynamics (MHD) is a study about electrically accompanying fluids in magnetic field. It is called magneto-fluid dynamics. Plasmas, electrolytes, saltwater, and liquid metals are examples of magneto-fluids. Hannes Alfvin pioneered study of Magnetohydrodynamics, and earned the Nobel Prize in Physics in 1970. The magneto-

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Table 1
Thermophysical attributes of nanofluids [Hamilton & Crosser model] [45].

Density	$\rho_{nf} = (1-\varphi)\rho_{H_2O} + \varphi\rho_{Cu}$
Viscosity	$\mu_{nf} = \mu_f(1-\varphi)^{-2.5}$
Thermal diffusivity & suction	$\alpha_{nf} = \dfrac{k_{nf}}{(\rho c_p)_{nf}}, a_2 = -V_0$
Thermal expansion (Fluid)	$(\rho\beta)_{nf} = (1-\varphi)(\rho\beta)_{H_2O} + \varphi(\rho\beta)_{Cu}$
Heat capacity	$(\rho c_p)_{nf} = (1-\varphi)(\rho c_p)_{H_2O} + \varphi(\rho c_p)_{Cu}$
Thermal expansion (Solid)	$(\rho\beta)^*_{nf} = (1-\varphi)(\rho\beta)^*_{H_2O} + \varphi(\rho\beta)^*_{Cu}$
Thermal conductivity	$k_{nf} = k_{H_2O}\dfrac{k_s + (n-1)k_{H_2O} - (n-1)\varphi(k_{H_2O} - k_{Cu})}{k_{Cu} + (n-1)k_{H_2O} + \varphi(k_{H_2O} - k_{Cu})}$

Table 2
Thermophysical properties of Water and Copper Oztop [46].

Physical properties	water	Cu
$\rho(kg/m^3)$	997.1	8933
$Cp(J/KgK)$	4179	385
$K(W/mK)$	0.613	401
$\beta \times 10^5(1/K)$	21	1.67
$\beta^* \times 10^6(m2/h)$	298.2	3.05

nanofluid blends the properties of liquids with magnets. The magnetic effects cause a rebuilding of absorption and polarize atoms in the liquid system, and also the change in temperature transmission. Magnetic nanoparticles are applied in the biomedical industry as it has more viscid tissue cells than non-malignant particles and the tissues increase the blood flow. Mittal et al. [11] have been reviewed theoretical and experimental study of magnetohydrodynamics of nanofluids. Ali et al. [12] explored the natural convective flow across the angled plate entrenched in absorbent medium with MHD effects. Abbas et al. [13] explored the thermophoresis diffusion MHD motion of transient nanofluid flow moving in a rotating system. They employed copper, titanium dioxide, and aluminium oxide nanoparticles in various forms such as spherical, cylindrical, and brick (shape factor = 3, 6, 3.7) in their investigation. Hussain et al. [14] explored the MHD nanofluid over an absorbent medium with radiation. Sobamowo et al. [15] studied the MHD free convective nanofluid over dangle plate with a fixed heat in a circulating reference. Das et al. [16] analyzed nanofluid flow across a moving vp working in MHD, radiation. Ferdows et al. [17] explored the nanofluid movement across the plate with suction and thermal production. MHD natural convective nanofluid over a moving v.p with two magnetic fields related to the nanofluid or plate was described by Pavar et al. [18]. Also some other references can be found in Refs. [19,20].

The chemical reaction effects are the most important effects in the mass transfer area, and it has been applicable in many industries like food processing, material production, humidification, freezing of nuclear reactors, oxidation, thermal insulation, pollution studies, geothermal pool, production of ceramics. Mahanthesh et al. [21] has deliberated the thermal transfer of CNTs movement in stretched spinning disk with thermal source, and convective state effects.Many technical applications, such as polymeric, ceramic, and metallic foams, rely on heat transmission in porous media. The thermal process has been investigated using the traditional idea of unidirectional transmission of conductive materials. Ibrahim et al. [22] investigated rotating fluid with significant porosity move along vertical fascia. Numerous researchers [23–27] have explored the nanofluid over vertical frame with various parameter constraints. Naveed khan et al. [28] investigated the heat and mass transfer effect of maxwell fluid over perpendicular plate with sloped and isothermal wall temperature and with the boundary condition based on the maxwell fluid with the carrier fluid is EG. Sravan Kumar et al. [29] examined analyzed three different nanoparticles inserted in water-based nanofluid flow over a numeric stimulating vertical plate with MHD. Anjali Devi et al. [30] have studied the Blasius and Sakiadis flow of nanofluids past an inclained plate. Reddy et al. [31] analyzed the prominence of radiation on heat and mass transfer nanofluid over an inclined vertical plate embedded in an absorptive.The flow and thermal behavior of nano ($Ni/C_2H_6O_2$) and hybrid nanofluids ($Ni, Al_2O_3/C_2H_6O_2$) transport across an eccentric annulus were theoretically addressed by Iskander [33]. Using the Cattaneo–Christov heat flux model, Nayak et al. [34] investigated the entropy reduction related to the electromagnetic flow of nanofluids containing SWCNT/MWCNT suspensions on the surface of a thin needle inserted in a Darcy–Forchheimer environment. Sami et al. [35] researched the bioconvection occurrence of a pair of stress nanofluid comprising gyrotactic microorganisms across a periodic accelerated surface. Iskander [36] investigated the heat transmission of Casson and normal liquids over a stretched surface by causing cross-diffusion, thermophoresis, the Brownian moment, and Joule heating. Sheikholeslami.M.et al. demonstrated a new method namely CVFEM applied for radiative nanoparticles through a permeable medium using Darcy's Law. Puneet et al. [39] analyzed Ethylene glycol-based nanofluid flow over a vertical plate induced by buoyancy effects with the presence of quadratic thermal radiation.

