Communications in Mathematics and Applications
Vol. 14, No. 2, pp. 619–631, 2023
ISSN 0975-8607 (online); 0976-5905 (print)
Published by RGN Publications
DOI: 10.26713/cma.v14i2.2147

http://www.rgnpublications.com

Research Article

Micropolar Nanofluid Flow, Thermal and Mass Transfer Properties Across a Stretching Sheet With a Predetermined Surface Heat Flux

D. Hymavathi

Department of Mathematics, University College of Science, Mahatma Gandhi University, Yellareddygudem, Nalgonda, Telangana, India
dyapahyma@gmail.com

Received: December 21, 2022 **Accepted:** May 5, 2023

Abstract. The features of two-dimensional immiscible laminar flow of micropolar nanofluid over an unstable stretching sheet with a predetermined surface heat flux are examined in this problem. The thermal boundary conditions have an impact on heat transfer properties. The similarity transformations are utilized to transfigure highly non-linear guided PDE into ODEs. Shooting technique is used to resolve these equations. There are several flow characteristics that are relevant to this issue, including the unsteadiness parameter (S), material parameter (m), viscosity (K), Prandtl number (Pr), Brownian motion parameter (Nb), and thermophoretic parameter (Nt). Graphs are used to study the impact of various flow parameters on liquid velocity, micropolar, temperature, and nonoparticle concentration profile. In order to obtain the findings for this problem, we used the `tbvp4c` Matlab programme. We noticed that velocity profile, thermal profile, microrotation of the particle, and nanoparticle concentration profile all diminish as an unsteady number S increasing, micropolar profile increases. With a rise in boundary parameter m, the micropolar fluid profile and the concentration of nanoparticle profiles are dropping while the velocity profile and temperature profile are rising. The temperature profile is rising while the volume fraction of nanoparticle is falling as the Brownian motion Nb increasing. The thermal profile and nanoparticle concentration profile both rise with an increase in the thermophoretic number Nt. With an increasing of magnetic field parameter M, the velocity profile and micropolar profile are declining, but the thermal and nanoparticle concentration profile is rising.

Keywords. Micropolar nanofluid, Brownian motion, Thermophoresis, Unsteady parameter, Material parameter and shooting technique

Mathematics Subject Classification (2020). 74F05, 80A19

1. Introduction

It is common knowledge that heat transfer plays a crucial role in flow mechanism of many industrial processes. Orthodox liquids have poor thermal conductivity, resulting in restrictive applications in engineering fields. This shortcoming of the fluids was taken into account by Choi and Eastman [6]. Due to the ideal potential of heat and mass exchanging impacts, the nanofluids have pulled in consideration of analysis worldwide, this model is becoming more widely used since it empowers us to efficiently explore different applications in the marvel of science and technology. Hybrid nanofluid had been explored as a new class of nanofluid it is marked by Subhani and Nadeem [32]. Kalyani *et al*. [18], and Sundarnath and Muthucumarswamy [33] investigated and analyzed the diffusion and ramped temperature influences through porous medium of MHD fluid flows. Fluids having microstructure are known as micropolar fluids. They fall under the category of fluids with nonsymmetry stress tensors that we will refer to as polar fluids, which also includes the well-known Navier-Stokes model of classical fluids can be thought of as fluids made up of rigid, randomly oriented (or spherical) particles suspended in a viscous medium without consideration for the fluid particles deformation. In the research of the thermo-micropolar fluids, the model of micropolar fluids proposed by Eringen [8] also produced other types of micropolar fluids, Eringen [10] first included the thermal effects in an isotropic medium before extending his theory to the anisotropic medium. The memory-dependent orientable non-local micropolar fluids were recently introduced by Eringen [7,9]. Bourantas *et al*. [5] Developed a theoretical model for micropolar nanofluid with consideration of microrotation of the nano size particle. Patel *et al*. [25] analyzed computationally the effect of radiative micro polar nanofluids flow over a stretching and shinking sheet. Computational study done by Rafique *et al*. [29] for the micropolar nanofluid through an inclined surface. Several studies on the effects of MHD on the stretched sheet have been published in literature. These studies include a wide range of heat transfer-related flows, including MHD power producers, solar energy devices, and biomedical field for hyperthermia cancer cure and brain tumour therapy. The process of crystal development creates a flow of the micropolar liquid in boundary on a constantly moving plane as an important topic of research due to their valued affects in many engineering and industrial operations like plastic sheet extrusion and polymer. Stepha and Jacob [31] investigated the physical properties for temperature dependent heat and mass transfer flow of MHD microplar nanofluid. Non-Fourier heat flux model was developed for micropolar MHD flow across a coagulated sheet by Kumar *et al*. [19]. Radiation effects and Buoyancy forces with viscous dissipation of MHD nanofluid across a stretching sheet is studied by Assres *et al*. [3], and Hymavathi *et al*. [13], Anuar and Bachok [2] developed and analyzed the mathematical modeling of unsteady Cu-Al_2O_3 fluid flow with the effect of thermal radiation. With effect of convective boundary conditions, a triple solution for micropolar nanofluid over an exponentially permeable shrinking surface along with radiation explored by Lund *et al*. [21]. Ibrahim and Zemedu [16], and Ibrahim and Gadisa [17] computationally examined micropolarnanofluid over a nonisothermal rotating disk and stretching surface by employing finite element analysis and `bvp4c` technique. The flow caused by a stretching sheet with heat transfer is now the subject of a wealth of literature. A theoretical study for ternary nanofluid flow past a stretching sheet was investigated by

Manjunatha *et al*. [22]. Rashidi *et al*. [30] investigated the radiation and Buoyancy effects on MHD nanofluid over a stretching sheet. A computational analysis was explored for the Maxwell nanfluid over stretched sheet with thermal radiation by Mukhtar *et al*. [24]. Gangadhar *et al*. [11] spectral quasi-linearization method was employed for micropolar ferrofluid flow past a stretching surface. On an inclined surface with the help of Keller-Box technique, a computation result was obtained by Rafique *et al*. [28]. By consideration cross-diffusion and radiative heat transport of polar nanofluid is developed by by Mishra *et al*. [23]. Computationally investigated the flow past a bidirectional stretching sheet for MHD nanofluid by Ahmad *et al*. [1]. A slip flow on a stretching/ shrinking sheet for unsteady micropolar nanofluid is investigated by Latiff *et al*. [20], Pourmehran *et al*. [27] explored the numerical solution for the flow induced by stretching sheet of an external magnetic field of MHD nanofluid. Apart from all these research Hsiao [12] explored the impacts of viscous dissipation of micropolar nanofluid with multimedia feature over a stretching sheet. Prandtl nanofluid flow due to heated stretching sheet under the control of radiation and chemical reaction is investigated by Patil *et al*. [26]. Recently, many researchers [4, 14, 15] investigated computationally and analyzed the results of boundary layer flow of MHD nanofluids with impacts of different geometrical conditions by employing finite difference scheme. Beneficial to address a noted deficiency, we set out investigate a combined impacts of mass and thermal transfer on hydro dynamic magnetic flow of micropolar nanoliquid across a stretching sheet with convective boundary conditions. The higher ordered coupled ordinary differential equations were solved via shooting method. Graphical representations are used, together with numerical values assigned for the specified physical parameters.

