Advances in Nano Research, *Vol. 16, No. 4 (2024) 427-434*
https://doi.org/10.12989/anr.2024.16.4.427

Influence of thermal radiation and magnetohydrodynamic on the laminar flow: Williamson fluid for velocity profile

Muzamal Hussain*[1], Humaira Sharif[2], Mohammad Amien Khadimallah[3], Hamdi Ayed[4], Abir Mouldi[5],
Muhammad Naeem Mohsin[6], Sajjad Hussain[7] and Abdelouahed Tounsi[8,9]

[1]*Department of Mathematics, University of Sahiwal, Sahiwal, 57000, Faisalabad, Pakistan*
[2]*Department of Mathematics, Govt. College University Faisalabad, 38000, Faisalabad, Pakistan*
[3]*Department of Civil Engineering, College of Engineering in Al-Kharj, Prince Sattam Bin Abdulaziz University, Al-Kharj, 11942, Saudi Arabia*
[4]*Department of Civil Engineering, College of Engineering, King Khalid University, Abha - 61421, Saudi Arabia*
[5]*Department of Industrial Engineering, College of Engineering, King Khalid University, Abha - 61421, Saudi Arabia*
[6]*Institute for Islamic Theological Studies, University of Vienna, Schenkenstrabe 8-10,1010, Vienna*
[7]*Department of mathematics, Government Post graduate college, Layyah, Pakistan*
[8]*Materials and Hydrology Laboratory University of Sidi Bel Abbes, Algeria Faculty of Technology Civil Engineering Department*
[9]*Department of Civil and Environmental Engineering, King Fahd University of Petroleum and Minerals,*
31261 Dhahran, Eastern Province, Saudi Arabia

(*Received December 16, 2021, Revised February 18, 2024, Accepted March 2, 2024*)

Abstract. Latest advancement in field of fluid dynamics has taken nanofluid under consideration which shows large thermal conductance and enlarges property of heat transformation in fluids. Motivated by this, the key aim of the current investigation scrutinizes the influence of thermal radiation and magnetohydrodynamic on the laminar flow of an incompressible two-dimensional Williamson nanofluid over an inclined surface in the presence of motile microorganism. In addition, the impact of heat absorption/generation and Arrhenius activation energy is also examined. A mathematical modeled is developed which stimulate the physical flow problem. By using the compatible similarities, we transfer the governing PDEs into ODEs. The analytic approach based on Homotopy analysis method is introduced to impose the analytic solution by using Mathematica software. The impacts of distinct pertinent variable on velocity profiles are investigated through graphs.

Keywords: activation energy; bio-convection; inclined surface; thermal radiation; Williamson nanofluid

1. Introduction

In recent years, the analysis of heat transfer with the help of nano-materials becomes a hot area of investigation for the latest researchers. Researchers have made immense struggle to intensify the indigent thermal conductivity of traditional liquids. With quick advancement in technology, the challenges for increasing efficiency of energy exchanger and techniques for saving of energy are being met with the use of new materials. Moreover, conventional heat exchanger fluids could not meet exclusive conditions such as stable intensity of heat exchanger (Yang *et al*. 2022). On scrutinizing and exploring nanoparticles, (Choi 1995, Long *et al*. 2023, Sun *et al*. 2023) originated the term 'nano-fluids'. Nano liquid, as a new generation of super operative medium, has been swiftly appearing as an innovative medium to increase the heat exchanger coefficient of traditional liquids (Yang *et al*. 2023). The development of nanofluids has appeared as an impulsive direction, especially in the past time. The area of nanofluids analysis has tangle continuous investigation, amounts of somatic assets, steaming heat exchanger, mass exchanger and some national research or model growth. Nanofluids contain nanoparticles or robust nanofibres having measurements of 1-100 nm. By the moderate size of nanofluids, nano-materials have stable suspension strength and capability to transfer deprived of clogging the outflow system. Since the nanofluids have exceptional thermal efficiency than the base fluid, nanoliquids noticed as good coolants particularly in domestic refrigerators-freezers, nuclear reactor, machines, electric gadgets. By considering above mentioned applications, many researchers establish method to utilize nanoliquids as an elective technique to enhance the energy transfer adequacy. Buongiorno (2006) employed the non-homogeneous equilibrium structure, which consist of convective transport in nanoliquids. Tiwari and Das (2007) proposed a homogeneous structure by incorporating the nanomaterials fractions impact. Sheikholeslami *et al*. (2019) inspected the influence of variable magnetic forces on magnetizable hybrid nano liquid heat exchanger through a circular cavity. (Yuan *et al*. 2019) explored the numerical analysis of MHD influence on nanoliquid heat exchanger in a baffled U-shaped enclosure.

They observed that heat exchanger improvement by introducing nanoliquid diminish as enhancing Rayleigh number, but it enhance as enhancing the Hartmann number. Zhixiong *et al*. (2019) presented the Nanoliquid transfer of heat in a porous duct in the existence of Lorentz forces parameter using the lattice Boltzmann approach. They noticed that the LBM was elected to describe the effect of magnetic (Ha), Reynolds (Re) and Darcy (Da) parameters

---

*Corresponding author, Ph.D.,
E-mail: muzamalhussain@uosahiwal.edu.pk

Copyright © 2024 Techno-Press, Ltd.
http://www.techno-press.org/?journal=journal=anr&subpage=5
ISSN: 2287-237X (Print), 2287-2388 (Online)

on the nanoliquid behavior. A variety of the related literature may be seen in the Refs (Anwar *et al.* 2019, Chaudhary and Kanika 2019, Ambreen and Kim 2018, Shafee *et al.* 2019, Sheikholeslami 2018, Fu *et al.* 2020, Zhu *et al.* 2017). Many investigators declare the importance of MHD in various energy based flows developed by stretching sheet. Due to its powerful applications, it has received much attention in the practical area and engineering such as treatment of brain tumor, cure of hyperthermia cancer, reactors cooling, etc. The physical impact of magnetic material offer significant circumstances in heat exchanger liquid flow problems. According to Lenz's law, electric current is produced by motion of electrons in conductor in the existence of magnetic field. The nano fluids show interaction with Lorentz (sum of electric and magnetic field) forces. Zangooee *et al.* (2019) noticed the analysis of Hydrothermal of MHD nanoliquid flow between two radiative stretching and rotating disks. They noticed that concentration profile is a diminish function of Re while temperature profile is an enhancing one. Also it is investigated that local Nusselt number increases with stretchable parameter and effect of Reynolds number at uppermost disk while it is decline at lower one. Ullah *et al.* (2019) studied the MHD Viscoelastic Nanoliquid Flow of Thin Film over an Unsteady Vertical Stretchable Surface with Entropy Generation. Rashid and Liang (2020) observed the analysis of nanomaterials shape influence on MHD nanoliquid flow and heat exchanger over a rotating stretchable disk through porous media, one can see the researcher reports on magnetohydrodynamic flows in the refs (Izadi *et al.* 2019, Abbasi *et al.* 2019, Shehzad *et al.* 2019, Turkyilmazoglu 2017, Hsiao 2017, Dong *et al.* 2024, Fu *et al.* 2024, Akbaş 2016a, b, 2017a, b, 2018a, b).