Reddy et al. [40] analyzed radiation absorption and chemical reaction effects on MHD free convective flow of a nanofluid through a flat plate. Rajesh et al. [41] explored the analytic approach of MHD hybrid nanofluid flow over an infinite vertical plate with ramped wall temperature and thermal radiation. Madaki et al. [42] investigated a comparative study of an unsteady squeezing nanofluid between two lateral plates with the two different kinds of solving premisses, and they found the fourth-order R–K method gave the best accuracy more than HPM.The examination of these novel flow characteristics separates our study from previous studies. Although several studies have been conducted, the flow of a nanofluid in the presence of Cu-nanoparticles, magnetic fields, and heat radiation has yet to be examined. As a result, the purpose of this scientific contribution is to fill that void. The perturbation strategy is used to solve the governing equations. The findings presented here may be used for cooling systems, energy generation, solar systems [44], improving the thermal performance of various devices, engineering applications, extrusion processes, and many other applications. The current investigation was carried out in the presence of magnetic field effects, which play an important role in engineering fields such as manufacturing via MHD pumps, nuclear plants, laser pulse heating, turbines, material dying, and MHD generators.

Keeping the above-mentioned facts. We performed analytical and numerical calculations on natural convective, transient, MHD nanofluid flow over infinite movable upright plate in the existence of uniform suction, chemical reaction, and nonlinear thermal in the present research. Nanofluid is formed by copper solid particles dissolved in water as base fluid. A perturbation method is applied to solve the governing system of associated nonlinear ODEs. For stated values of the thermophysical constraints, numerical results of velocity, temperature, and concentration fields were produced.Furthermore, graphs and tables are used to describe a comparative examination of the velocity and temperature profile heat transfer enhancement level caused by the suspension of *Cu*-water nanofluid ($\varphi \neq 0$) and carrier fluid ($\varphi = 0$). The assessable conclusions are in best concurrence with the mathematical solutions, which correspond to the experimental answers.

2. Physical model and solution of the problem

We follow the model Transient, incompressible nanofluid over an infinite moving upright plate contained inside the permeable medium, and the nanofluid flow is moving along the plate direction. Transverse magnetic force B_0 effects can be enforced upright to the plate and normal to the flow direction. Here the flow moving along only in an upward direction ($y > 0$), is graphically presented in Fig. 1. The following are the

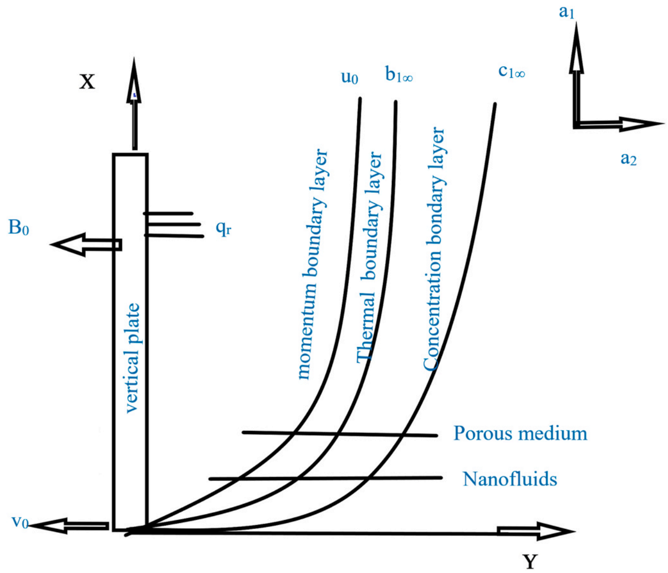

Fig. 1. Flow model.

current problem's assumptions.

1. In this case, the pressure gradient is ignored.
2. A radiative heat flow q_r is applied to the plate in the normal direction
3. The base fluid and the nanoparticle floating in it are in thermal equilibrium.
4. In the equations of motion, density is considered to be linearly dependent on temperature and buoyancy forces.

2.1. Flow description

1. From outset ($t' \leq 0$) the plate and the fluid temperature same as $b_{1\infty}$; species concentration of the plate and fluid are same as $c_{1\infty}$.
2. For ($t' > 0$), The plate moves with constant velocity u_0 with the non-uniform temperatureand the concentration

$$b_1(y', t') = b_{1w} + (b_{1w} - b_{1\infty})\epsilon e^{iwt'},$$

$$c_1(y', t') = c_{1w} + (c_{1w} - c_{1\infty})\epsilon e^{iwt'} \quad \text{is considered.}$$