2. Mathematical Formulation

Ponder about the laminar flow of an incompressible micropolar nanofluid in two dimensions across a stretching sheet. The sheet is abruptly stretched at time $t=0$ along the x-axis with velocity $U_w(x,t)$ let the genesis fixed in the liquid at temperature at ambiance T. Positive x-axis of the stationary Cartesian coordinate system extends along the sheet from its origin at the leading edge, and the y-axis is measured perpendicular to the sheets surface. It is possible to write the boundary layer equations as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\left(\frac{\mu+k}{\rho}\right)\frac{\partial^2 u}{\partial y^2}+\frac{k}{\rho}\frac{\partial w}{\partial x}-\frac{\sigma B_0^2(x)}{\rho}u, \tag{2}$$

$$\rho j\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}\right)=\gamma\frac{\partial^2 w}{\partial y^2}-K\left(2w+\frac{\partial u}{\partial y}\right), \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right], \tag{4}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right), \tag{5}$$

subject to the boundary conditions

$$\left.\begin{array}{l} u = U_w,\ v = 0,\ w = -m\frac{\partial u}{\partial y},\ \frac{\partial T}{\partial y} = -\frac{q_w}{k} \text{ at } y = 0, \\ u \to 0,\ w \to 0,\ T \to T_\infty,\ C \to C_\infty \text{ as } y \to \infty, \end{array}\right\} \tag{6}$$

where m boundary parameter with $0 \le 1 \le m$, u, v are velocity components in directions x and y respectively, T is a fluid heat while in the barrier layer, w is micorotation or oblique velocity and j, γ, μ, K, ρ, and α are the micro inertia per mass unit, gradient spin viscosity, spirited viscosity, liquid density, gyre viscosity, and diffusivity. Assumed that stretching speed $U_w(x,t)$ and the surface thermal flux $q_w(x,t)$ are of in the forms $U_w(x,t) = \frac{ax}{1-ct} q_w(x,t) = \frac{bx}{1-ct}$ where a, b, c are taken as constants such that $a > 0$, $b \ge 0$, $c \ge 0$ (with $ct < 1$) and a and c possess dimension time^{-1}. It has to be noted at $t = 0$ (initial motion), the governing eqs. (1)-(5) define the uniform flow on a stretching surface. These particular forms $U_w(x,t)$ and $q_w(x,t)$ have been taken in order to be able to devise a suitable substitution, it converts governing PDEs (1)-(5) into set of ODEs, thereby facilitating the exploration of the impacts of the controlling numbers. The spin-gradient viscosity γ can be defined as $\gamma = (\mu + k/2)j = \mu\left(1+\frac{K}{2}\right)j$ where $K = k/\mu$ dimensionless viscosity ratio and is called the material parameter. The relation $U_w(x,t)$ and $q_w(x,t)$ are implore to permit the equations the appropriate behavior in the restrict case when impacts of microstructure become ignorable and the total spin w reduces to angular speed. The continuity eq. (1) fulfilled by assuming a stream function ψ defined as

$$u = \frac{\partial \psi}{\partial y},\quad v = -\frac{\partial \psi}{\partial x}. \tag{7}$$

The following transformation can be used to convert the equations for momentum, angular momentum, and energy into their equivalent ordinary differential equations

$$\eta = \left(\frac{U_w}{vx}\right)^{\frac{1}{2}},\quad \psi = (vxU_w)^{\frac{1}{2}} f(\eta),\quad w = U_w\left(\frac{U_w}{vx}\right)^{\frac{1}{2}} g(\eta),$$

$$\theta(\eta) = \frac{k(T-T_\infty)}{q_w}\left(\frac{U_w}{vx}\right)^{\frac{1}{2}},\quad \phi(\eta) = \frac{k(C-C_\infty)}{q_w}\left(\frac{U_w}{vx}\right)^{\frac{1}{2}},$$

where η the similarity variable and transformed nonlinear ordinary differential equation are:

$$(1+K)f''' + ff'' - f'^2 + Kg' - S\left(f' + \frac{1}{2}\eta f''\right) - Mf' = 0, \tag{8}$$

$$\left(1+\frac{K}{2}\right)g'' + fg' - f'g - K(2g + f'') - S\left(\frac{3}{2}g + \frac{1}{2}\eta g'\right) = 0, \tag{9}$$

$$\frac{1}{Pr}\theta'' + f\theta' - f'\theta - S\left(\theta + \frac{1}{2}\eta\theta'\right) + Nb\theta'\phi' + Nt\theta'^2 = 0, \tag{10}$$

$$\frac{1}{Sc}\phi'' + f\phi' - f'\phi - S\left(\phi + \frac{1}{2}\eta\phi'\right) + \frac{Nt}{Nb}\theta'' = 0, \tag{11}$$

where prime represents derivative with respect to η, $Pr = \frac{\vartheta}{\alpha}$ is Prandtl number, $S = \frac{c}{a}$ is unsteadiness parameter, $Nb = \frac{D_B\tau}{\alpha}$ is Brownian motion and $Nt = \frac{D_B\tau}{T_\infty}$, is thermophoresis and $Sc = \frac{\vartheta}{D}$ is Schmidt number.