In past few decades, concept of non-linear dynamics of non-Newtonian liquids has been the subject of immense interest due to their impressive significance in numerous natural phenomenons including, processing of food, geophysics, technology and engineering applications. The non-Newtonian fluids are distinct and not quite easy to investigate like viscous liquids. The non-Newtonian liquids obtain attractive features such as memory of fluid, shear thin / thicken features. Among various non-Newtonian structures, Pseudoplastic liquids are also properties of nonlinear liquids models. Williamson liquid is also non-Newtonian liquid. Williamson (1929) studied the Pseudoplastic flow and shows a model equation to investigate the Pseudoplastic liquids outflow and justify the outcomes experimentally. Blasius (1950) reported the characteristics of momentum boundary layer developed in the liquid flow over a flat area. Khan *et al.* (2017) investigated an impressive research on Williamson nano-liquid flow past a cone. The particular case was reported with plate. The investigation declared that temperature field diminish for higher values of Prandtl but a reduction is examined towards a durable thermophoretic force. Hayat *et al.* (2016) examined a Magnetohydro-dynamic analysis of Williamson liquid over surface of nonlinear variable. Nadeem *et al.* (2013) examined the outflow of liquid, transfer of heat and mass mechanism over a stretchable surface where the subject liquid was taken as Williamson liquid. Salahuddin *et al.* (2016) discussed flow of Williamson liquid over stretchable area using the Cattaneo–Christov theory for mass and heat transport advancements, Whereas the influence of Dufour and Soret on Williamson liquid flow was examined by (Hayat *et al.* 2015) using convective boundary conditions. The outcomes reveal that solute as well as thermal Biot numbers is enhancing factors for temperature distribution. A collection of literature considering the model of new methodologies can be found in Refs. (Nadeem *et al.* 2013, Khan *et al.* 2017, 2018, Shah *et al.* 2018, Malik *et al.* 2016, Bilal *et al.* 2018, Li *et al.* 2020, Zhang *et al.* 2024).

Bio-convection is a phenomenon that appears when small density micro-organism swim upward of liquid as result instability occur. Because the swimming in the upper portion, these motile micro-organisms are just like algae tend to accumulate in the uppermost part of liquid layer thus resulting in large density stratification over upper part that usually becomes unstable. In the articles, (Hill *et al.* 1989, Pedley and Kessler 1992), different kinds of bio-convectional structure are investigated. In bio-medical process, bio-convection has an immense scope (Kuznetsov 2010). Process of bio-convection and nanofluid are relatively attractive for modern micro-fluidic devices. Siddiqa *et al.* (2016) reported on heat and mass exchange in bio-convection flow of water- based nanoliquids with microorganism. Beg *et al.* (2015) numerically examined the non-Newtonian nanoliquids through a permeable media in the presence of gyrotactic microorganism. Mutuku and Makinde (2014) reported the MHD nanoliquid flow with mass and heat exchanger over a vertical plate containing Bioconvection phenomenon. Further, new literature on flow of fluid can be seen in Refs (Khan *et al.* 2013, Xun *et al.* 2017, Zuhra *et al.* 2018, Waqas *et al.* 2019, Zhu *et al.* 2023). Recently some researcher used different methods for nonlinear modeling (Avcar 2019, Karami *et al.* 2017, 2018, Madani *et al.* 2016, Simsek 2011). Recently some researcher used different methods for nonlinear modeling (Eltaher *et al.* 2019, Ebrahimi *et al.* 2019, Safaei *et al.* 2019, Shahsavari *et al.* 2019, Benmansour *et al.* 2019, Farokhian 2020, Nazemnezhad and Shokrollahi 2020, Afzali and Rostamiyan, 2020, Mirjavadi *et al.* 2020, Demir *et al.* 2020, Hejri *et al.* 2020, Noroozi *et al.* 2020, She *et al.* 2020, Fenjan *et al.* 2020, Boulal *et al.* 2020, Sahmani *et al.* 2020, Hosseini *et al.* 2020, Nejadi and Mohammadimehr, 2020, Ahmed *et al.* 2020, Guo *et al.* 2023, Kuang *et al.* 2018)

According to above mentioned literature, the purpose of current analysis is to investigate the effect of Williamson nanoliquid flow over an inclined surface by considering the effect of thermal radiation, heat source/sink, activation energy and bio-convection. In this problem, the governing PDE's are altered into ODE's is then tackled analytically by using Homotopy analysis approach. Moreover, the pertinent parameters that occur in the governing equations are investigated with the help of tables and graphs.

2. Formulation

We consider a 2D incompressible flow of the non-Newtonian Williamson nanoliquid over an inclined stretching surface in the presence of motile microorganism. α is inclination between the direction of liquid flow and vertical line. The temperature equation is extended by considering thermal radiation and heat source/sink effect. Further, the energy activation feature is utilized in the concentration equation. The ambient temperature, concentration and micro-organism are T_∞, C_∞ and n_∞ respectively. In the interpretation of above assumptions, the following flow equations are articulated as:

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

$$\begin{gathered} u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+\sqrt{2}\nu\Gamma\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial y^2}+ \\ g\cos\alpha\,[\beta_c(C-C_\infty)+\beta_t(T-T_\infty)]-\frac{\sigma {B_0}^2}{\rho}u \end{gathered} \tag{2}$$

$$\begin{gathered} u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_m\frac{\partial^2 T}{\partial y^2}-\frac{1}{(\rho c)_f}\frac{\partial q_r}{\partial y} \\ +\tau\left[\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}D_B+\left(\frac{\partial T}{\partial y}\right)^2\frac{D_T}{T_\infty}\right]+\frac{Q}{(\rho c)_f}(T-T_\infty) \end{gathered} \tag{3}$$

$$\begin{gathered} u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}+D_B\frac{\partial^2 C}{\partial y^2} \\ -{K_r}^2(C-C_\infty)\left(\frac{T}{T_\infty}\right)^n exp\left(\frac{-E_a}{kT}\right) \end{gathered} \tag{4}$$

$$u\frac{\partial n}{\partial x}+v\frac{\partial n}{\partial y}+\frac{bW_c}{C_w-C_\infty}\left[\frac{\partial}{\partial y}\left(n\frac{\partial C}{\partial y}\right)\right]=D_n\left(\frac{\partial^2 n}{\partial y^2}\right) \tag{5}$$