3. Along the negative direction of the y-axis of the plate a uniform suction v_0 is present.

2.2. Governing equations

The momentum and energy equations in the presence of a magnetic field and heat radiation past a moving vertical plate may be stated as follows under the aforementioned assumptions (Das and Jana [16]): By the flow model-description, the flow equation are described as follows:

$$\frac{\partial a_2}{\partial y'} = 0 \tag{1}$$

$$\rho_{nf}\left(\frac{\partial a_1}{\partial t'} + a_2\frac{\partial a_1}{\partial y'}\right) = \mu_{nf}\frac{\partial^2 a_1}{\partial y^2} + (\rho\beta)_{nf} g(b_1 - b_{1\infty}) + (\rho\beta)^*_{nf} g(c_1 - c_{1\infty}) - \sigma B_0^2 a_1 - \frac{\gamma_{nf}}{k^*}a_1 \tag{2}$$

$$\frac{\partial b_1}{\partial y'} = \alpha_{nf}\frac{\partial^2 b_1}{\partial y'^2} - \frac{1}{(\rho c_p)_{nf}}\frac{\partial q_r}{\partial y'} \tag{3}$$

$$\frac{\partial c_1}{\partial y'} = D_B\frac{\partial^2 c_1}{\partial y'^2} - K_r^*(c_1 - c_{1\infty}) \tag{4}$$

The following boundary conditions are related with the present mathematical model:

when $t' \leq 0$,

$$\left.\begin{array}{l} a_1(y', t') = 0, \\ b_1(y', t') = b_{1\infty}, \\ c_1(y', t') = c_{1\infty} \end{array}\right\} \text{ at } y' = 0$$

when $t' > 0$,

$$\left.\begin{array}{r} a_1(y', t') = u_0, \\ b_1(y', t') = b_{1w} + (b_{1w} - b_{1\infty})\epsilon e^{iwt'}, \\ c_1(y', t') = c_{1w} + (c_{1w} - c_{1\infty})\epsilon e^{iwt'}, \end{array}\right\} \text{ at } y' = 0$$

when $t' > 0$,

$$\left.\begin{array}{l} a_1(y', t') = 0, \\ b_1(y', t') = b_{1\infty}, \\ c_1(y', t') = c_{1\infty} \end{array}\right\} \text{ at } y'_\infty \to \infty.$$

The Rosseland diffusion approximation Hossain [32] and follows Raptis [16] is applied to get the total radiation heat flux q_r is the expression,

$$q_r = \frac{4\sigma_1 b_{1\infty}^3}{3k_2}\frac{\partial b_1^4}{\partial y'}. \tag{5}$$

Here σ_1 and k_2 are the Stefan-Boltzmann constant and the coefficient of Rosseland value. The thermal changes inside the flow are necessarily lesser.so b_1^4 can be a linear function only,

$$b_1^4 \approx 4b_{1\infty}^3 b_1 - 3b_{1\infty}^4. \tag{6}$$

Using (5) and (6) in equation (3), we get

$$\frac{\partial q_r}{\partial y'} = -\frac{16\sigma_1 b_{1\infty}^3}{3k_2}\frac{\partial^2 b_1}{\partial y'^2}. \tag{7}$$

Forward moving the governing equations to ODE by the way of the dimensionless variables:

$$U = \frac{a_1}{u_0}, y = \frac{u_0 y'}{\gamma_f}, t = \frac{u_0^2 t'}{\gamma_f}, \omega = \frac{\gamma_f \omega'}{u_0^2},$$

$$T = \frac{b_1 - b_{1\infty}}{b_{1w} - b_{1\infty}}, \psi = \frac{c_1 - c_{1\infty}}{c_{1w} - c_{1\infty}}, N_r = \frac{4\sigma_1 b_{1\infty}'^3}{K_f K_e}$$

$$G_r = \frac{\beta_f g \gamma_f (b_{1w} - b_{1\infty})}{u_0^3}, P_r = \frac{\gamma_f}{\alpha_f},$$

$$S = \frac{v_0}{u_0}, S_c = \frac{\gamma_f}{D_B}, K_r = \frac{K_r^* \gamma_f}{u_0^2},$$

$$G_m = \frac{\beta_f^* g \gamma_f (c_{1w} - c_{1\infty})}{u_0^3}, K = \frac{K' \rho_f u_0^2}{\gamma^2},$$

$$M = \frac{\sigma^* B_0^2 \gamma_f}{\rho_f u_0^2}.$$

These non-dimensional variables are substituted in (2)-(4) and the governing equations has become,

$$A\left[\frac{\partial U}{\partial t} - S\frac{\partial U}{\partial y}\right] = E_2\frac{\partial^2 U}{\partial y^2} + E_3 Gr(T) + E_4 Gm(\psi) - \left(M - \frac{1}{K}\right)U \tag{8}$$

$$\frac{\partial T}{\partial t} - S\frac{\partial T}{\partial y} = E_1\frac{1}{Pr}\frac{\partial^2 T}{\partial y^2} \tag{9}$$

$$\frac{\partial\psi}{\partial t} - S\frac{\partial\psi}{\partial y} = E_1\frac{1}{Sc}\frac{\partial^2\psi}{\partial y^2} - K_r\psi. \tag{10}$$

The following are the non-dimensional boundary conditions:

$$\begin{array}{llllll} t \le 0; & U = 0, & T = 0, & \psi = 0 & \forall\ y \ge 0, \\ t > 0; & U = 1, & T = 1 + \varepsilon e^{i\omega t}, & \psi = 1 + \varepsilon e^{i\omega t} & \text{at } y = 0 \\ t > 0; & U = 0, & T = 0, & \psi = 0 & \text{as } y \to \infty \end{array} \tag{11}$$

when the value of $S > 0$, it is suction and when $S < 0$, it is the injection parameter. The magnetic parameter is represented by M and the other parameters represented are Kr (chemical reaction), Sc (Schmidt number), Gr (Grashof number), K (permeability), Nr (Thermal radiation).

