emeraldinsight

Multidiscipline Modeling in Materials and Structures

A note on some solutions of micropolar fluid in a channel with permeable walls
Jawad Raza, Azizah M. Rohni, Zurni Omar,

Article information:

RMIT UNIVERSITY

For Authors

If you would like to write for this, or any other Emerald publication, then please use our Emerald for Authors service information about how to choose which publication to write for and submission guidelines are available for all. Please visit www.emeraldinsight.com/authors for more information.

About Emerald www.emeraldinsight.com

Emerald is a global publisher linking research and practice to the benefit of society. The company manages a portfolio of more than 290 journals and over 2,350 books and book series volumes, as well as providing an extensive range of online products and additional customer resources and services.

Emerald is both COUNTER 4 and TRANSFER compliant. The organization is a partner of the Committee on Publication Ethics (COPE) and also works with Portico and the LOCKSS initiative for digital archive preservation.

*Related content and download information correct at time of download.

A note on some solutions of micropolar fluid in a channel with permeable walls

Jawad Raza, Azizah M. Rohni and Zurni Omar

School of Quantitative Sciences, Universiti Utara Malaysia, Sintok, Malaysia

Abstract

Purpose – The purpose of this paper is to investigate different branches of the solution of micropolar fluid in a channel with permeable walls. Moreover, the intention of the study is to examine the effect of different physical parameters on fluid flow.

Design/methodology/approach – The mathematical modeling is performed on the basis of law of conservation of mass, momentum and angular momentum. The governing partial differential equations were transformed into ordinary differential equations by applying suitable similarity transformation. Afterwards, the set of nonlinear ordinary differential equations was solved numerically by a shooting method.

Findings – The study reveals that various branches of the solution of the proposed problem exist only in the case of strong suction.

Originality/value – The investigation of new branches of the solution of non-Newtonian micropolar fluid is relatively difficult as far as the single solution is concern. This study explores the new branches of the solution of a micropolar fluid in a channel with suction/injection. Simultaneous effect of suction Reynolds number and vortex viscosity parameter on velocity and micro-rotation profile is examined for different branches of solution in order to make the analysis more interesting.

Keywords Micropolar fluid, Micro-rotation, Multiple solutions

Paper type Technical paper

1. Introduction

Fluid flow through a channel has innumerable uses on the basis of its behavior in many fields like engineering, science, environmental, biomedical and chemical engineering, etc. (Ali and Ashraf, 2014; Majdalani, 2008; Rawool *et al.*, 2006; Dehghan *et al.*, 2014; Rauf *et al.*, 2016), exclusively for those which have nonlinear relationship between the shear stresses and the rate of deformation, such as micropolar fluid. This fluid actually belongs to the following class of fluids having nonsymmetrical stress tensor with micro-structure molecular bounding. The theory of micropolar fluid was presented by Eringen (1964). Complex fluid problems can be studied with the help of Eringen's theory, including flow of blood, liquid crystals, low concentration suspensions and turbulent sheer flows. As compared to the classical Newtonian fluids, micropolar fluids possess five additional coefficients of viscosity. Eringen (1964) claimed that the effect of micro-rotations in a micro-structure model is observed in micropolar fluid. These fluids can support stress momentum and body momentum and are usually influenced by the spin inertia dynamically. As micropolar fluids consist of micro-structures, so the effects seen on microscopic level are present on the micro-structure level by the micro motions of fluid elements. Physically it may be explained as the rigid, spherical or bar like elements that are randomly oriented dispersed in a viscous medium and thus the deformation of fluid particles in it is ignored completely. These fluids have crystals of dumb-bell shaped molecules, like in animal blood. In addition, the mathematical models of the fluids with certain additives or polymeric fluids resemble the mathematical model of micropolar fluids

(Mekheimer and El Kot, 2008; Nadeem *et al.*, 2010; Busuke and Tatsuo, 1969; Kelson and Desseaux, 2001; Joneidi *et al.*, 2009).

In engineering problems, solving nonlinear ordinary differential equations and partial differential equations was always a difficult task to the researchers. Therefore, with the passage of time, many techniques came to exist to solve this issue. One of the most prominent knowledge of the current issue is addressed in the form of literature related to analytical methods, semi-analytical methods and numerical methods. In the field of heat transfer, main structures of the problems are often in the form of nonlinear ordinary differential equations. Many researchers solved the nonlinear ODEs by utilizing analytical and semi-analytical methods such as perturbation method by Ganji *et al.* (2007); homotopy perturbation method (HPM) by Turkyilmazoglu (2012), Sheikholeslami, Hatami and Ganji (2013), Sheikholeslami, Ganji and Ashorynejad (2013) and Mirgolbabaei *et al.* (2009); variational iteration method by Turkyilmazoglu (2016a), Mirgolbabaei *et al.* (2009) and Samaee *et al.* (2015); homotopy analysis method by Sheikholeslami, Hatami and Ganji (2014), Sheikholeslami, Ellahi, Ashorynejad, Domairry and Hayat (2014), Sheikholeslami *et al.* (2012) and Turkyilmazoglu (2011b); parameterized perturbation method by Ashorynejad *et al.* (2014); collocation method (CM) by Hoshyar *et al.* (2015); Adomian decomposition method by Sheikholeslami, Hatami and Ganji (2013) and Sheikholeslami, Ganji and Ashorynejad (2013); least square method (LSM) by Fakour *et al.* (2014); Galerkin method (GM) by Turkyilmazoglu (2014a, b); and so on.