The boundary conditions become

$$\left.\begin{array}{l} f(0)=0,\ \ f'(0)=0,\ \ g(0)=-mf''(0),\ \ \theta'(0)=-1,\ \ \phi'(0)=-1, \\ f'(\eta)\to 0,\ \ g(\eta)\to 0,\ \ \theta(\eta)\to 0,\ \ \phi(\eta)\to 0\ \text{ as } \eta\to\infty \end{array}\right\} \tag{12}$$

3. Numerical Method

To obtain the computational results of equations with respect to the boundary conditions (7)-(12), Shooting technique is employed. Conditions (7)-(11) are reduced to the first order ordinary differential equations, such that

$$f(\eta)=f(1),\ \ f'(\eta)=f(2),\ \ f''(\eta)=f(3),\ \ g(\eta)=f(4),\ \ g'(\eta)=f(5),\ \ \theta(\eta)=f(6),$$
$$\theta'(\eta)=f(7),\ \ \phi(\eta)=f(8),\ \ \phi'(\eta)=f(9).$$

The reduced ordinary differential equations become

$$(1+K)f'(3)=f^2(2)-f(1)f(3)-Kf(5)+S\left(f(2)+\frac{1}{2}\eta f(3)\right)+Mf(2),$$
$$\left(1+\frac{K}{2}\right)f'(5)=-f(1)f(5)+f(2)f(4)+K(2f(4)+f(3))+S\left(\frac{3}{2}f(4)+\frac{1}{2}\eta f(5)\right),$$
$$\frac{1}{Pr}f'(7)=-f(1)f(7)+f(2)f(6)+S\left(f(6)+\frac{1}{2}\eta f(7)\right)-Nb\,f(7)f(9)Nt\,f(7),$$
$$\frac{1}{Sc}f'(9)=-f(1)f(9)+f(2)f(8)+S\left(f(8)+\frac{1}{2}\eta f(9)\right)-\frac{Nt}{Nb}f'(7).$$

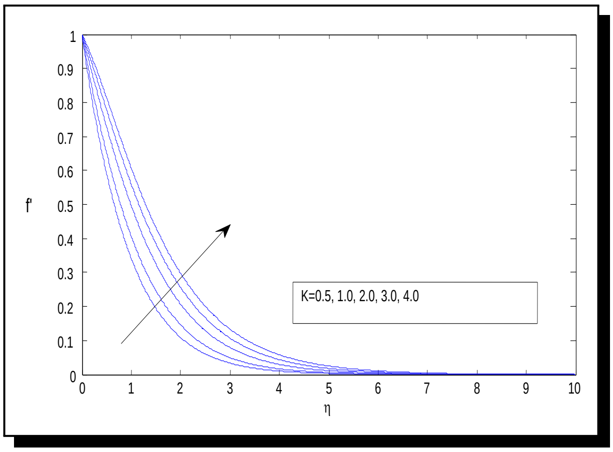
Appropriate transformed boundary conditions are

$$fa(1)=0,\ \ fa(2)=0,\ \ fa(4)=-mfa(3),\ \ fa(7)=-1,\ \ fa(9)=-1,$$
$$fb(2)=0,\ \ fb(4)=0,\ \ fb(6)=0,\ \ fb(8)=0.$$

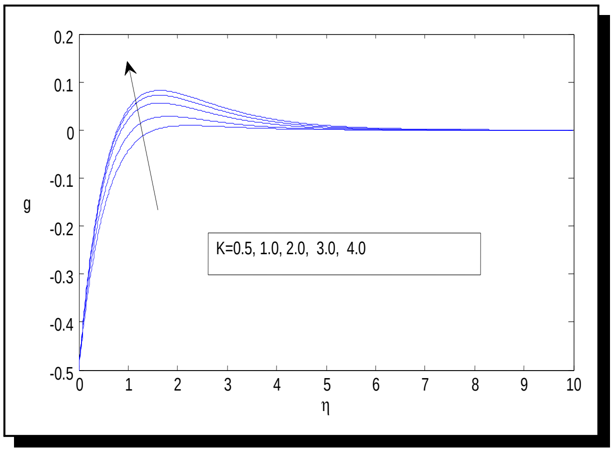
4. Results and Discussion

It is possible to perform a parametric research using the numerical findings, which demonstrate the effects of the unsteadiness parameter S, viscosity parameter K, boundary parameter m, Nb Brownian motion parameter, thermophoretic parameter Nt, and Prandtl number Pr. Cases of $S=0$ (steady-state flow) and $K=0$ (viscous fluid) have also been taken into consideration for the numerical method know as shooting method employed in this work to be validated and the results accurate.

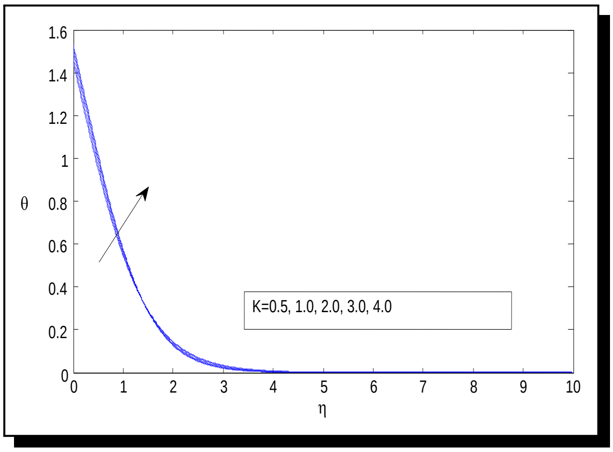
The viscosity of a fluid measures its resistance to flow under an applied shear stress. Figures 1(a)-(d) illustrate the impacts of Viscosity, they indicate that as viscosity value k increases, velocity profile, micropolar profile, and temperature profile rise while nanoparticle volume fraction profile falls, and it is clear that as k rises the boundary layer thickness does too. As k rises, the velocity gradient near the surface reduces. As results, the drag of micropolar fluids is lower than that of viscous fluids. The consequences of unsteady number S on velocity, micropolar, thermal and volume fraction profile of nanoparticles are shown in Figures 2(a)-(d). Unsteady flow is a flow in which the amount of liquid flowing per second varies. Unsteady flow is a momentary occurrence. With time the flow can stabilities or ceases entirely. The momentum profile, temperature profile, and nanoparticle volume fraction profile all show a decline with an increasing of unsteady number S, however the micropolar profile shows an increase, signifying an increase in the rate of heat pass on at the surface.