3. Perturbation analysis

The non-linear mathematical equations 8–10 are solved by transforming the unsteady flow overlaid on the mean steady into ODE.Let us choose;

$$U(y,t) = u_0 + \varepsilon u_1 e^{i\omega t} \tag{12}$$

$$T(y,t) = T_0 + \varepsilon T_1 e^{i\omega t} \tag{13}$$

$$\psi(y,t) = \psi_0 + \varepsilon \psi_1 e^{i\omega t}. \tag{14}$$

Equations 8–10 are shorted to

$$E_2 u_0'' + ASu_0' - \left(M + \frac{1}{K}\right)u_0 = -E_3 GrT_0 - E_4 Gm\psi_0 \tag{15}$$

$$E_2 u_1'' + ASu_1' - \left(M + \frac{1}{K} + Ai\omega\right)u_1 = -E_3 GrT_1 - E_4 Gm\psi_1 \tag{16}$$

$$E_1 T_0'' + P_r ST_0' = 0 \tag{17}$$

$$E_1 T_1'' + P_r ST_1' - P_r(i\omega)T_1 = 0 \tag{18}$$

$$\psi_0'' + S_C S\psi_0' - S_C K_r \psi_0 = 0 \tag{19}$$

$$\psi_1'' + S_C S\psi_1' - (i\omega + K_r)\psi_1 = 0. \tag{20}$$

The boundary conditions of (11) becomes

$$\left.\begin{array}{ll} u_0 = 1, & u_1 = 0, \\ T_0 = 1, & T_1 = 1, \\ \psi_0 = 1, & \psi_1 = 1 \end{array}\right\} \text{ at } y = 0 \tag{21}$$

and

$$\left.\begin{array}{ll} u_0 = 0, & u_1 = 0, \\ T_0 = 0, & T_1 = 0, \\ \psi_0 = 0, & \psi_1 = 0 \end{array}\right\} \text{ at } y \to \infty.$$

Solving (16)-(23) and using (24), we have

$$\begin{aligned} U(y,t) &= [(1 + R_1 + R_2)e^{-m_4 y} - R_1 e^{-m_3 y} \\ &\quad - R_2 e^{-m_1 y})] + \varepsilon[(1 - R_3 - R_4)e^{-m_2 y} \\ &\quad + R_3 e^{-(s_3 + is_4)y} + R_4 e^{-(s_1 + is_2)y}]e^{i\omega t} \end{aligned} \tag{22}$$

$$T(y,t) = e^{-m_3 y} + \varepsilon e^{-(s_3 + is_4)y} e^{i\omega t} \tag{23}$$

$$\psi(y,t) = e^{-m_1 y} + \varepsilon e^{-(s_1 + is_2)y} e^{i\omega t}. \tag{24}$$

4. Discussions on the results

The MHD natural convective nanofluid moving upright plate in the existence of uniform suction, radiative, and chemical effects are the crux of the present study. The nonlinear flow simulation equations are transformed into ODEs, which are evaluated analytically by applying perturbation techniques. A parametric analysis was performed and the resulting geometric results are presented in a graphical representation to understand the problem physically. For several standards of physical parameters such as Thermal radiation (*Nr*), Grashof number (*Gr*), Grashof mass number (*Gm*.), Prandtl number (*Pr*), Schmidt number (*Sc*), Microscopic medium penetration (*K*), solidparticle volume fraction (φ) and suction (S) which are computed the dimensionless velocity U, temperature T, and species concentration ψ is deliberated in taskforce. The graphical results are represented in Figs. 2–13. The outcomes are calculated by assuming parameters as $M = 2$, $\varepsilon = 0.05$, $\omega = 0.005$, $Gr = 2$, $Gm = 5$, $Sc = 0.78$, $t = 1$, $k = 3$, $S = 0.3$ and $Kr = 1$. The calculated values are convincing.

4.1. Parameter effects on velocity profiles

Fig. 2 shows the non-dimensional liquid velocity for different volume fraction parameters (φ) of *Cu*-nanoparticle soluble with water. As $\varphi = 0, 0.05, 0.1, 0.15, 0.2$ on the *Cu*-nanoparticles increases, then the non-dimensional velocity also tends to increase. A rise in values leads to the boundary layer regime thickening. Fig. 3 exposes that nanofluid velocity drops when the intensity of (M = 0,1,4,7) increases. The cross-sectional magnetic field on a fluid that conducts electricity creates a Lorentz Force. This force decreases the fluid movement in the B.L regime. The nanofluid has a lower velocity than pure fluid. Fig. 4 exposes the (*Nr*) on velocity of both pure fluid and nanofluid, as *Nr*(Nr = 1,2,3,5), increases, then the velocity of both copper nanofluid and base fluid also increases. When heat is fascinated, it is evident that the buoyancy force develops the flow. The nanofluid has a lower velocity than pure fluid. The velocity increase of nanofluid was found to be smaller than that of pure fluid. A high (*Nr*) value indicates better control of conduction over absorption radiation, which grows up the boundary layer thickness. The non-dimensional velocity reduces with increasing (Kr = 0,2,4), as seen in Fig. 5. Fig. 6 depicts the effect of (S) on the U-profile for pure and copper-water nanofluid. As the suction parameter S (S = 1,2,3,4) increases, the velocity profiles U of both pure and *Cu*-water nanofluid drop. The velocity increase of nanofluid was found to be more than that of pure fluid. Fig. 7 depicts superior cooling of the surface, non-dimensional velocity increases when the Grashof, and mass Grashof values should be increases. It is fact that when (*Gr*), and (*Gm*), has to increase the mass buoyancy effect.