Here, the radiation heat flux is characterized as

$$q_r=\frac{-4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y^4} \tag{6}$$

where σ^* denotes the Stefan –Boltzmann constant and k^*represents the mean absorption coefficient. Whereas

$$T^4\cong 4{T_\infty}^3-3{T_\infty}^4 \tag{7}$$

Substituting Eq. (7) into Eq. (6), we get:

$$q_r=-\frac{16{T_\infty}^3\sigma^*}{3k^*}\frac{\partial T}{\partial y} \tag{8}$$

Substituting Eq. (8) into Eq. (3), the expression becomes:

$$\begin{gathered} u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left(\alpha_m+\frac{16\sigma^*{T_\infty}^3}{3k^*(\rho c)_f}\right)\frac{\partial^2 T}{\partial y^2} \\ +\tau\left[\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}D_B+\left(\frac{\partial T}{\partial y}\right)^2\frac{D_T}{T_\infty}\right]+\frac{Q}{(\rho c)_f}(T-T_\infty) \end{gathered} \tag{9}$$

The physical conditions at boundary are:

$$\begin{gathered} u=u_w(x)=ax,\qquad v=0,\qquad T=T_w, \\ C=C_w,\ n=n_w,\ \text{at}\ y=0,\ u\to 0, \\ T\to T_\infty,\ C\to C_\infty, n\to n_\infty,\ \text{at}\ y\to\infty, \end{gathered} \tag{10}$$

Here, $\psi=\psi(x,y)$ is stream function and similarity transformation are delimit as:

$$u=\frac{\partial\psi}{\partial y},\qquad v=-\frac{\partial\psi}{\partial x},\qquad \psi=\sqrt{a\nu}xf(\eta), \tag{11}$$

$$\begin{gathered} \eta=y\sqrt{\frac{a}{\nu}},\qquad g(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \\ j(\eta)=\frac{C-C_\infty}{C_w-C_\infty},\qquad \chi(\eta)=\frac{n-n_\infty}{n_w-n_\infty} \end{gathered} \tag{12}$$

After applying the above similarity transformation into Eqs. (2), (4), (5) and (9), we give us the following ODE’s:

$$\begin{gathered} f'''+ff''-f'^2+W_1f''f'''+\cos\alpha\,(Grg+Gmj) \\ -Mf'=0, \end{gathered} \tag{13}$$

$$\frac{1}{Pr\left(1+\frac{4}{3}Rd\right)^{''''''2}} \tag{14}$$

$$\begin{gathered} j''+Lefj'+\frac{Nt}{Nb}g'' \\ -(Le)\sigma(1+\Omega_1 g)^{n_1}exp\left(\frac{-E}{1+\Omega_1 g}\right)j=0, \end{gathered} \tag{15}$$

$$\chi''+Lbf\chi'-Pe[j''(\chi+\delta)+\chi'j']=0, \tag{16}$$

where $M=\frac{\sigma {B_0}^2}{\rho a}$ is magnetic field parameter, $Pr=\frac{\nu}{\alpha_m}$ is Prandtl number, $Le=\frac{\nu}{D_B}$ denotes the Lewis number, $Nt=\frac{\tau D_T(T_w-T_\infty)}{T_\infty\nu}$ is thermophoresis factor, $Nb=\frac{\tau D_B(C_w-C_\infty)}{\nu}$ is Brownian movement parameter, $Gr=\frac{g\beta_T(T_w-T_\infty)}{a^2x}$ is Grashof number, $Gm=\frac{g\beta_c(C_w-C_\infty)}{a^2x}$is modified Grashof number, $\gamma=\frac{Q}{2a(\rho c)_f}$ is heat generation/absorption factor, $Lb=\frac{\nu}{D_m}$ is bio-convection Lewis number, $Pe=\frac{bW_c}{D_m}$ is bio-convection peclet number, $\delta=\frac{n_\infty}{n_w-n_\infty}$ is bio-convection concentration difference factor, $\Omega_1=\frac{T_w-T_\infty}{T_\infty}$ is temperature difference factor, $E=\frac{E_a}{kT_\infty}$is activation energy number, $W_1=\Gamma x\sqrt{\frac{2a^3}{\nu}}$is Williamson parameter.

The dimensionless form of boundary conditions is:

$$\begin{gathered} f(\eta)=0,\qquad f'(\eta)=1,\qquad g(\eta)=1, \\ j(\eta)=1,\ \chi(\eta)=1,\ \text{at}\ \eta=0, \\ f'(\eta)\to 0,\qquad g(\eta)\to 0, \\ j(\eta)\to 0,\ \chi(\eta)\to 0,\ \text{at}\quad \eta\to \end{gathered} \tag{17}$$

The essential physical quantities are: $c_f=\frac{\tau_w}{(ax)^2\rho}$ skin friction, $Nu_x=\frac{q_wx}{(T_w-T_\infty)k}$ Nusselt number, $Sh_x=\frac{q_mx}{(C_w-C_\infty)D_B}$ Sherwood number.

$$\begin{gathered} q_m=-D_B\left(\frac{\partial C}{\partial y}\right)_{y=0},\ q_w=\left[-\left(k+\frac{4{T_\infty}^3\sigma^*}{3k}\right)\frac{\partial T}{\partial y}\right]_{y=0}, \\ \tau_w=\left[\mu\left(\frac{\partial u}{\partial y}\right)+\frac{\Gamma}{2}\left(\frac{\partial u}{\partial y}\right)^2\right]_{y=o} \end{gathered} \tag{18}$$

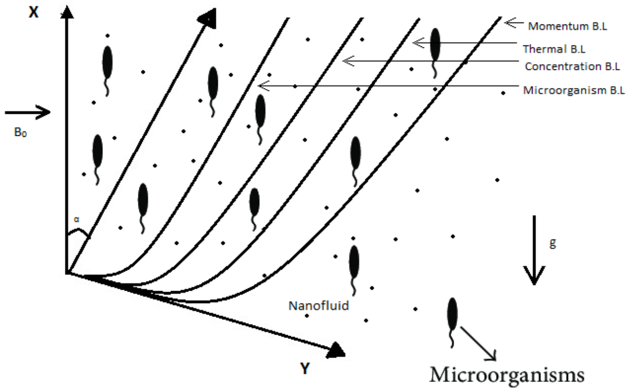

Fig. 1 Geometry of the flow problem

The non-dimensional form of skin friction coefficient, local Nusselt number, Sherwood number and motile number are:

$$C_{fx}(Re_x)^{\frac{1}{2}} = f''(0) + \frac{W_1}{2} f''(0)^2,$$
$$Nu_x\, Re^{\frac{-1}{2}} = -\, g'(0)\left(1 + \frac{4}{3} Rd\right), \tag{19}$$
$$Sh_x\, Re_x^{\frac{-1}{2}} = -j'(0),\ Nn_x\, Re_x^{\frac{-1}{2}} = -\chi'(0),$$

where $Re_x^{\frac{1}{2}} = \sqrt{\left(\frac{ax^2}{\nu}\right)}$ is local Reynolds number.