On the other hand, semi-analytical methods can be characterized into two main perspectives due to their solution procedure, one of them is known as the iterative-base method and other is trial function-base method. In the iterative-base method, for example, HPM, VIM, ADM and so on, the essential factor which influences the iterative methods is the number of iterations. Despite the fact that in these strategies we may accept a trial function, which depends on our independent function, in any case, with a specific end goal to accomplish an arrangement in each step, we need to explain previous step at first. As per said clarifications, it is obvious that iterative steps cannot be retrieved by related programming; we will confront the issue which will interfere with our solving procedure. Furthermore, to follow this procedure it will take more time to solve the governing equations. In the trial function-base method, for example, CM, LSM, Akbari-Ganji's Method and so forth, the fundamental factor which influences the solving procedure is trial function. In this technique, we will expect a proficient trial function based on the boundary and initial conditions of the given problem which contains constant coefficients. These constant coefficients will be obtained easily by solving a set of polynomials (Mirgolbabaee *et al.*, 2017). Recently, analytical investigation of the problem of micropolar fluid in a porous channel with suction/injection has been conducted by Aski *et al.* (2014). Approximate solution of a micropolar fluid in a channel subject to heat transfer and chemical reaction was presented by Sheikholeslami, Hatami and Ganji (2014). HPM was used in order to find approximate solution of governing nonlinear differential equations of a micropolar fluid. Sajid *et al.* (2009) analyzed the boundary layer flow of a micropolar fluid in a porous channel. Fakour *et al.* (2015) considered the heat transfer analysis of a micropolar fluid in a channel analytically and numerically. Approximate solution was obtained by the LSM and the results were compared with fourth-order Runge-Kutta method. The study revealed that the boundary layer thickness of velocity decreases by increasing the values of Reynolds number R. Moreover, fluid temperature increases with the increase in the strength of Peclet number Pe. Hydromagnetic flow of a micropolar fluid between parallel plates with heat transfer was examined by Mehmood *et al.* (2016). Resulting coupled nonlinear governing equations were solved by the optimal homotopy analysis method. The study revealed that coupling parameter increases the vortex viscosity of the fluid which reduces the fluid velocity. Sheikholeslami, Hatami and Ganji (2013)

investigated the problem of MHD nanofluid in a semi-porous channel analytically by the LSM. Results found an excellent agreement with the numerical technique known as GM. Differential transformation method and DTM-Pade transformation are applied in order to find the analytical solution of MHD nanofluid in a channel with nonparallel walls by Hatami *et al.* (2014). Mohammadian *et al.* (2015) examined the effect of thermal radiation of Cu-water nanofluid between two vertical plates by the HPM.

However, it is very hard to find the multiple solutions of the nonlinear fluid flow problems. Based on the solutions of nonlinear problems, it can be argued that numerous nonlinear fluid flow problems have multiple solutions. Without a doubt, it is stated that it is very hard to find all the branches of multiple solutions of a given nonlinear fluid flow problem. At the point when two various solutions are close to each other, most of the numerical techniques fail to identify the multiple solutions due to the fact that numerical solution might oscillate between two solutions. However, under certain circumstances, if one solution is known others may be determined (Raza *et al.*, 2016a, b).

Motivated from the above cited literature, the prime objective of this study is to investigate multiple solutions of laminar, incompressible micropolar fluid in a channel with porous walls. Shooting technique is applied in order to find the multiple solutions of the proposed problem. Velocity, micro-rotation and skin friction profiles are presented for the various values of suction Reynolds number R and vortex viscosity parameter C_1 which make the analysis more interesting.
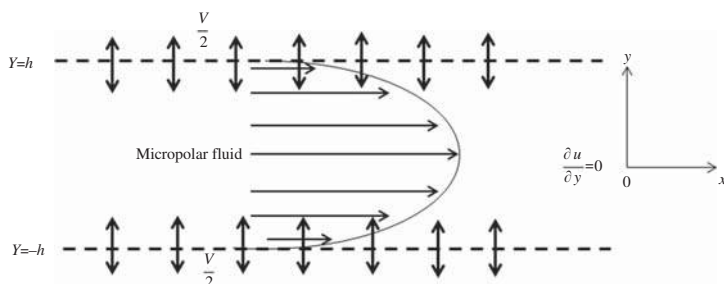
2. Mathematical formulation

A two-dimensional laminar, incompressible micropolar fluid in a porous channel is considered. The width of the channel is taken as $2h$ such that lower wall of the channel is located at $y = -h$ and upper wall is at $y = h$ as shown in Figure 1. Flow is driven by the constant inlet velocity U with a constant pressure. Fluid is considered to be symmetric in both axes. Moreover, fluid can be inserted or extracted into a channel through porous walls with constant velocity $V/2$, neglecting body forces and body couples of the fluid.