4.2. Parameter effects on temperature profiles

As the thermal boundary layer deepens, the heat flow rises, as seen in Fig. 8 by nanoparticle volume fraction $\varphi = 0, 0.05, 0.1, 0.15, 0.2$ increases.

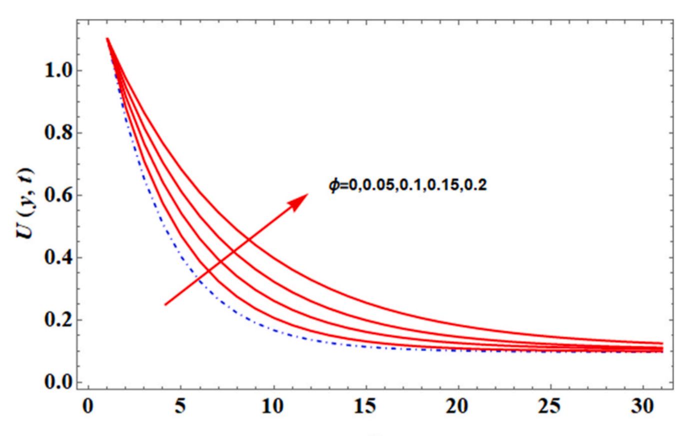

Fig. 2. U versus y for $Cu - H2O$ with nanoparticle volume fraction values of φ, with instability.

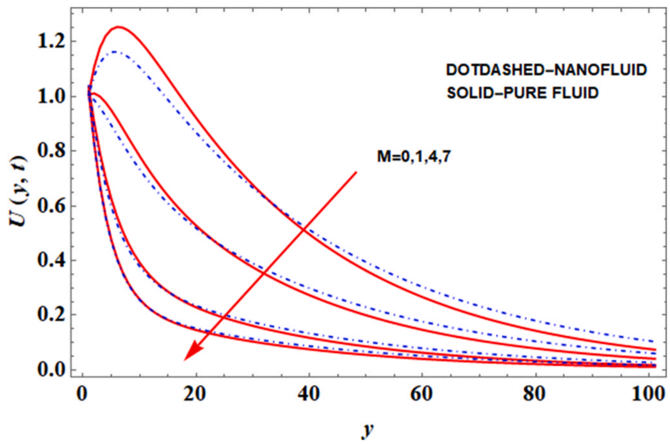

Fig. 3. U for $Cu–H_2O$ and Pure fluid with various M.

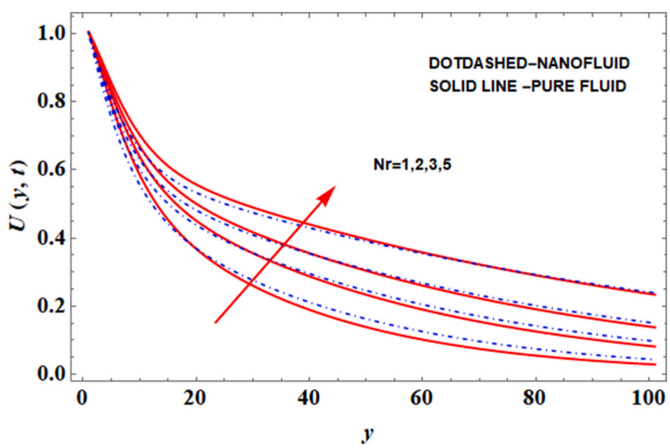

Fig. 4. U for $Cu–H_2O$ and Pure fluid with various Nr.

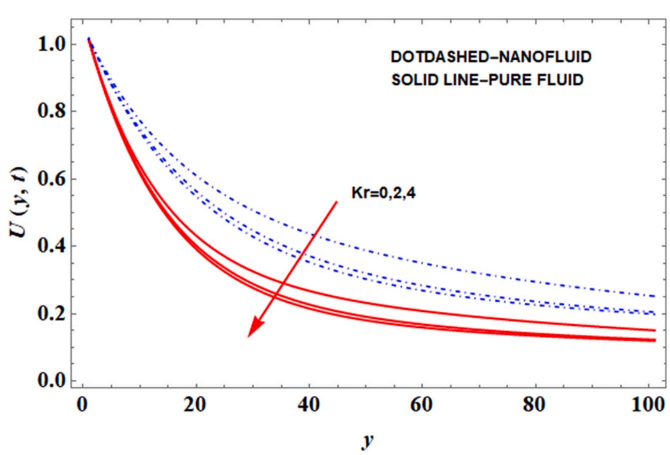

Fig. 5. U for $Cu–H_2O$ and Pure fluid with various Kr.