3. Solutions by homotopy analysis method

By considering the HAM (homotopy analysis method), we develop the convergent series solutions of Eqs. (13) – (16) via (17). Therefore (f_0, g_0, j_0, χ_0) initial guesses and (L_f, L_g, L_j, L_χ) linear operators can be expressed as:

$$f_0(\eta) = 1 - e^{-\eta}, \qquad g_0(\eta) = e^{-\eta}, \\ j_0(\eta) = e^{-\eta}, \qquad \chi_0(\eta) = e^{-\eta} \tag{20}$$

$$L_f[f(\eta)] = f''' - f',\ L_g[g(\eta)] = g'' - g, \\ L_j[j(\eta)] = j'' - j,\ L_\chi[\chi(\eta)] = \chi'' - \chi \tag{21}$$

The linear operator follow

$$L_f[B_1 + B_2 e^{\eta} + B_3 e^{-\eta}] = 0, \\ L_g[B_4 e^{\eta} + B_5 e^{-\eta}] = 0, \\ L_j[B_6 e^{\eta} + B_7 e^{-\eta}] = 0, \\ L_\chi[B_8 e^{\eta} + B_9 e^{-\eta}] = 0 \tag{22}$$

where $B_k (k = 1 - 9)$ are arbitrary constants.

4. Result and discussion

The main focus of this portion is to investigate the influence of various impressive parameters on velocity, temperature, concentration and microorganism fields through homotopy analysis method. The outcomes for appearing somatic parameters are conferred and schemed. Demonstration convergence of the HAM solution up to 25th order of iteration where, M =0.5, $Gr = W_1 = \delta =$ 0.1, Pr = 1.5, $Le = n = 1$, $\sigma = \Omega = E$ = 0.01, Lb = 0.7, Pe =0.9, Nt =0.28, Nb =0.35. as shown in Table 1. This section presents execution of the different physical parameters present in equation (6) namely non-dimensional magnetic field parameter M, Weissenberg number W_1, Grashof number Gr and modified Grashof number Gm on velocity profile f' as plotted in Figs. 2-5. The influence of Weissenberg number W_1 is shown in Fig. 2. It is seen that for enhancing the values of W_1, velocity profile f' decreases. Physically, Weissenberg number W_1 is related with investigating the viscoelastic flows where time relaxation parameter is affected. Large values of Weissenberg number W_1 is associated with time relaxation which establish more resistance period for liquid motion. Fig. 3 is display the influence of magnetic parameter M on velocity field f'. velocity profile f' retarded gradually for enhancing the values of M. The reason is that liquid produces resistive force called as Lorentz force, which is opposite flow and result in decreasing the flow of the liquid,

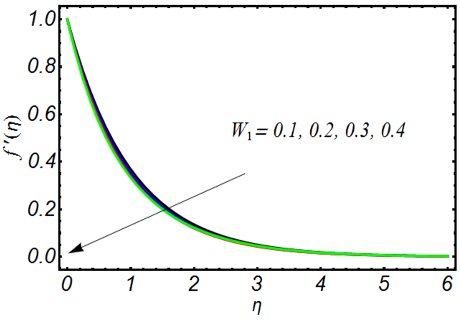

Fig. 2 $f'(\eta)$ variation for W_1

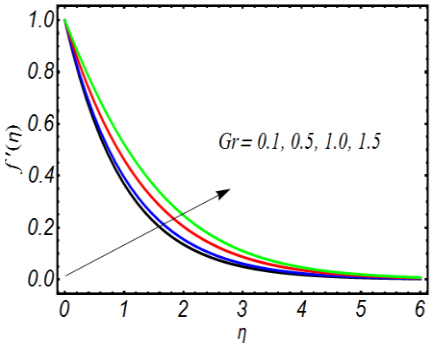

Fig. 3 $f'(\eta)$ variation for Gr

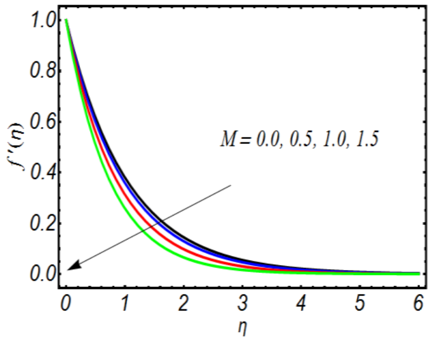

Fig. 4 $f'(\eta)$ variation for M

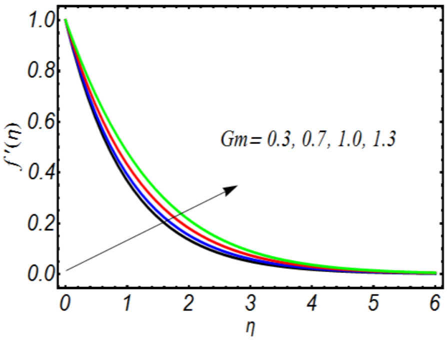

Fig. 5 $f'(\eta)$ variation for Gm

Table 1 Demonstration convergence of the HAM solution up to 25th order of iteration where, M =0.5, $Gr = W_1 = \delta =$ 0.1, $Pr =$ 1.5, $Le = n =$ 1, $\sigma = \Omega = E =$ 0.01, Lb =0.7, Pe =0.9, Nt =0.28, Nb =0.35.

Approximation order	$f''(0)$	$g'(0)$	$j'(0)$	$\chi'(0)$
1	1.0583	0.6364	0.8649	0.9417
6	1.0641	0.5579	0.8668	0.7961
15	1.0607	0.5614	0.8924	0.7558
18	1.0598	0.5625	0.8941	0.7503
20	1.0598	0.5630	0.8948	0.7484
21	1.0598	0.5630	0.8952	0.7478
22	1.0598	0.5630	0.8952	0.7478

in return reduces the velocity profile. Fig. 4 shows that increasing the values of Grashof number Gr, velocity profile f' increases. Physically justified progressing the buoyancy effect, the force of viscous reduces which enhances the motion of fluid. Fig. 5 demonstrates the relation between velocity field f' and solutal buoyancy forces. The reason beyond this modified Grashof number Gm shows its effect on length, concentration differences and kinematic viscosity of the liquid. There is an opposite relation between velocity of the liquid and viscosity. Therefore, fluid viscosity reduces once it has enhanced the modified Grashof number magnitude, due to which increases f'. Finally, there is a direct relation between modified Grash of number Gm and velocity field f'.