The general equations governing the motion of micropolar fluids as given by Eringen (1964) may be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \overline{V} \right) = 0 \tag{1}$$

$$(\lambda + 2\mu + \kappa) \nabla \left(\nabla \cdot \overline{V} \right) - (\mu + \kappa) \nabla \times \nabla \times \overline{V} + \kappa \nabla \times \overline{v} - \nabla p + \rho \overline{f} = \rho \dot{\overline{V}} \tag{2}$$

$$(\alpha + \beta + \gamma) \nabla (\nabla \cdot \overline{v}) - \gamma (\nabla \times \nabla \times \overline{v}) + \kappa \nabla \times \overline{V} - 2\kappa \overline{v} + \rho \overline{l} = \rho j \dot{\overline{v}} \tag{3}$$

Figure 1.
Physical model of the proposed problem

where $\overline{V}$ is the velocity field; $\overline{v}$ the micro-rotation vector; ρ the density; p the pressure; $\overline{f}$ and $\overline{l}$ the body force and body couple per unit mass, respectively; j the micro-inertia; and λ, μ, α, β, γ and κ the micropolar material constants (or viscous coefficients), dot signifies material derivatives.

Components of the velocity vector $\overline{V}$ and micro-rotation $\overline{v}$ are in the form of the following equation:

$$\overline{V} = (u(x,y), v(x,y), 0)\, \overline{v} = (0, 0, g(x,y))$$

where g is the component of the micro-rotation normal to the xy-plane.

Governing equations of the flow for the proposed problem are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{-1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu+\kappa}{\rho}\nabla^2 u + \frac{\kappa}{\rho}\frac{\partial g}{\partial y} \tag{5}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{-1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu+\kappa}{\rho}\nabla^2 v - \frac{\kappa}{\rho}\frac{\partial g}{\partial x} \tag{6}$$

$$\rho \overline{j}\left(u\frac{\partial g}{\partial x} + v\frac{\partial g}{\partial y}\right) = \gamma\nabla^2 g + \kappa\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) - 2\kappa g \tag{7}$$

Corresponding to the boundary conditions at the lower and upper walls:

$$\left.\begin{array}{l} u(x, \pm h) = 0 \\ v(x, \pm h) = \frac{V}{2} \\ g(x, \pm h) = 0 \end{array}\right\} \tag{8}$$

where $V > 0$ corresponds to suction and $V < 0$ is for injection. Moreover, micro-rotation component g is taken to be 0 because we neglect body coupling near the channel walls (i.e. $\nabla \times \overline{V} = 0$).

In order to articulate governing partial differential equations, i.e. (4)-(7) into ordinary differential equations, we use similarity transformation suggested by Berman (1953):

$$\psi(x,y) = (Uh - Vx)f(\eta), \quad g(x,y) = -\left(U - \frac{Vx}{h}\right)\frac{\varphi(\eta)}{h}, \eta = \frac{y}{h} \tag{9}$$

By applying Equation (9) into (4)-(7) and eliminating the pressure term from Equations (5) and (6), we obtain the following equation:

$$f'''' - C_1\varphi'' + R(f'f'' - ff''') = 0, \tag{10}$$

$$\varphi'' + C_2\left(f'' + 2\varphi\right) - C_3\left(f'\varphi - f\varphi'\right) = 0 \tag{11}$$

Subject to the appropriate boundary conditions, we get:

$$\left.\begin{array}{l} f(1) = \frac{1}{2},\ f'(1) = 0,\ \varphi(1) = 0 \\ f''(0) = 0, \varphi(0) = 0 \end{array}\right\} \tag{12}$$

where $R = ((\rho V h)/(\mu + \kappa))$ is the Reynolds number ($R > 0$ suction, $R < 0$ injection), $C_2 = (\kappa h^2)/(\gamma)$ is the spin gradient viscosity and $C_3 = (\rho j V h)/(\gamma)$ is the micro-inertia density.