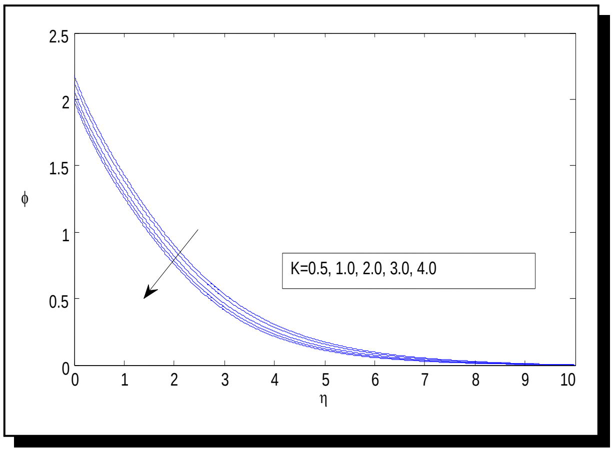
(a) Effects of viscosity on velocity profile



(b) Effects of viscosity on micropolar profile



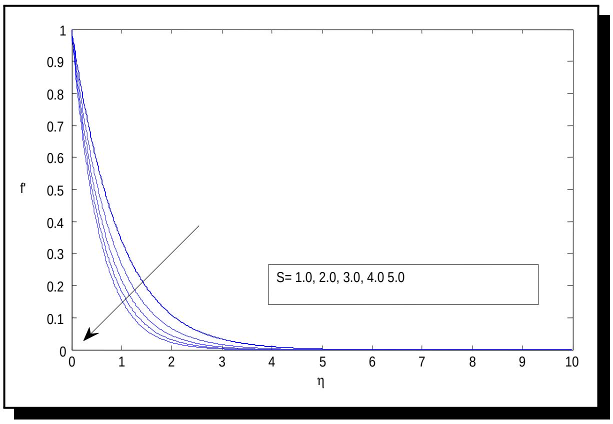
(c) Effects of viscosity on temperature profile



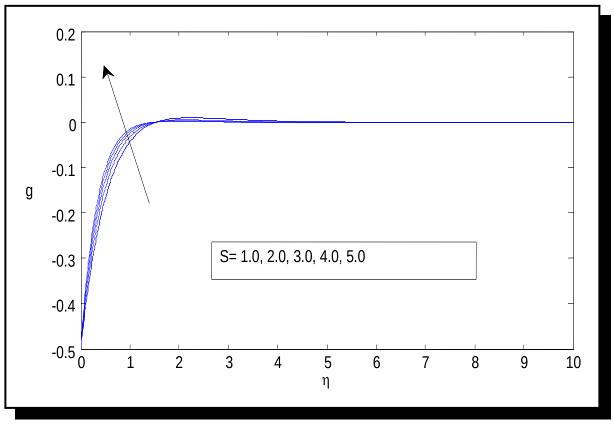
(d) Effects of viscosity on nano particles

Figure 1

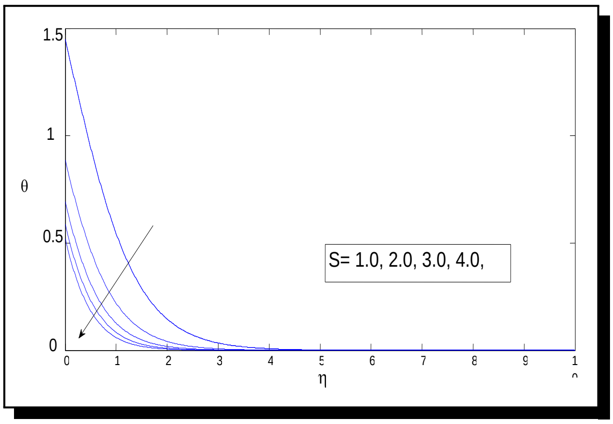
We examine the impacts of boundary parameter m on momentum, micropolar fluid, temperature, and concentration of nanofluid particles from Figures 3(a)-(d). The velocity and temperature profiles grow as the boundary parameter increases, whereas the micropolar fluid profile and the concentration of nanoparticle profiles decrease. The impact of the Brownian parameter Nb on thermal profile and concentration profiles are shown in Figures 4(a)-(d). The temperature profile is rising while the volume fraction of nanoparticles is failing as the Brownian motion parameter raises. The liquid temperature increases as a result of big Brownian parameter Nb, which confirms the cause of the delayed expansion in the measurement of nanoparticles with Nb. Figure 5(a)-(b) shown that thermal profile and nanoparticle concentration profile are increasing with an increases of the thermophoresis parameter Nt. Since under a constant thermal gradient, the thermophoresis mechanism is connected to elements averaged Brownian motion. The effects of Prandtl number Pr on temperature and the volume fraction profile of nanoparticles are depicted in Figures 6(a)-(b).



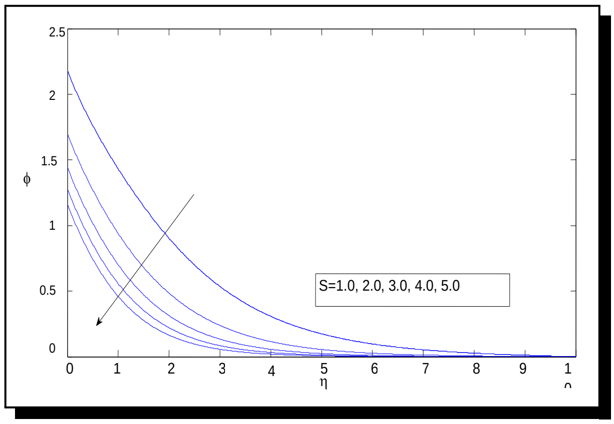
(a) Effects of unsteady number on velocity profile



(b) Effects of unsteady parameter on micropolar profile



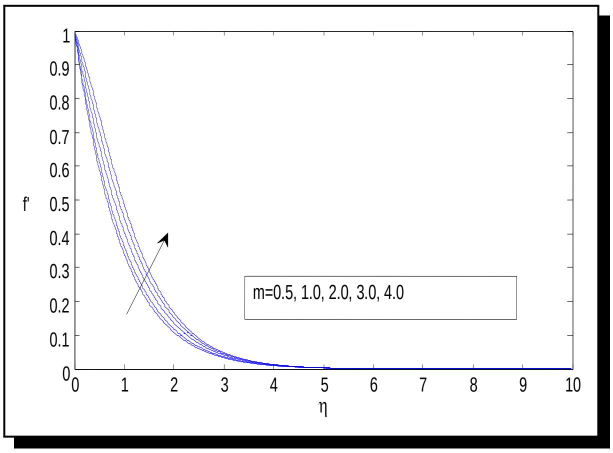
(c) Effects of unsteady parameter on temperature profile



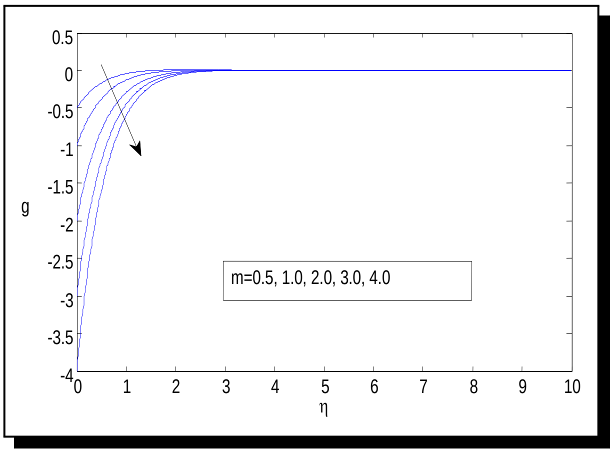
(d) Effects of unsteady number on nano particles