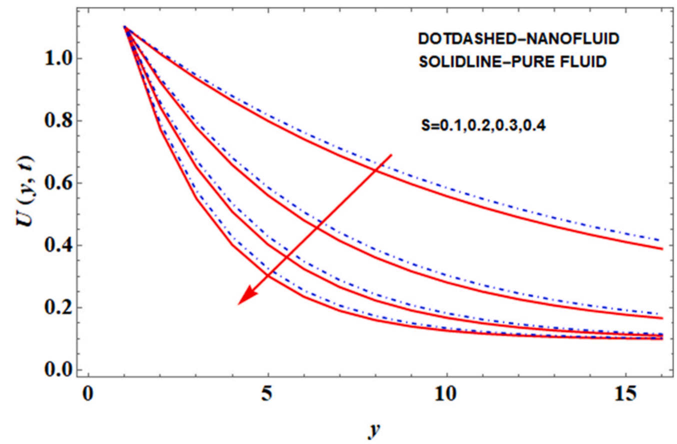

Fig. 6. U for $Cu–H_2O$ and Pure fluid with various S.

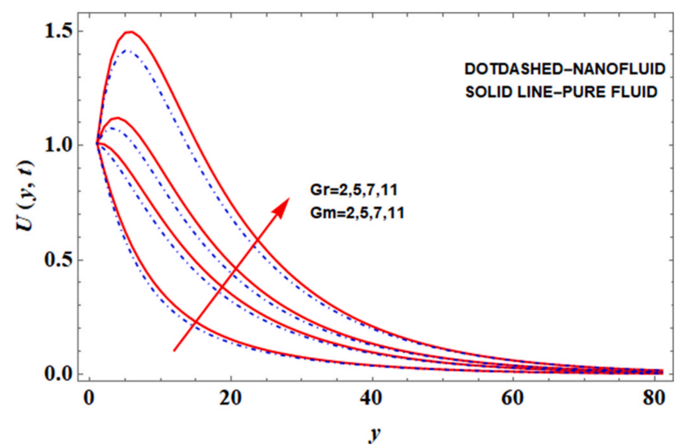

Fig. 7. U for $Cu–H_2O$ with various Gr and Gm.

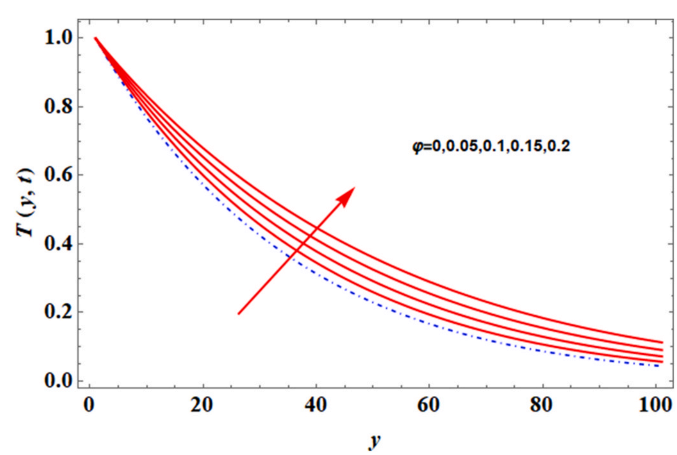

Fig. 8. T for $Cu–H_2O$ and Pure fluid with different φ

Also, the heat dissemination effect of nanofluid is greater than the base fluid because Copper is a first-class heat and electric conductor. Fig. 9 demonstrates the radiation effects in the T-profile for both pure fluid and nanofluid. As Nr($\mathrm{Nr} = 1,2,3,4$) increases then the temperature profile grows of Cu-water and pure fluid, the increment of nanofluid is greater than the pure fluid. This allows the nanofluid to discharge the heat energy then the system becomes cool. It is fact when growing the Roseland grades in a temperature increase. Fig. 10 illustrates the effect of a suction parameter $S = 1,2,3,4$ temperature profile in pure fluid and nanofluid, if suction parameter (S) rises, the temperature profile of both pure fluid and nanofluid decreases. Fig. 11 demonstrates the $\mathrm{Pr} = 0.72,2,3,5$ grows as the thermal boundary layer thickness decreases. Moreover, it gives as nanofluid temperature increment is higher than water.

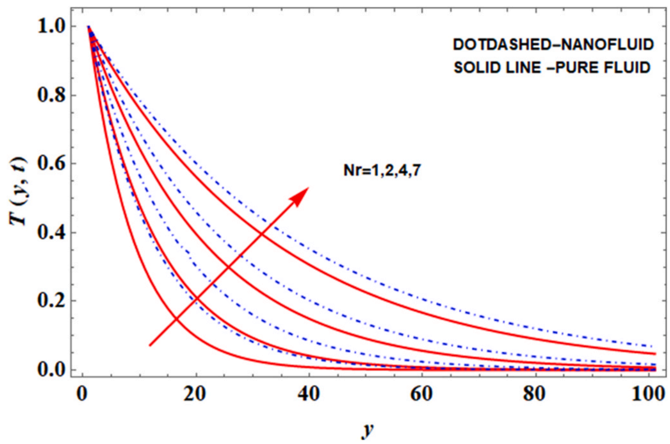

Fig. 9. T for *Cu–H$_2$O* and Pure fluid with different *Nr*.