3. Numerical computation

In order to solve Equations (10) and (11) subject to boundary condition (12) numerically, we employ the shooting technique. For this, we convert it into a first-order initial value problem by setting $\Gamma_1 = \eta$, $\Gamma_2 = f$, $\Gamma_3 = f'$, $\Gamma_4 = f''$, $\Gamma_5 = f'''$, $\Gamma_6 = \varphi$ and $\Gamma_7 = \varphi'$:

$$
\begin{pmatrix}
\Gamma_1' \\
\Gamma_2' \\
\Gamma_3' \\
\Gamma_4' \\
\Gamma_5' \\
\Gamma_6' \\
\Gamma_7'
\end{pmatrix}
=
\begin{pmatrix}
1 \\
\Gamma_3 \\
\Gamma_4 \\
\Gamma_5 \\
C_1(C_3(\Gamma_3\Gamma_6 - \Gamma_2\Gamma_7) - C_2(\Gamma_4 + 2\Gamma_6)) - R(\Gamma_3\Gamma_4 - \Gamma_2\Gamma_5) \\
\Gamma_7 \\
C_3(\Gamma_3\Gamma_6 - \Gamma_2\Gamma_7) - C_2(\Gamma_4 + 2\Gamma_6)
\end{pmatrix}
\tag{13}
$$

With initial conditions, we obtain:

$$
\begin{pmatrix}
\Gamma_1 \\
\Gamma_2 \\
\Gamma_3 \\
\Gamma_4 \\
\Gamma_5 \\
\Gamma_6 \\
\Gamma_7
\end{pmatrix}
=
\begin{pmatrix}
1 \\
\frac{1}{2} \\
0 \\
\alpha \\
\beta \\
0 \\
\gamma
\end{pmatrix}
\tag{14}
$$

where α, β and γ are unknown initial conditions. We have to shoot these initial conditions with some arbitrary slope such that solution of the system (13) satisfies the given conditions at the boundary. Hit and trail approach is acquired in order to find the unknown initial conditions. Once the slope of α, β and γ is assumed, then numerical integration is made for the initial value problem and the accuracy of missing initial conditions is checked by comparing the calculated value with the given terminal point. The details of shooting method with Maple implementation shoot has been described by Meade *et al.* (1996). Recently, Raza *et al.* (2016a, b) and Raza *et al.* (2017) successfully employed the shooting method on fluid flow problems to find solve system of fourth-order nonlinear ordinary differential equations. Results were acknowledged and multiple solutions were investigated through the shooting technique.

4. Results and discussions

In this section, we have prepared figures in order to elaborate our numerical findings. Our main objective is to investigate some different branches of the solution for the variation of suction Reynolds number R and vortex viscosity parameter C_1. Figures are drawn by varying numerical values of one parameter at a time while fixing the other parameter invariant. It is important to know that C_2 and C_3 on velocity and micro-rotation do not have a significant effect, so therefore we fixed $C_2 = 0.1$ and $C_3 = 0.3$ throughout this study (Rauf *et al.*, 2016).

In Figure 2, we plot skin friction $-f''(1)$ at the wall against suction Reynolds number $R > 0$ by setting $C_1 = C_2 = 0.1$, $C_3 = 0.3$. Based on the findings of multiple solutions of the proposed problem, it can be argued that the solution satisfies the existence and uniqueness theorem for $0 \leqslant R < 24.33$. So, from this pictorial representation of numerical investigation, it is claimed that there is only single solution within the range $0 \leqslant R < 24.33$, while in the range $24.33 \leqslant R < \infty$ three solutions exist for every value of suction Reynolds number R. Therefore, $R = R_{\text{critical}} = 24.33$ is the critical value of the suction Reynolds number R where solution has more than one branch and it can be seen clearly in Figure 2. Furthermore, for the values of $R \geqslant 70$, the first branch of solution conspires with the second branch of the solution. Without loss of any generality, we can say that triple solutions of the proposed problem exist only for $R \geqslant R_{\text{critical}} = 24.33$. Effect of suction Reynolds number R on velocity profile $f'(\eta)$ for $C_1 = 0.5$ for different branches of the solution are plotted in Figure 3. Velocity profile $f'(\eta)$ increases near the channel wall $\eta \approx 1$ by the enhancement of suction Reynolds number $R = 30, 35, 40$ for the first and third branch of the solutions. It is because of this fact that the suction adds up an extra forcing agents to the fluid particles, thus the velocity boosts up further incalculably by increasing R. However, totally opposite behavior is observed near the wall for the second branch of the solution. Figure 4 depicts the behavior of micro-rotation in a channel for different values of suction Reynolds number R. Profiles of micro-rotation for different branches of solution are seemed to be like parabolic in nature. Micro-rotation profile is amassed upwards by increasing the values of suction Reynolds number $R = 30, 35, 40$ for the first and third branches of the solution. Profile of the first branch is concaved up and concaved down for the second and third branches of the solution. Micro-rotation profile for the second branch decreases by increasing the values of suction Reynolds number R. Point of concavity $\eta \approx 0.8$ where micro-rotation changes its sign from negative to positive is actually the point where the shear stresses due to the suction resulting in zero micro-rotation. Before the point of concavity, the micro-rotation profile decreases and increases afterwards.