Figure 2

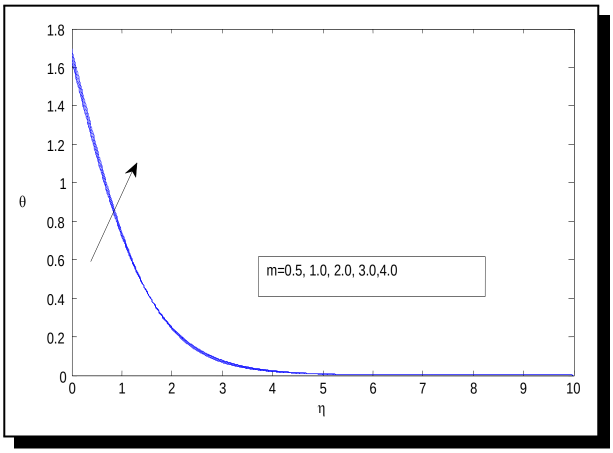
The temperature drops as Prandtl number rises, while the volume fraction profiles of nanoparticles rise. When $Pr \gg 1$, the thermal boundary layers viscous forces and the bigger viscous boundary layers viscous and inertial forces are both in equilibrium. The Prandtl number has no effect on velocity and micropolar fluid motion according to the governed momentum and micropolar angular velocity equations. The lowest diffusivity at the highest Pr causes temperature decline. Schmidt number Sc, which is a ratio of liquid boundary layer to salutal transfer thickness boundary layer, has an effect on temperature profile and nanoparticle volume fraction profile, as shown in Figures 7(a)-(b). When a result, the graph shows that as Schmidt value rises, the thermal profile and volume fraction of nanoparticles both decline. Figures 8(a)-(d) show the impact of magnetic parameters on different flow parameters. For all values of M, the velocity profile starts at its highest values at the plane and it gradually declines till it reaches its lowest value at, the end of the boundary. Presents of magnetic field number M in thermally conducting liquid introduces forces like pressure of Lorentz, which works against liquid flow if a magnetic field is applied in the normal as in the current issue. It is interesting to observe that influence of magnetic force is most pronounced at a point of peak number. Velocity profile is lowered as a result. The velocity and micropolar profiles are decreasing as magnetic parameter M increases. However, as magnetic parameter increases, so do the thermal profile and nanoparticle concentration profile.



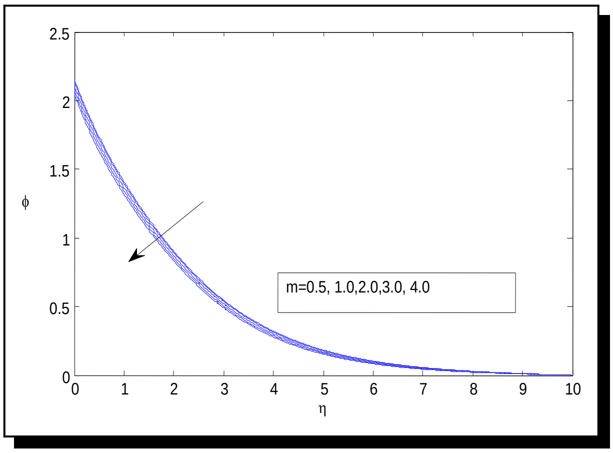
(a) Effects of boundary number on velocity profile