5. Conclusions

A mathematical analysis of two dimensional flow of Williamson nanofluid over an inclined stretchable surface has been carried out. Highly non-linear coupled equations are successfully solved by Homotopy analysis approach. It is seen that for enhancing the values of W_1, velocity profile f' decreases. velocity profile f' retarded gradually for enhancing the values of M. Physically justified progressing the buoyancy effect, the force of viscous reduces which enhances the motion of fluid. There is an opposite relation between velocity of the liquid and viscosity. Therefore, fluid viscosity reduces once it has enhanced the modified Grashof number magnitude, due to which increases f'.

Acknowledgments

The author extends their appreciation to the deanship of Scientific Research at King Khalid University for funding this work through research groups under grant number RGP2/126/44". The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

Abbasi, F.M., Shanakhat, I. and Shehzad, S.A. (2019), "Entropy generation analysis for peristalsis of nanofluid with temperature dependent viscosity and Hall effects", *J. Magn. Magn. Mater.*, **474**, 434-441. https://doi.org/10.1016/j.jmmm.2018.10.132

Afzali, M. and Rostamiyan, Y. (2020), "Study the effect of machining process and Nano Sio2 on GFRP mechanical performances", *Struct. Eng. Mech.*, **76**(2), 175-191. https://doi.org/10.12989/sem.2020.76.2.175

Ahmed, R.A., Al-Maliki, A.F. and Faleh, N.M. (2020), "Dynamic characteristics of multi-phase crystalline porous shells with using strain gradient elasticity", *Adv. Nano Res*, **8**(2), 157-167. https://doi.org/10.1007/s00366-020-01103-

Akbaş Ş.D. (2017a), "Free vibration of edge cracked functionally graded microscale beams based on the modified couple stress theory", *Int. J. Struct. Stabil. Dyn.*, **17**(3), 1750033. https://doi.org/10.1142/S021945541750033X

Akbaş, Ş.D. (2016a), "Forced vibration analysis of viscoelastic nanobeams embedded in an elastic medium", *Smart Struct. Syst.*, **18**(6), 1125-1143. https://doi.org/10.12989/sss.2016.18.6.1125

Akbaş, Ş.D. (2016b), "Analytical solutions for static bending of edge cracked micro beams", *Struct. Eng. Mech.*, **59**(3), 579-599. https://doi.org/10.12989/sem.2016.59.3.579

Akbaş, Ş.D. (2017b), "Forced vibration analysis of functionally graded nanobeams", *Int. J. Appl. Mech.*, **9**(7), 1750100. https://doi.org/10.1142/S1758825117501009

Akbas, S.D. (2018a), "Forced vibration analysis of cracked functionally graded microbeams", *Adv. Nano Res.*, **6**(1), 39. https://doi.org/10.12989/anr.2018.6.1.039

Akbaş, Ş.D. (2018b), "Bending of a cracked functionally graded nanobeam", *Adv. Nano Res.*, **6**(3), 219. https://doi.org/10.12989/anr.2018.6.3.219

Ambreen, T. and Kim, M.H. (2018), "Effect of fin shape on the thermal performance of nanofluid-cooled micro pin-fin heat sinks", *Int. J. Heat Mass Transf.*, **126**, 245-256. https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.164

Anwar, M.I., Ali, M., Rafique, K. and Shehzad, S.A. (2019), "Soret–Dufour and radiative aspects in hydromagnetized nano-fluid flow in stratified porous medium", *SN Appl. Sci.*, **1**(11), 1430. https://doi.org/10.1007/s42452-019-1473-5

Avcar M. (2019), "Free vibration of imperfect sigmoid and power law functionally graded beams", *Steel Compos. Struct.*, **30**(6), 603-615. https://doi.org/10.12989/scs.2019.30.6.603

Bég, O.A., Uddin, M.J. and Khan, W.A. (2015), "Bioconvective non-Newtonian nanofluid transport in porous media containing micro-organisms in a moving free stream", *J. Mech. Med. Biol.*, **15**(05), 1550071. https://doi.org/10.1142/S0219519415500712

Benmansour, D.L., Kaci, A., Bousahla, A.A., Heireche, H., Tounsi, A., Alwabli, A.S., Alhebshi, A.M., Al-ghmady, K. and Mahmoud, S.R. (2019), "The nano scale bending and dynamic properties of isolated protein microtubules based on modified strain gradient theory", *Adv. Nano Res.*, **7**(6), 443.

https://doi.org/10.12989/anr.2019.7.6.443

Bilal, M., Sagheer, M. and Hussain, S. (2018), "Numerical study of magnetohydrodynamics and thermal radiation on Williamson nanofluid flow over a stretching cylinder with variable thermal conductivity", *Alexandria Eng. J.*, **57**(4), 3281-3289. https://doi.org/10.1016/j.aej.2017.12.006

Blasius, H. (1950), "The boundary layers in fluids with little friction", *Zeitschrift fuer Mathematik und Physik*, **56**(1). https://ntrs.nasa.gov/citations/20050028493

Boulal, A., Bensattalah, T., Karas, A., Zidour, M., Heireche, H. and Bedia, E.A. (2020), "Buckling of carbon nanotube reinforced composite plates supported by Kerr foundation using Hamilton's energy principle", *Struct. Eng. Mech.*, **73**(2), 209-223. https://doi.org/10.12989/sem.2020.9.73.209

Buongiorno, J. (2006), "Convective transport in nanofluids", *J. Heat Transf.*, **128**(3), 240-250. https://doi.org/10.1115/1.2150834

Chaudhary, S. and Kanika, K.M. (2019), "Impacts of viscous dissipation and Joule heating on hydromagnetic boundary layer flow of nanofluids over a flat surface subjected to Newtonian heating", *SN Appl. Sci.*, **1**(12), 1709. https://doi.org/10.1007/s42452-019-1714-7

Choi, S.U. and Eastman, J.A. (1995), "Enhancing thermal conductivity of fluids with nanoparticles (No. ANL/MSD/CP-84938; CONF-951135-29)", Argonne National Lab., IL, U.S.A.