Effect of vortex viscosity parameter C_1 on the velocity and micro-rotation profile for $R = 30$, $C_2 = 0.1$ and $C_3 = 0.3$ is presented in Figures 5 and 6, respectively. Velocity profile $f'(\eta)$ shifted away from the channel wall as we increase the strength of vortex viscosity parameter $C_1 = 0.5, 5, 10$, this means that the velocity increases near the center of the channel $\eta \approx 0$ for first and second branches of the solution. Physically, we can say that shear stress at the wall $f''(1)$ decreases by increasing the values of C_1, which conforms with the
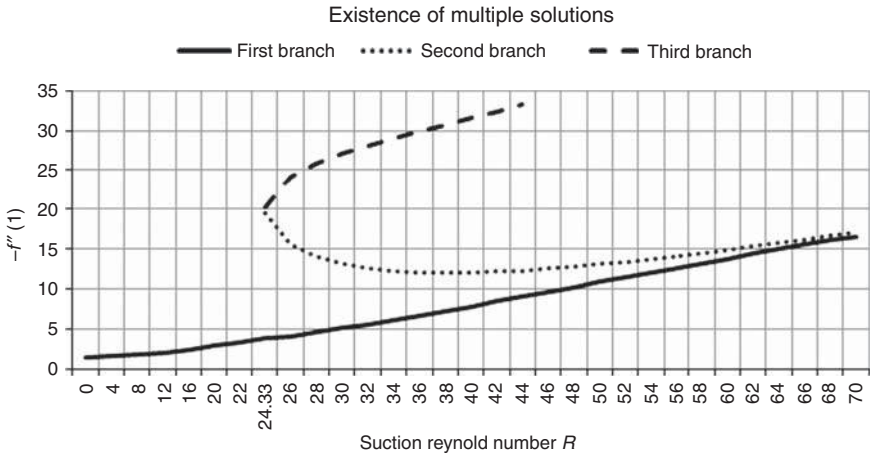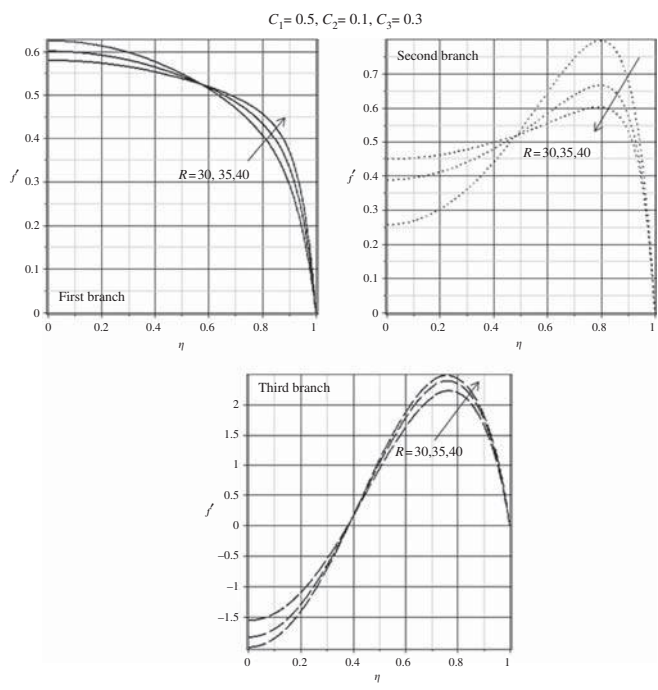

Figure 2.
Skin friction $-f''(1)$ at the wall against suction Reynolds number R

Figure 3.
Effect of suction
Reynolds number R
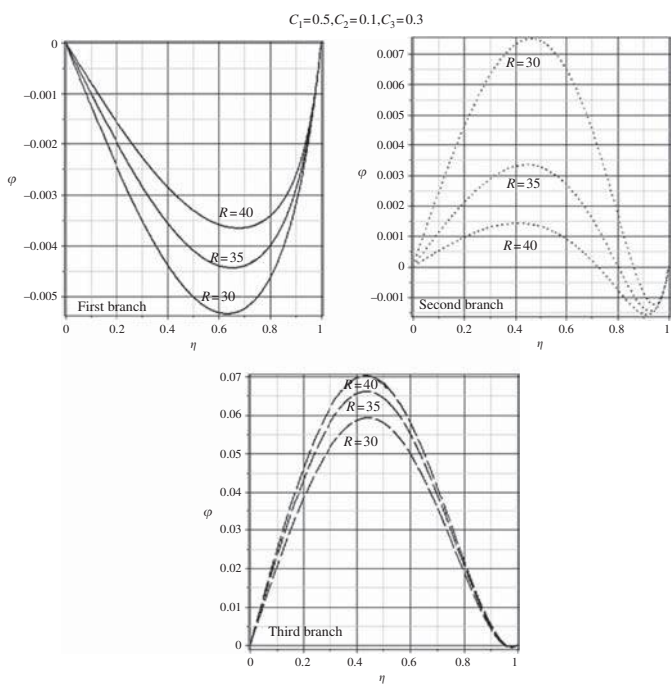on velocity profile $f'(\eta)$