(b) Effects of boundary parameter on micropolar profile

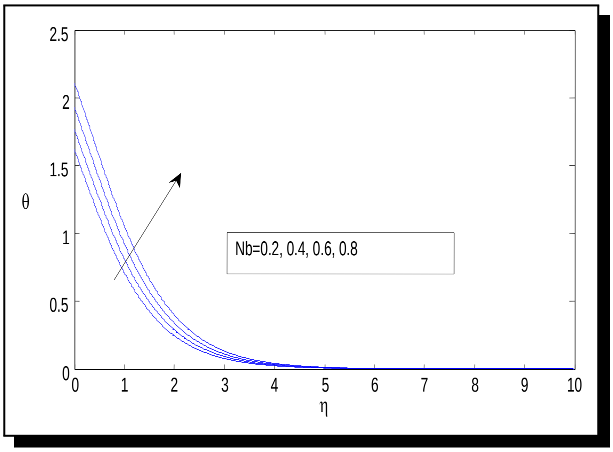


(c) Effects of boundary parameter on thermal profile

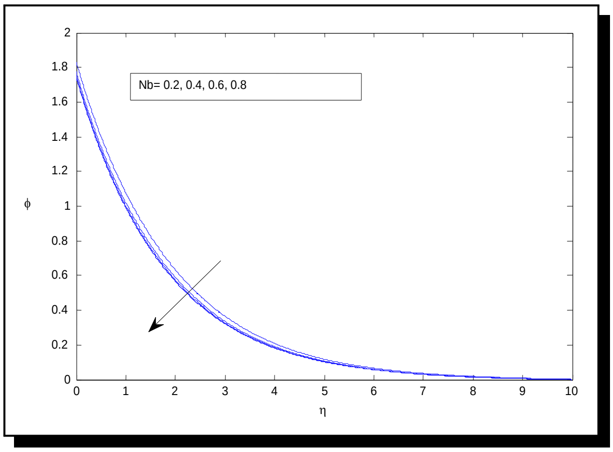


(d) Effects of boundary parameter on nano particles

Figure 3

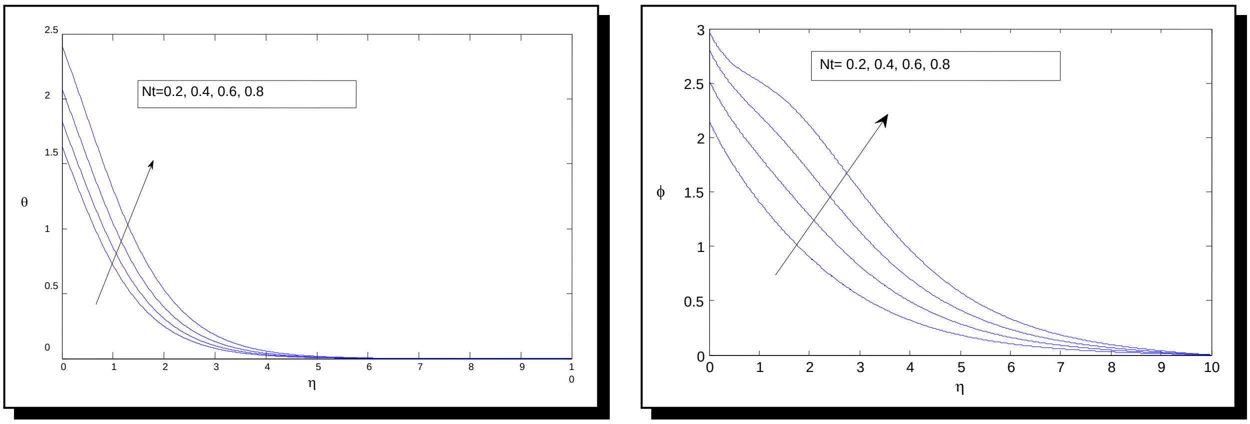


(a) Effects of Brownian number on temperature



(b) Effects of Brownian number on nano particles

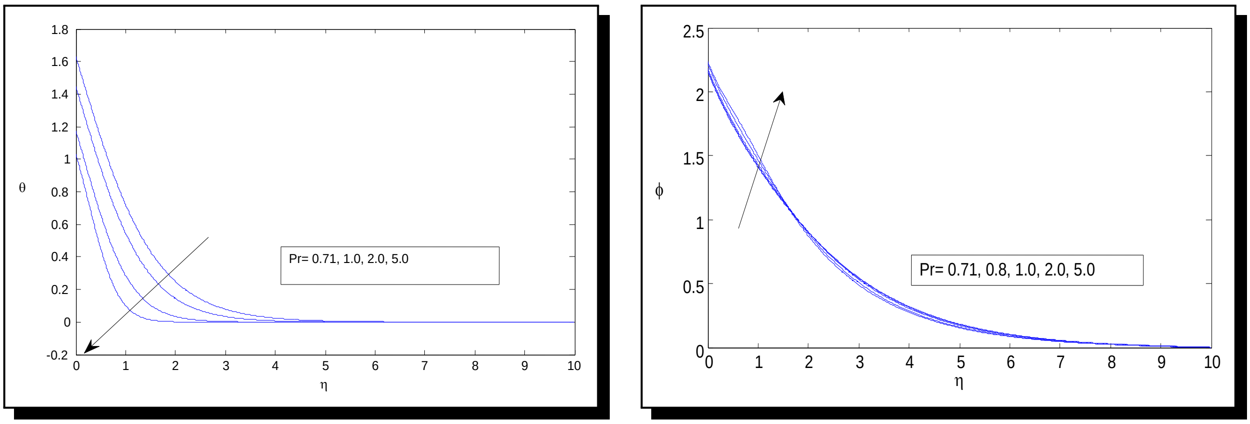
Figure 4



(a) Effects of thermophoresis number on Temperature profile

(b) Effects of thermophoresis on nano particles

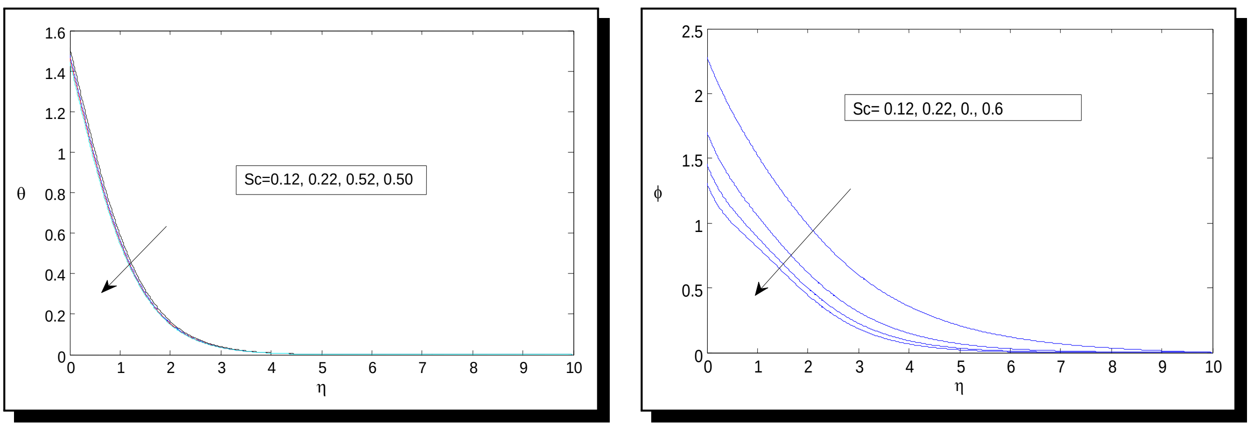
Figure 5



(a) Effects of Prandtle number on temperature profile

(b) Effects of Prandtl number on nano particles

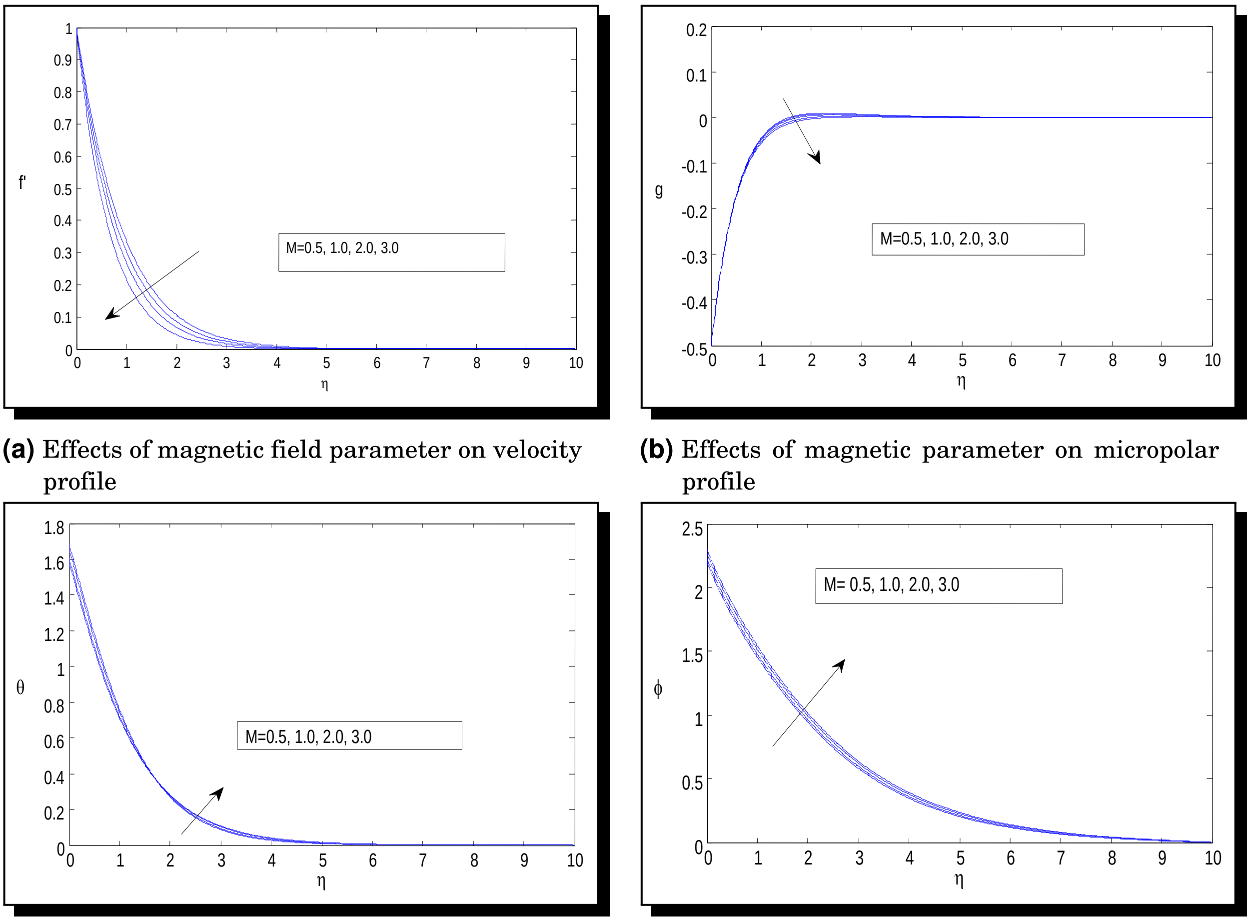
Figure 6



(a) Effects of Schmidt number on temperature

(b) Effects of Schmidt number on nano particles

Figure 7



(a) Effects of magnetic field parameter on velocity profile

(b) Effects of magnetic parameter on micropolar profile

(c) Effects of magnetic parameter on temperature profile

(d) Effects of magnetic parameter on nanoparticle volume fraction profile

Figure 8

5. Conclusions

The temperature, concentration, microrotation, and velocity of the nanofluid across a stretching plane have all been computationally investigated. The parameters unsteadiness parameter S, material parameter m, viscosity K, Prandtl number Pr, Brownian motion Nb, and thermophoresis Nt parameter are all put into practice. Additionally, a graphic representation of how the aforementioned parameters affect the fluid properties at the boundary is provided.

The following are the final conclusions

- Although the micropolar profile indicates that an increases, the velocity, thermal, and nanoparticle concentration profile all show a reduction with an increase in the unsteady parameter S.
- While the micropolar fluid profile and the concentration of nanoparticles decrease as the boundary parameter rises, the velocity and temperature profiles climb.
- The controlled momentum and micropolar angular velocity equations show that the Prandtl number has no impact on velocity or micropolar fluid motion.

- The thermal profile and the concentration profile of nanoparticles both decreases as the Schmidt number increases.
- As a magnetic field parameter rises, the momentum and micropolar profiles fall. However, the temperature profileand nanoparticle volume fraction profile also grow as the magnetic parameter does.

Competing Interests

The author declares that he has no competing interests.

Authors' Contributions

The author wrote, read and approved the final manuscript.

References