Demir, E., Çallıoğlu, H., Sayer, M. and Kavla, F. (2020), "Effect of chitosan/carbon nanotube fillers on vibration behaviors of drilled composite plates", *Steel Compos. Struct.*, **35**(6), 789-798. https://doi.org/10.12989/scs.2020.35.6.789

Dong, Z., Li, X., Yamaguchi, H. and Yu, P. (2024), "Magnetic field effect on the sedimentation process of two non-magnetic particles inside a ferrofluid", *J. Magn. Magn. Mater.*, **589**, 171501. https://doi.org/10.1016/j.jmmm.2023.171501

Ebrahimi, F., Dabbagh, A., Rabczuk, T. and Tornabene, F. (2019), "Analysis of propagation characteristics of elastic waves in heterogeneous nanobeams employing a new two-step porosity-dependent homogenization scheme", *Adv. Nano Res.*, **7**(2), 135. https://doi.org/10.12989/anr.2019.7.2.135

Eltaher, M.A., Almalki, T.A., Ahmed, K.I. and Almitani, K.H. (2019), "Characterization and behaviors of single walled carbon nanotube by equivalent-continuum mechanics approach", *Adv. Nano Res.*, **7**(1), 39. https://doi.org/10.12989/anr.2019.7.1.039

Farokhian, A. (2020), "The effect of voltage and nanoparticles on the vibration of sandwich nanocomposite smart plates", *Steel Compos. Struct.*, **34**(5), 733-742. https://doi.org/10.12989/scs.2020.34.5.733

Fenjan, R.M., Faleh, N.M. and Ridha, A.A. (2020), "Strain gradient based static stability analysis of composite crystalline shell structures having porosities", *Steel Compos. Struct.*, **36**(6), 631-642. https://doi.org/10.12989/scs.2020.36.6.631

Fu, Y., Liu, Y., Wang, J., Wang, Y., Xu, G. and Wen, J. (2024), "Local resistance characteristics of elbows for supercritical pressure RP-3 flowing in serpentine micro-tubes", *Propuls. Power Res.*, In Press. https://doi.org/10.1016/j.jppr.2023.02.009

Fu, Z.H., Yang, B.J., Shan, M.L., Li, T., Zhu, Z.Y., Ma, C.P., Zhang, X., Gou, G.Q., Wang, Z.R, and Gao, W. (2020), "Hydrogen embrittlement behavior of SUS301L -MT stainless steel laser-arc hybrid welded joint localized zones", *Corros. Sci.*, **164**, 108337. https://doi.org/10.1016/j.corsci.2019.108337

Guo, J., Ding, B., Wang, Y. and Han, Y. (2023), "Co-optimization for hydrodynamic lubrication and leakage of V-shape textured bearings via linear weighting summation", *Physica Scripta*, **98**(12), 125218. https://doi.org/10.1088/1402-4896/ad07be

Hayat, T., Bashir, G., Waqas, M. and Alsaedi, A. (2016), "MHD 2D flow of Williamson nanofluid over a nonlinear variable thicked surface with melting heat transfer", *J. Mol. Liq.*, **223**, 836-844. https://doi.org/10.1016/j.molliq.2016.08.104

Hayat, T., Saeed, Y., Asad, S. and Alsaedi, A. (2015), "Soret and Dufour effects in the flow of Williamson fluid over an unsteady stretching surface with thermal radiation", *Zeitschrift für Naturforschung A*, **70**(4), 235-243. https://doi.org/10.1515/zna-2014-0252

Hejri, Z., Hejri, M., Omidvar, M. and Morshedi, S. (2020), "A novel nanocomposite as adsorbent for formaldehyde removal from aqueous solution", *Adv. Nano Res.*, **8**(1), 1. https://doi.org/10.12989/anr.2020.8.1.001

Hill, N.A., Pedley, T.J. and Kessler, J.O. (1989), "Growth of bioconvection patterns in a suspension of gyrotactic micro-organisms in a layer of finite depth", *J. Fluid Mech.*, **208**, 509-543. https://doi.org/10.1017/S0022112089002922

Hosseini, S.M. (2020), "A GN-based modified model for size-dependent coupled thermoelasticity analysis in nano scale, considering nonlocality in heat conduction and elasticity: An analytical solution for a nano beam with energy dissipation", *Struct. Eng. Mech.*, **73**(3), 287-302. https://doi.org/10.12989/sem.2020.73.3.287

Hsiao, K.L. (2017), "Micropolar nanofluid flow with MHD and viscous dissipation effects towards a stretching sheet with multimedia feature", *Int. J. Heat Mass Transf.*, **112**, 983-990. https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.042

Izadi, M., Mohebbi, R., Delouei, A.A. and Sajjadi, H. (2019), "Natural convection of a magnetizable hybrid nanofluid inside a porous enclosure subjected to two variable magnetic fields", *Int. J. Mech. Sci.*, **151**, 154-169. https://doi.org/10.1016/j.ijmecsci.2018.11.019

Karami B, Janghorban, M. and Tounsi, A. (2018), "Nonlocal strain gradient 3D elasticity theory for anisotropic spherical nano-particles", *Steel Compos. Struct.*, **27**(2), 201-216. https://doi.org/10.12989/scs.2018.27.2.201

Karami, B., Janghorban, M. and Tounsi, A. (2017), "Effects of triaxial magnetic field on the anisotropic nanoplates", *Steel Compos. Struct.*, **25**(3), 361-374. https://doi.org/10.12989/scs.2017.25.3.361

Khan, M., Malik, M.Y., Salahuddin, T., Rehman, K.U. and Naseer, M. (2017), "MHD flow of Williamson nanofluid over a cone and plate with chemically reactive species", *J. Mol. Liq.*, **231**, 580-588. https://doi.org/10.1016/j.molliq.2017.02.031

Khan, S.U., Shehzad, S.A. and Ali, N. (2018), "Interaction of magneto-nanoparticles in Williamson fluid flow over convective oscillatory moving surface", *J. Brazil. Soc. Mech. Sci. Eng.*, **40**(4), 195. https://doi.org/10.1007/s40430-018-1126-4

Khan, W.A., Uddin, M.J. and Ismail, A.M. (2013), "Free convection of non-Newtonian nanofluids in porous media with gyrotactic microorganisms", *Transp. Por. Med.*, **97**(2), 241-252. https://doi.org/10.1007/s11242-012-0120-z

Khan, W., Gul, T., Idrees, M., Islam, S. and Khan, I. (2017), "Dufour and Soret effect with thermal radiation on the nano film flow of Williamson fluid past over an unsteady stretching sheet", *J. Nanofl.*, **6**(2), 243-253. https://doi.org/10.1166/jon.2017.1328

Kuang, W., Wang, H., Li, X., Zhang, J., Zhou, Q. and Zhao, Y. (2018), "Application of the thermodynamic extremal principle to diffusion-controlled phase transformations in Fe-C-X alloys: Modeling and applications", *Acta Materialia*, **159**, 16-30. https://doi.org/10.1016/j.actamat.2018.08.00