Figure 4.
Effect of suction
Reynolds number R
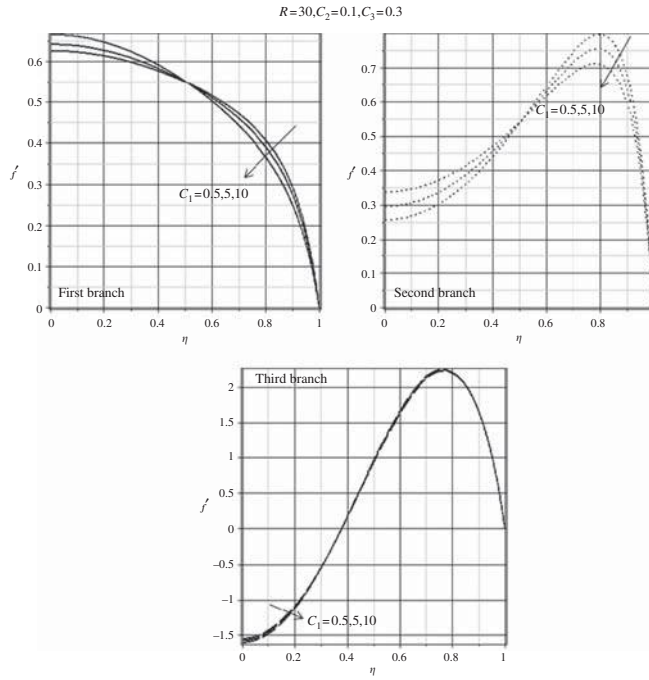on micro-rotation
profile $\varphi(\eta)$

Figure 5.
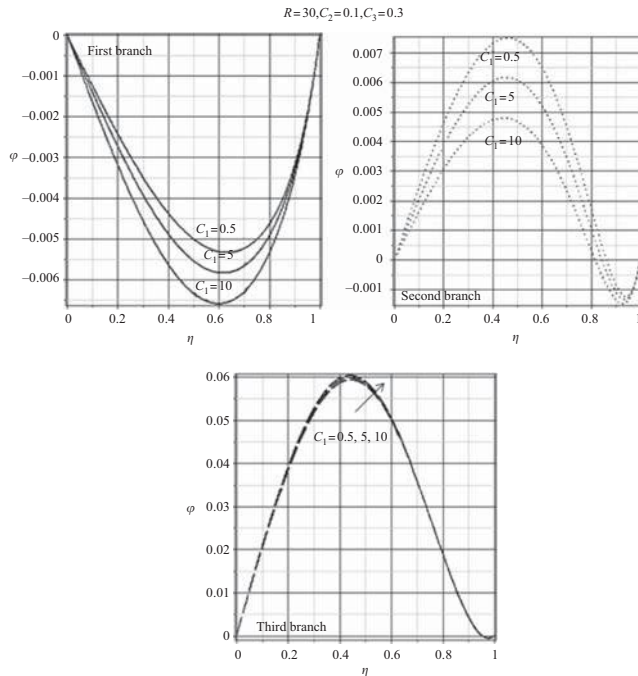Effect of C_1 on velocity profile $f'(\eta)$

Figure 6.
Effect of C_1 on micro-rotation profile $\varphi(\eta)$

results derived by Hoyt and Fabula (1964). However, totally reversed phenomena are observed for the third branch of the solution.

Micro-rotation profile $\varphi(\eta)$ decreases for the first and second branches of the solution by increasing the values of vortex viscosity parameter C_1, it is due to the fact that couple stress $\varphi'(\eta)$ increases by increasing the numerical values of $C_1 = 0.5, 5, 10$.

5. Conclusion

The present paper is motived to investigate the multiple solutions of a micropolar fluid in a channel with porous walls. A numerical study is carried out in order to find different branches of the solution for the variation of suction Reynolds number R on the shear stresses and micro-rotation field. Based on the findings of numerical investigation, the following conclusion has been engendered:

(1) multiple solutions of the problem occur only for the case of large suction within the range of $24.33 \leqslant R < \infty$;

(2) velocity profile $f'(\eta)$ increases near the wall of the channel $\eta \approx 1$ for the first and third branches of the solution;

(3) enhancement of the vortex viscosity parameter C_1 reduces the velocity of the fluid particles near the channel wall, this result is a good argument of the previous experimental study of Hoyt and Fabula (1964); and

(4) micro-rotation profile $\varphi(\eta)$ decreases by increasing the values of $C_1 = 0.5, 5, 10$ for the first and second branches of the solution.

References

Ali, K. and Ashraf, M. (2014), "Numerical simulation of the micropolar fluid flow and heat transfer in a channel with a shrinking and a stationary wall", *Journal of Theoretical and Applied Mechanics*, Vol. 52 No. 2, pp. 557-569.

Ashorynejad, H.R., Javaherdeh, K., Sheikholeslami, M. and Ganji, D.D. (2014), "Investigation of the heat transfer of a non-Newtonian fluid flow in an axisymmetric channel with porous wall using parameterized perturbation method (PPM)", *Journal of the Franklin Institute*, Vol. 351 No. 2, pp. 701-712.