[1] R. Ahmad, M. Mustafa, T. Hayat and A. Alsaedi, Numerical study of MHD nanofluid flow and heat transfer past a bidirectional exponentially stretching sheet, *Journal of Magnetism and Magnetic Materials* **407** (2016), 69 – 74, DOI: 10.1016/j.jmmm.2016.01.038.

[2] N. S. Anuar and N. Bachok, Double solutions and stability analysis of micropolar hybrid nanofluid with thermal radiation impact on unsteady stagnation point flow, *Mathematics* **9**(3) (2021), 1 – 18, DOI: 10.3390/math9030276.

[3] H. D. Assres, D. Hymavathi and N. Kishan, Heat transfer of a nanofluid over a stretching sheet with velocity slip and temperature jump in porous medium in the presence of chemical reaction and radiation, *Journal of Advances in Mathematics* **9**(6) (2014), 2710 – 2722.

[4] N. Bachok, A. Ishak and R. Nazar, Flow and heat transfer over an unsteady stretching sheet in a micropolar fluid with prescribed surface heat flux, *International Journal of Mathematical Models and Methods in Applied Sciences* **4**(3) (2010), 167 – 176, URL: https://www.naun.org/main/NAUN/ijmmas/19-354.pdf.

[5] G. C. Bourantas and V. C. Loukopoulos, Modeling the natural convective flow of micropolar nanofluids, *International Journal of Heat and Mass Transfer* **68** (2014), 35 – 41, DOI: 10.1016/j.ijheatmasstransfer.2013.09.006.

[6] S. U. S. Choi and J. A. Eastman, Enhancing thermal conductivity of fluids with nanoparticles, in: *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, (1995), URL: https://www.osti.gov/servlets/purl/196525.

[7] A. C. Eringen, Memory-dependent orientable nonlocal micropolar fluids, *International Journal of Engineering Science* **29**(12) (1991), 1515 – 1529, DOI: 10.1016/0020-7225(91)90123-K.

[8] A. C. Eringen, Micropolar fluids with stretch, *International Journal of Engineering Science* **7**(1) (1969), 115 – 127, DOI: 10.1016/0020-7225(69)90026-3.

[9] A. C. Eringen, Theory of anisotropic micropolar fluids, *International Journal of Engineering Science* **18**(1) (1980), 5 – 17, DOI: 10.1016/0020-7225(80)90003-8.

[10] A. C. Eringen, Theory of thermomicrofluids, *Journal of Mathematical Analysis and Applications* **38**(2) (1972), 480 – 496, DOI: 10.1016/0022-247X(72)90106-0.

[11] K. Gangadhar, D. Vijayakumar, A. J. Chamkha, T. Kannan and G. Sakthivel, Effects of Newtonian heating and thermal radiation on micropolar ferrofluid flow past a stretching surface: Spectral quasi-linearization method, *Heat Transfer* **49**(2) (2019), 838 – 857, DOI: 10.1002/htj.21641.

[12] K.-L. Hsiao, Micropolar nanofluid flow with MHD and viscous dissipation effects towards a stretching sheet with multimedia feature, *International Journal of Heat and Mass Transfer* **112** (2017), 983 – 990, DOI: 10.1016/j.ijheatmasstransfer.2017.05.042.