Kuznetsov, A.V. (2010), "The onset of nanofluid bioconvection in a suspension containing both nanoparticles and gyrotactic micro-organisms", *Int. Commun. Heat Mass Transf.*, **37**(10), 1421-1425. https://doi.org/10.1016/j.icheatmasstransfer.2010.08.015

Li, X., Yu, P., Niu, X., Yamaguchi, H. and Li, D. (2020), "Non-contact manipulation of nonmagnetic materials by using a uniform magnetic field: Experiment and simulation", *J. Magn. Magn. Mater.*, **497**, 165957. https://doi.org/10.1016/j.jmmm.2019.165957

Li, Z., Sheikholeslami, M., Mittal, A.S., Shafee, A. and Haq, R.U. (2019), "Nanofluid heat transfer in a porous duct in the presence of Lorentz forces using the lattice Boltzmann method", *Eur. Phys. J. Plus*, **134**(1), 1-10. https://doi.org/10.1140/epjp/i2019-12406-8

Long, X., Chong, K., Su, Y., Du, L. and Zhang, G. (2023), "Connecting the macroscopic and mesoscopic properties of sintered silver nanoparticles by crystal plasticity finite element method", *Eng. Fract. Mech.*, **281**, 109137. https://doi.org/10.1016/j.engfracmech.2023.109137

Ma, Y., Mohebbi, R., Rashidi, M. M., Manca, O. and Yang, Z. (2019), "Numerical investigation of MHD effects on nanofluid heat transfer in a baffled U-shaped enclosure using lattice Boltzmann method", *J. Therm. Anal. Calorim.*, **135**(6), 3197-3213. https://doi.org/10.1007/s10973-018-7518-y

Madani H, Hosseini H, and Shokravi M. (2016), "Differential cubature method for vibration analysis of embedded FG-CNT-reinforced piezoelectric cylindrical shells subjected to uniform and non-uniform temperature distributions", *Steel Compos. Struct.*, **22**(4), 889-913. https://doi.org/10.12989/scs.2016.22.4.889

Malik, M.Y., Bibi, M., Khan, F. and Salahuddin, T. (2016), "Numerical solution of Williamson fluid flow past a stretching cylinder and heat transfer with variable thermal conductivity and heat generation/absorption", *AIP Adv.*, **6**(3), 035101. https://doi.org/10.1063/1.4943398

Mirjavadi, S.S., Forsat, M., Barati, M.R. and Hamouda, A.M.S. (2020), "Nonlinear forced vibrations of multi-scale epoxy/CNT/fiberglass truncated conical shells and annular plates via 3D Mori-Tanaka scheme", *Steel Compos. Struct.*, **35**(6), 765-777. https://doi.org/10.12989/scs.2020.35.6.765

Mutuku, W.N. and Makinde, O.D. (2014), "Hydromagnetic bio-convection of nanofluid over a permeable vertical plate due to gyrotactic microorganisms", *Comput. Fl.*, **95**, 88-97. https://doi.org/10.1016/j.compfluid.2014.02.026

Nadeem, S., Hussain, S.T. and Lee, C. (2013), "Flow of a Williamson fluid over a stretching sheet", *Brazil. J. Chem. Eng.*, **30**(3), 619-625. http://doi.org/10.1590/S0104-66322013000300019

Nazemnezhad, R. and Shokrollahi, H. (2020), "Free axial vibration of cracked axially functionally graded nanoscale rods incorporating surface effect", *Steel Compos. Struct.*, **35**(3), 449-462. https://doi.org/10.12989/scs.2020.35.3.449

Nejadi, M.M. and Mohammadimehr, M. (2020), "Buckling analysis of nano composite sandwich Euler-Bernoulli beam considering porosity distribution on elastic foundation using DQM", *Adv. Nano Res.*, **8**(1), 59. https://doi.org/10.12989/anr.2020.8.1.059

Noroozi, R., Barati, A., Kazemi, A., Norouzi, S. and Hadi, A. (2020), "Torsional vibration analysis of bi-directional FG nano-cone with arbitrary cross-section based on nonlocal strain gradient elasticity", *Adv. Nano Res.*, **8**(1), 13-24. https://doi.org/10.12989/anr.2020.8.1.013

Pedley, T.J. and Kessler, J.O. (1992), "Hydrodynamic phenomena in suspensions of swimming microorganisms", *Annual Rev. Fl. Mech.*, **24**(1), 313-358. https://doi.org/10.1146/annurev.fl.24.010192.001525

Rashid, U. and Liang, H. (2020), "Investigation of nanoparticles shape effects on MHD nanofluid flow and heat transfer over a rotating stretching disk through porous medium", *Int. J. Numer. Meth. Heat Fl. Flow.*, **30**(12), 5169-5189. https://doi.org/10.1108/HFF-10-2019-0743

Sadoughifar, A., Farhatnia, F., Izadinia, M. and Talaeetaba, S. B. (2020), "Size-dependent buckling behaviour of FG annular/circular thick nanoplates with porosities resting on Kerr foundation based on new hyperbolic shear deformation theory", *Struct. Eng. Mech.*, **73**(3), 225-238. https://doi.org/10.12989/sem.2020.73.3.225

Safaei, B., Khoda, F.H. and Fattahi, A.M. (2019), "Non-classical plate model for single-layered graphene sheet for axial buckling", *Adv Nano Res*, **7**(4), 265-275. https://doi.org/10.12989/anr.2019.7.4.265

Sahmani, S., Fattahi, A.M. and Ahmed, N.A. (2020), "Develop a refined truncated cubic lattice structure for nonlinear large-amplitude vibrations of micro/nano-beams made of nanoporous materials", *Eng. Comput.*, **36**, 359-375. https://doi.org/10.1007/s00366-019-00703-6

Salahuddin, T., Malik, M. Y., Hussain, A., Bilal, S. and Awais, M. (2016), "MHD flow of Cattanneo–Christov heat flux model for Williamson fluid over a stretching sheet with variable thickness: Using numerical approach", *J. Magn. Magn. Mater.*, **401**, 991-997. https://doi.org/10.1016/j.jmmm.2015.11.022

Shafee, A., Haq, R.U., Sheikholeslami, M., Herki, J.A.A. and Nguyen, T.K. (2019), "An entropy generation analysis for MHD water based Fe3O4 ferrofluid through a porous semi annulus cavity via CVFEM", *Int. Commun. Heat Mass Transf.*, **108**, 104295. https://doi.org/10.1016/j.icheatmasstransfer.2019.104295