Aski, F.S., Nasirkhani, S.J., Mohammadian, E. and Asgari, A. (2014), "Application of Adomian decomposition method for micropolar flow in a porous channel", *Propulsion and Power Research*, Vol. 3 No. 1, pp. 15-21.

Berman, A.S. (1953), "Laminar flow in channels with porous walls", *Journal of Applied Physics*, Vol. 24 No. 9, pp. 1232-1235.

Busuke, H. and Tatsuo, T. (1969), "Two-dimensional shear flows of linear micropolar fluids", *International Journal of Engineering Science*, Vol. 7 No. 5, pp. 515-522.

Dehghan, M., Jamal-Abad, M.T. and Rashidi, S. (2014), "Analytical interpretation of the local thermal non-equilibrium condition of porous media imbedded in tube heat exchangers", *Energy Conversion and Management*, Vol. 85, pp. 264-271.

Eringen, A.C. (1964), "Simple microfluids", *International Journal of Engineering Science*, Vol. 2 No. 2, pp. 205-217.

Fakour, M., Ganji, D.D. and Abbasi, M. (2014), "Scrutiny of underdeveloped nanofluid MHD flow and heat conduction in a channel with porous walls", *Case Studies in Thermal Engineering*, Vol. 4, pp. 202-214.

Fakour, M., Vahbzadeh, A., Ganji, D.D. and Hatami, M. (2015), "Analytical study of micropolar fluid flow and heat transfer in a channel with permeable walls", *Journal of Molecular Liquids*, Vol. 204, pp. 198-204.

Ganji, D.D., Hosseini, M.J. and Shayegh, J. (2007), "Some nonlinear heat transfer equations solved by three approximate methods", *International Communications in Heat and Mass Transfer*, Vol. 34 No. 8, pp. 1003-1016.

Hatami, M., Sheikholeslami, M., Hosseini, M. and Ganji, D.D. (2014), "Analytical investigation of MHD nanofluid flow in non-parallel walls", *Journal of Molecular Liquids*, Vol. 194, pp. 251-259.

Hoshyar, H.A., Rahimipetroudi, I., Ganji, D.D. and Majidian, A.R. (2015), "Thermal performance of porous fins with temperature-dependent heat generation via the homotopy perturbation method and collocation method", *Journal of Applied Mathematics and Computational Mechanics*, Vol. 14 No. 4, pp. 53-65.

Hoyt, J.W. and Fabula, A.G. (1964), "The Effect Of Additives On Fluid Friction", No. NOTS-TP-3670, Naval Ordnance Test Station China Lake, CA.

Joneidi, A.A., Ganji, D.D. and Babaelahi, M. (2009), "Micropolar flow in a porous channel with high mass transfer", *International Communications in Heat and Mass Transfer*, Vol. 36 No. 10, pp. 1082-1088.

Kelson, N.A. and Desseaux, A. (2001), "Effect of surface conditions on flow of a micropolar fluid driven by a porous stretching sheet", *International Journal of Engineering Science*, Vol. 39 No. 16, pp. 1881-1897.

Majdalani, J. (2008), "Exact Navier-Stokes solution for the pulsatory viscous channel flow with arbitrary pressure gradient", *Journal of Propulsion and Power*, Vol. 24 No. 6, pp. 1412-1423.

Meade, D.B., Haran, B.S. and White, R.E. (1996), "The shooting technique for the solution of two-point boundary value problems", *Maple Technical Newsletter*, Vol. 3 No. 1, pp. 1-8.

Mehmood, R., Nadeem, S. and Masood, S. (2016), "Effects of transverse magnetic field on a rotating micropolar fluid between parallel plates with heat transfer", *Journal of Magnetism and Magnetic Materials*, Vol. 401, pp. 1006-1014.

Mekheimer, K.S. and El Kot, M.A. (2008), "The micropolar fluid model for blood flow through a tapered artery with a stenosis", *Acta Mechanica Sinica*, Vol. 24 No. 6, pp. 637-644.

Mirgolbabaee, H., Ledari, S.T. and Ganji, D.D. (2017), "Semi-analytical investigation on micropolar fluid flow and heat transfer in a permeable channel using AGM", *Journal of the Association of Arab Universities for Basic and Applied Sciences*.

Mirgolbabaei, H, Ganji, D.D., Etghani, M.M. and Sobati, A. (2009), "Adapted variational iteration method and axisymmetric flow over a stretching sheet", *World Journal of Modelling and Simulation*, Vol. 5 No. 4, pp. 307-314.

Mohammadian, E., Ghasemi, S.E., Poorgashti, H., Hosseini, M. and Ganji, D.D. (2015), "Thermal investigation of Cu-water nanofluid between two vertical planes", *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, Vol. 229 No. 1, pp. 36-43.

Nadeem, S., Akbar, N.S. and Malik, M.Y. (2010), "Exact and numerical solutions of a micropolar fluid in a vertical annulus", *Numerical Methods for Partial Differential Equations*, Vol. 26 No. 6, pp. 1660-1674.