[13] D. Hymavathi and K. Naikoti, Study on radiative MHD nanofluid flow over a vertically stretching sheet in the presence of buoyancy forces with viscous dissipation, *Newest Updates in Physical Science Research* **10** (2021), 44 – 58, DOI: 10.9734/bpi/nupsr/v10/2523E.

[14] D. Hymavath, S. Jagadha and N. Kishan, Hall current effects on MHD free convection nanofluid over an inclined hot plate with viscous dissipation, *Journal of Ultra Scientist of Physical Sciences* **31**(4) (2019), 32 – 42, DOI: 10.22147/jusps-a/310401.

[15] D. Hymavathi, K. Naikoti and Jagada, Effects of MHD free convective heat transfer of micropolar nanofluid over vertical plate along with the chemical reaction and thermal radiation, *Advances and Applications in Fluid Mechanics* **22**(1) (2019), 1 – 23, DOI: 10.17654/fm022010001.

[16] W. Ibrahim and C. Zemedu, MHD nonlinear natural convection flow of a micropolar nanofluid past a nonisothermal rotating disk, *Heat Transfer* **50**(1) (2021), 564 – 595, DOI: 10.1002/htj.21894.

[17] W. Ibrahim and G. Gadisa, Finite element analysis of couple stress micropolar nanofluid flow by non-Fourier's law heat flux model past stretching surface, *Heat Transfer – Asian Research* **48**(8) (2019), 3763 – 3789, DOI: 10.1002/htj.21567.

[18] C. Kalyani, M. C. K. Reddy and N. Kishan, MHD mixed convection flow past a vertical porous plate in a porous medium with heat source/sink and soret effects, *Chemical Science International Journal* **7**(3) (2015), 150 – 159, DOI: 10.9734/acsj/2015/16257.

[19] K. A. Kumar, V. Sugunamma and N. Sandeep, A non-Fourier heat flux model for magnetohydrodynamic micropolar liquid flow across a coagulated sheet, *Heat Transfer – Asian Research* **48**(7) (2019), 2819 – 2843, DOI: 10.1002/htj.21518.

[20] N. A. A. Latiff, M. J. Uddin, O. A. Bég and A. I. Ismail, Unsteady forced bioconvection slip flow of a micropolar nanofluid from a stretching/shrinking sheet, Unsteady forced bioconvection slip flow of a micropolar nanofluid from a stretching/shrinking sheet, *Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanomaterials, Nanoengineering and Nanosystems*, **230**(4) (2016), 177 – 187, DOI: 10.1177/1740349915613817.

[21] L. A. Lund, Z. Omar, J. Raza and I. Khan, Triple solutions of micropolar nanofluid in the presence of radiation over an exponentially preamble shrinking surface: Convective boundary condition, *Heat Transfer* **49**(5) (2020), 3075 – 3093, DOI: 10.1002/htj.21763.

[22] S. Manjunatha, V. Puneeth, B. J. Gireesha and A. J. Chamkha, Theoretical study of convective heat transfer in ternary nanofluid flowing past a stretching sheet, *Journal of Applied and Computational Mechanics* **8**(4) (2022), 1279 – 1286, DOI: 10.22055/JACM.2021.37698.3067.

[23] S. Mishra, B. Mahanthesh, J. Mackolil and P. K. Pattnaik, Nonlinear radiation and cross-diffusion effects on the micropolar nanoliquid flow past a stretching sheet with an exponential heat source, *Heat Transfer* **50**(4) (2021), 3530 – 3546, DOI: 10.1002/htj.22039.

[24] T. Mukhtar, W. Jamshed, A. Aziz and W. Al-Kouz, Computational investigation of heat transfer in a flow subjected to magnetohydrodynamic of Maxwell nanofluid over a stretched flat sheet with thermal radiation, *Numerical Methods for Partial Differential Equations* **39**(5) (2020), 3499 – 3519, DOI: 10.1002/num.22643.

[25] H. R. Patel, A. S. Mittal and R. R. Darji, MHD flow of micropolar nanofluid over a stretching/shrinking sheet considering radiation, *International Communications in Heat and Mass Transfer* **108** (2019), 104322, DOI: 10.1016/j.icheatmasstransfer.2019.104322.

[26] A. B. Patil, P. P. Humane, V. S. Patil and G. R. Rajput, MHD Prandtl nanofluid flow due to convectively heated stretching sheet below the control of chemical reaction with thermal radiation, *International Journal of Ambient Energy* **43**(1) (2022), 4310 – 4322, DOI: 10.1080/01430750.2021.1888803.

[27] O. Pourmehran, M. Rahimi-Gorji and D. D. Ganji, Heat transfer and flow analysis of nanofluid flow induced by a stretching sheet in the presence of an external magnetic field, *Journal of the Taiwan Institute of Chemical Engineers* **65** (2016), 162 – 171, DOI: 10.1016/j.jtice.2016.04.035.

[28] K. Rafique, M. I. Anwar, M. Misiran and M. I. Asjad, Energy and mass transport of micropolar nanofluid flow over an inclined surface with Keller-Box simulation, *Heat Transfer* **49**(8) (2020), 4592 – 4611, DOI: 10.1002/htj.21843.

[29] K. Rafique, H. Alotaibi, T. A. Nofal, M. I. Anwar, M. Misiran and I. Khan, Numerical solutions of micropolar nanofluid over an inclined surface using keller box analysis, *Journal of Mathematics* **2020** (2020), Article ID 6617652, DOI: 10.1155/2020/6617652.

[30] M. M. Rashidi, N. V. Ganesh, A. K. A. Hakeem and B. Ganga, Buoyancy effect on MHD flow of nanofluid over a stretching sheet in the presence of thermal radiation, *Journal of Molecular Liquids* **198** (2014), 234 – 238, DOI: 10.1016/j.molliq.2014.06.037.

[31] N. G. Stepha and D. K. Jacob, Analysis on physical properties of micropolar nanofluid past a constantly moving porous plate, *IOP Conference Series: Materials Science and Engineering* **1206** (2021), 012004, DOI: 10.1088/1757-899x/1206/1/012004.

[32] M. Subhani and S. Nadeem, Numerical analysis of micropolar hybrid nanofluid, *Applied Nanoscience* **9** (2019), 447 – 459, DOI: 10.1007/s13204-018-0926-2.

[33] J. K. Sundarnath and R. Muthucumarswamy, Hall effects on Mhd flow past an accelerated plate with heat transfer, *International Journal of Applied Mechanics and Engineering* **20**(1) (2015), 171 – 181, DOI: 10.1515/ijame-2015-0012.