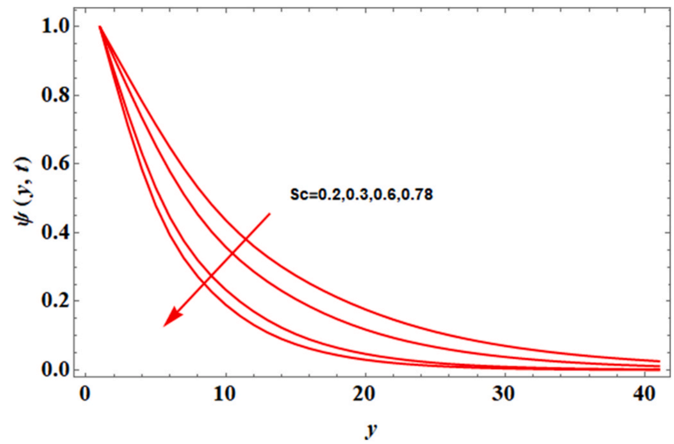

Fig. 12. ψ for two cases of $Kr = 0, 5$ with various *Sc*.

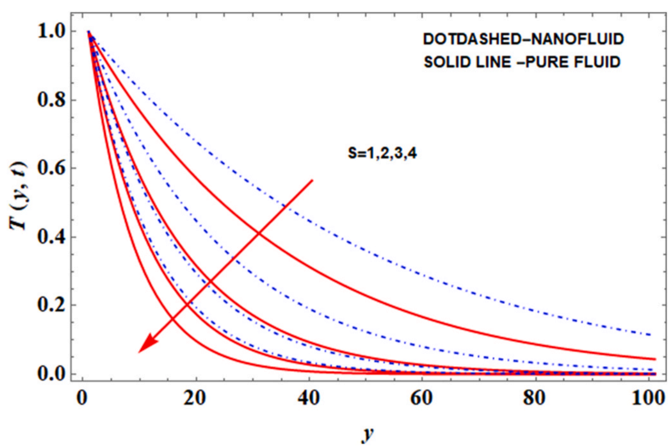

Fig. 10. T for *Cu–H$_2$O* and Pure fluid with different *S*.

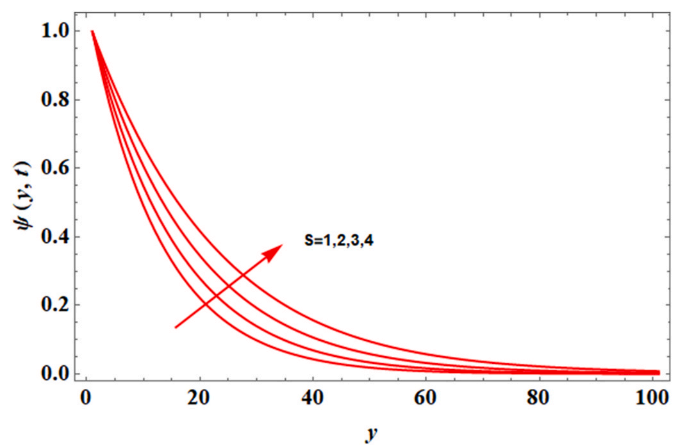

Fig. 13. ψ for *Cu–H$_2$O* with different *S*.

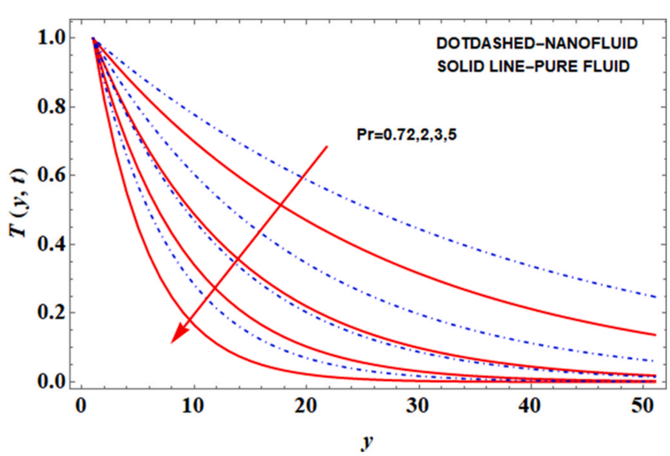

Fig. 11. T for *Cu–H$_2$O* and Pure fluid with different *Pr*.

4.3. Parameter effects on concentration profiles

Fig. 12 exposes the output of the (*S*) suction parameter concerning the concentration profiles of several species. The thickness of the solubility limit layer reduces as the concentration of the suction species rises. It is a well-known fact that absorption slows the development of boundaries. Fig. 13 displays the influence of *Kr* and heavier species concentration of *Cu*-water nano fluid. Moreover, the heavier species decelerates the concentration graph and it has taken a vital role in the mass transfer rate. Fig. 14 illustrates that as *Sc* grows, so does the concentration profile decay. As a result, the solvent boundary layer is thicker and inversely proportionate to lower *Sc* levels. When $Kr = 0$, the coefficient has a higher rate in all the real gases for higher species, and $Kr = 5$ the coefficient decreases. *Sc* values of 0.22 (hydrogen), 0.30 (helium), 0.60 (water wapour), 0.78 (amonia) were chosen. This results are excellent agreement with the results of veera krishna [41].