Rauf, A., Shahzad, S.A., Siddiq, M.K., Raza, J. and Meraj, M.A. (2016), "Mixed convective thermally radiative micro nanofluid flow in a stretchable channel with porous medium and magnetic field", *AIP Advances*, Vol. 6 No. 3, pp. 035126-1-11.

Rawool, A.S., Mitra, S.K. and Kandlikar, S.G. (2006), "Numerical simulation of flow through microchannels with designed roughness", *Microfluidics and Nanofluidics*, Vol. 2 No. 3, pp. 215-221.

Raza, J., Rohni, A.M. and Omar, Z. (2016a), "A note on some solutions of copper-water (cu-water) nanofluids in a channel with slowly expanding or contracting walls with heat transfer", *Mathematical and Computational Applications*, Vol. 21 No. 2, pp. 24-33.

Raza, J., Rohni, A.M. and Omar, Z. (2016b), "MHD flow and heat transfer of Cu–water nanofluid in a semi porous channel with stretching walls", *International Journal of Heat and Mass Transfer*, Vol. 103, pp. 336-340.

Raza, J., Rohni, A.M., Omar, Z. and Awais, M. (2017), "Rheology of the Cu-H2O nanofluid in porous channel with heat transfer: multiple solutions", *Physica E: Low-dimensional Systems and Nanostructures*, Vol. 86, pp. 248-252.

Sajid, M., Abbas, Z. and Hayat, T. (2009), "Homotopy analysis for boundary layer flow of a micropolar fluid through a porous channel", *Applied Mathematical Modelling*, Vol. 33 No. 11, pp. 4120-4125.

Samaee, S.S., Yazdanpanah, O. and Ganji, D.D. (2015), "New approaches to identification of the Lagrange multiplier in the variational iteration method", *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 37 No. 3, pp. 937-944.

Sheikholeslami, M., Ganji, D.D. and Ashorynejad, H.R. (2013), "Investigation of squeezing unsteady nanofluid flow using ADM", *Powder Technology*, Vol. 239, pp. 259-265.

Sheikholeslami, M., Hatami, M. and Ganji, D.D. (2013), "Analytical investigation of MHD nanofluid flow in a semi-porous channel", *Powder Technology*, Vol. 246, pp. 327-336.

Sheikholeslami, M., Hatami, M. and Ganji, D.D. (2014), "Micropolar fluid flow and heat transfer in a permeable channel using analytical method", *Journal of Molecular Liquids*, Vol. 194, pp. 30-36.

Sheikholeslami, M., Ashorynejad, H.R., Domairry, G. and Hashim, I. (2012), "Flow and heat transfer of Cu-water nanofluid between a stretching sheet and a porous surface in a rotating system", *Journal of Applied Mathematics*.

Sheikholeslami, M., Ellahi, R., Ashorynejad, H.R., Domairry, G. and Hayat, T. (2014), "Effects of heat transfer in flow of nanofluids over a permeable stretching wall in a porous medium", *Journal of Computational and Theoretical Nanoscience*, Vol. 11 No. 2, pp. 486-496.

Turkyilmazoglu, M. (2011b), "Convergence of the homotopy perturbation method", *International Journal of Nonlinear Sciences and Numerical Simulation*, Vol. 12 Nos 1-8, pp. 9-14.

Turkyilmazoglu, M. (2012), "MHD fluid flow and heat transfer due to a stretching rotating disk", *International Journal of Thermal Sciences*, Vol. 51, pp. 195-201.

Turkyilmazoglu, M. (2014a), "A note on micropolar fluid flow and heat transfer over a porous shrinking sheet", *International Journal of Heat and Mass Transfer*, Vol. 72, pp. 388-391.

Turkyilmazoglu, M. (2014b), "Unsteady convection flow of some nanofluids past a moving vertical flat plate with heat transfer", *Journal of Heat Transfer*, Vol. 136 No. 3.

Turkyilmazoglu, M. (2016a), "Convergent optimal variational iteration method and applications to heat and fluid flow problems", *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 26 Nos 3/4, pp. 790-804.

Further reading

Raza, J., Rohni, A.M. and Omar, Z. (2016c), "Rheology of micropolar fluid in a channel with changing walls: investigation of multiple solutions", *Journal of Molecular Liquids*, Vol. 223, pp. 890-902.

Shrestha, G. (1967), "Perturbation techniques in laminar flow", *The Quarterly Journal of Mechanics & Applied Mathematics*, Vol. 20, pp. 233-246.

Turkyilmazoglu, M. (2011a), "Analytic approximate solutions of rotating disk boundary layer flow subject to a uniform vertical magnetic field", *Acta Mechanica*, Vol. 218 No. 3, pp. 237-245.

Turkyilmazoglu, M. (2016b), " Flow of a micropolar fluid due to a porous stretching sheet and heat transfer", *International Journal of Non-Linear Mechanics*, Vol. 83, pp. 59-64.

Corresponding author
Jawad Raza can be contacted at: jawad_6890@yahoo.com