Shah, Z., Bonyah, E., Islam, S., Khan, W. and Ishaq, M. (2018), "Radiative MHD thin film flow of Williamson fluid over an unsteady permeable stretching sheet", *Heliyon*, **4**(10), e00825. https://doi.org/10.1016/j.heliyon.2018.e00825

Shahsavari, D., Karami, B. and Janghorban, M. (2019), "Size-dependent vibration analysis of laminated composite plates", *Adv. Nano Res.*, **7**(5), 337-349. https://doi.org/10.12989/anr.2019.7.5.337

She, G.L., Liu, H.B. and Karami, B. (2020), "On resonance behavior of porous FG curved nanobeams", *Steel Compos. Struct.*, **36**(2), 179-186. https://doi.org/10.12989/scs.2020.36.2.179

Shehzad, S.A., Abbas, Z. and Rauf, A. (2019), "Finite difference approach and successive over relaxation (SOR) method for MHD micropolar fluid with Maxwell–Cattaneo law and porous medium", *Physica Scripta*, **94**(11), 115228. https://doi.org/10.1088/1402-4896/ab3264

Sheikholeslami, M. (2018), "Application of Darcy law for nanofluid flow in a porous cavity under the impact of Lorentz forces", *J. Mol. Liq.*, **266**, 495-503. https://doi.org/10.1016/j.molliq.2018.06.083

Sheikholeslami, M., Mehryan, S.A.M., Shafee, A. and Sheremet, M.A. (2019), "Variable magnetic forces impact on magnetizable hybrid nanofluid heat transfer through a circular cavity", *J. Mol. Liq.*, **277**, 388-396. https://doi.org/10.1016/j.molliq.2018.12.104

Siddiqa, S., Begum, N., Saleem, S., Hossain, M.A. and Gorla, R.S.R. (2016), "Numerical solutions of nanofluid bioconvection due to gyrotactic microorganisms along a vertical wavy cone", *Int. J. Heat Mass Transf.*, **101**, 608-613. https://doi.org/10.1016/j.ijheatmasstransfer.2016.05.076

Simsek M. (2011), "Forced vibration of an embedded single-walled carbon nanotube traversed by a moving load using nonlocal Timoshenko beam theory", *Steel Compos. Struct.*, **11**(1), 59-76. https://doi.org/10.12989/scs.2011.11.1.059

Sun, L., Liang, T., Zhang, C. and Chen, J. (2023), "The rheological performance of shear-thickening fluids based on carbon fiber and silica nanocomposite", *Phys. Fl.*, **35**(3), 32002. https://doi.org/10.1063/5.0138294

Tiwari, R.K. and Das, M.K. (2007), "Heat transfer augmentation in a two-sided lid-driven differentially heated square cavity utilizing nanofluids", *Int. J. Heat Mass Transf.*, **50**(9-10), 2002-2018. https://doi.org/10.1016/j.ijheatmasstransfer.2006.09.034

Turkyilmazoglu, M. (2017), "Mixed convection flow of magneto-hydrodynamic micropolar fluid due to a porous heated/cooled deformable plate: exact solutions", *Int. J. Heat Mass Transf.*, **106**, 127-134. https://doi.org/10.1016/j.ijheatmasstransfer.2016.10.056

Ullah, A., Shah, Z., Kumam, P., Ayaz, M., Islam, S. and Jameel, M. (2019), "Viscoelastic MHD nanofluid thin film flow over an unsteady vertical stretching sheet with entropy generation", *Processes*, **7**(5), 262. https://doi.org/10.3390/pr7050262

Waqas, H., Khan, S.U., Imran, M. and Bhatti, M.M. (2019), "Thermally developed Falkner–Skan bioconvection flow of a magnetized nanofluid in the presence of a motile gyrotactic microorganism: Buongiorno's nanofluid model", *Physica Scripta*, **94**(11), 115304. https://doi.org/10.1088/1402-4896/ab2ddc

Williamson, R.V. (1929), "The flow of pseudoplastic materials", *Ind. Eng. Chem.*, **21**(11), 1108-1111. https://doi.org/10.1021/ie50239a035

Xun, S., Zhao, J., Zheng, L. and Zhang, X. (2017), "Bioconvection in rotating system immersed in nanofluid with temperature dependent viscosity and thermal conductivity", *International J. Heat Mass Transf.*, **111,** 1001-1006. https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.074

Yang, S., Zhang, Y., Sha, Z., Huang, Z., Wang, H., Wang, F. and Li, J. (2022), "Deterministic manipulation of heat flow via three-dimensional-printed thermal meta-materials for multiple protection of critical components", *ACS Appl. Mater. Interf.*, **14**(34), 39354-39363. doi: 10.1021/acsami.2c09602

Yang, W., Jiang, X., Tian, X., Hou, H. and Zhao, Y. (2023), "Phase-field simulation of nano-α′ precipitates under irradiation and dislocations", *J. Mater. Res. Technol.*, **22**, 1307-1321. https://doi.org/10.1016/j.jmrt.2022.11.165

Zangooee, M.R., Hosseinzadeh, K. and Ganji, D.D. (2019), "Hydrothermal analysis of MHD nanofluid (TiO2-GO) flow between two radiative stretchable rotating disks using AGM", *Case Stud. Therm. Eng.*, **14**, 100460. https://doi.org/10.1016/j.csite.2019.100460

Zhang, G., Yang, Z., Li, X., Deng, S., Liu, Y., Zhou, H., Peng, M., Fu, Z., Chen, R., Meng, D., Zhong, L., Zhou, Q. and Wei, S. (2024), "Gamma-ray irradiation induced dielectric loss of SiO2/ Si heterostructures in through-silicon vias (TSVs) by forming border traps", *ACS Appl. Electr. Mater.*, **6**(2), 1339-1346. https://doi.org/10.1021/acsaelm.3c01646

Zhu, Q., Chen, J., Gou, G., Chen, H. and Li, P. (2017), "Ameliorated longitudinal critically refracted—Attenuation velocity method for welding residual stress measurement", *J. Mater. Proc. Technol.* **246**, 267-275. https://doi.org/10.1016/j.jmatprotec.2017.03.022

Zhu, S., Li, X., Bian, Y., Dai, N., Yong, J., Hu, Y., Hu, Y, Li, J., Wu, D. and Chu, J. (2023), "Inclination-enabled generalized microfluid rectifiers via anisotropic slippery hollow tracks", *Adv. Mater. Technol.*, **8**(16), 2300267. https://doi.org/10.1002/admt.202300267

Zuhra, S., Khan, N.S. and Islam, S. (2018), "Magnetohydrodynamic second-grade nanofluid flow containing nanoparticles and gyrotactic microorganisms", *Comput. Appl. Math.*, **37**(5), 6332-6358. https://doi.org/10.1007/s40314-018-0683-6

CC