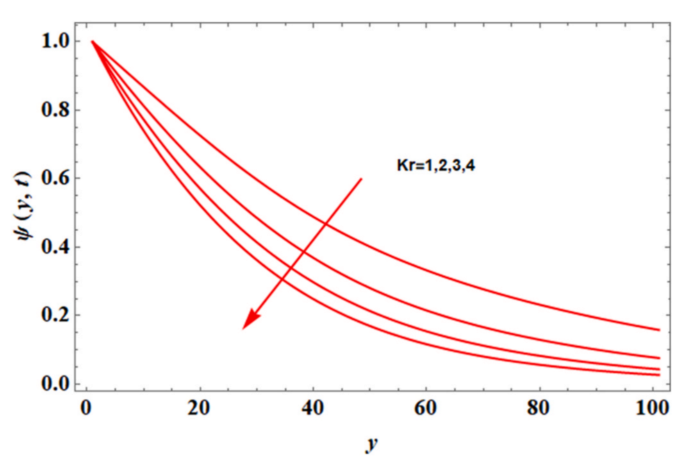

Fig. 14. ψ for *Cu–H$_2$O* with different *Kr*.

5. Conclusion

The combined impact of thermal radiation and chemical reaction on MHD free convective heat and mass transfer effects of the nanofluid have been investigated on an infinite moving upright plate. The perturbation applied to solve the dimensionless boundary layer equation with various thermo-physical properties taken into account, providing outstanding results as shown below.

- As the volume fraction of the solid particle increases, we observe that the velocity and increases consequently
- The interaction of the *Gr* and *Gm* links momentum boundary layer tension to growth velocity increase.
- The velocity of the nanofluids under temperature increased as the thermal radiation parameter *Nr* rose.
- At all cruxes, the increasing suction parameter reduces the velocity, temperature, and concentration following nanofluid fluid flow.
- The *Sc* and *Kr* parameter reduces the absorption of the nanofluid flow at all regions.
- The main findings pointed that *Cu*-water nanofluid is a better thermal conductor when compared with the conventional fluid (water), and pointed out when the *Kr* increases then the solutal boundary layer thickness decreases.

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Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

a_1	velocity along the x-direction
a_2	y - axis component velocity
B_0	transverse magnetic effects
b_1	fluid temperature
b_w	surface temperature
b_∞	ambient temperature
c_1	invariant species concentration
c_w	surface species concentration
c_∞	ambient species concentration
c_p	specific heat capacitance
Gr	thermal Grashof number
Gm	mass Grashof number
g	gravitational acceleration
K	permeability parameter
Kr	chemical reaction parameter
Nr	thermal radiation
Pr	Prandtl number
Sc	Schmidt number
S	suction parameter
t'	non-dimensional time
u_0	uniform velocity
v_0	uniform suction
M	magnetic parameter

Greek symbols

σ	Stefan-Boltzmann constant
β	thermal expansion coefficient
ρ	density
φ	solid particle volume fraction
ω	angular oscilation
ε	emissivity parameter
μ	dynamic viscosity

α	thermal diffusivity
γ	kinematic viscosity

Subscripts

f	Carrier fluid
nf	nanofluid
w	wall condition
∞	free stream level
s	solid particle

Appendix

$$
\begin{aligned}
m_1 &= \frac{ss_c \pm \sqrt{(ss_c)^2 + 4s_c k_r}}{2} \\
m_2 &= \frac{ss_c \pm \sqrt{(ss_c)^2 + 4s_c (k_r + i\omega)}}{2} \\
m_3 &= \frac{p_r s}{E_1} \\
m_4 &= \frac{p_r \pm \sqrt{(p_r s)^2 + 4E_1 p_r (i\omega)}}{2} \\
m_5 &= \frac{-s \pm \sqrt{s^2 + 4E_2 E_4 M}}{2E_2} \\
m_6 &= \frac{-s \pm \sqrt{s^2 + 4E_2 (E_r + i\omega)}}{2E_2} \\
R_1 &= \frac{E_{3Gr}}{E_2 m_3^2 - Sm_3 - E_4 M} \\
R_2 &= \frac{E_{5Gm}}{E_2 m_1^2 - Sm_1 - E_4 M} \\
R_3 &= \frac{E_{3Gr}}{(E_2 s_3^2 - E_2 s_4^2 - Ss_3 - E_4)^2 - (2s_3 s_4 - Ss_4 - \omega)^2} \\
R_4 &= \frac{E_{5Gm}}{(E_2 s_1^2 - E_2 s_2^2 - Ss_1 - E_4)^2 - (2E_2 s_1 s_2 - Ss_2 - \omega)^2} \\
s_1 &= \frac{\sqrt{2} ss_c + \sqrt{(ss_c)^2 + 4s_c k_r \pm \sqrt{(ss_c)^2 + 4(s_c k_r)^2 + 16 s_c^2 \omega^2}}}{2\sqrt{2}} \\
s_2 &= \frac{2\sqrt{2} s_c \omega}{\sqrt{(ss_c)^2 + 4s_c k_r \pm \sqrt{(ss_c)^2 + 4(s_c k_r)^2 + 16 s_c^2 \omega^2}}} \\
s_3 &= \frac{\sqrt{2} Pr + \sqrt{Prs^2 + \sqrt{(Prs)^2 + 16(E_1 \omega)^2}}}{2\sqrt{2} E_1} \\
s_4 &= \frac{\sqrt{2} \omega \sqrt{Pr}}{\sqrt{Prs^2 + \sqrt{(Prs)^2 + 16(E_1 \omega)^2}}}
\end{aligned}
$$

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