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Laminar Viscous Flow of Micropolar Fluid through Non-Darcy Porous Medium Undergoing Uniform Suction or Injection

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ABSTRACT: In this study, the micropolar fluid flow conveyed through suction or injection in a non-Darcy porous medium with high mass transfer is considered. The micropolar fluid flow is described by coupled systems of higher order, ordinary, nonlinear differential equations. Therefore the variation of parameters method is utilized in generating analytical solutions to the mathematical models arising from flow and rotation of the micropolar fluid. As the variation of parameters method is a relatively easy, yet efficient approach of analyzing both strongly and weakly dependent nonlinear equations with a rapid convergence rate. Pertinent rheological fluid parameter effects such as non-Darcy parameter and Reynolds number on flow and rotation are examined using the obtained analytical solutions. Observations from graphical representation of result illustrate flow increase during injection and slight radial velocity decrease for suction flow. Reynolds parameter effect on fluid particles micro rotation also shows decrease in rotation profile during injection while during suction increased particle rotation is observed as a result of high mass transfer. Results obtained from study compared against existing works in literature prove to be in satisfactory agreement. Therefore this paper can be used to further study of micropolar fluids applications such as blood flow, lubricants and micro channel flows amongst others.

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1- Introduction

Fluids having its micro constituent rotating against each other during flow are referred to as micropolar fluids. Fluids of this category have macroscopic velocity and particle spin which forms the internal structure, which are considered during flow and rotation of micro constituent. Foundational works on the micropolar fluids was performed by Eringen [1]. In the process of modeling the non-Newtonian fluid behavior, he considered fluid whose micro-constituent rotate during flow, therefore he included more micro rotation vectors and material parameters making the model more non-linear while effect of temperature gradient under convective heat transfer was studied by Idris [2] on micropolar fluids. Laminar flow behavior of micropolar fluids was investigated by Yuan [3] considering porous channel flow. Stretching sheet effect of micropolar fluid flow with strong suction/injection was presented by Kelson [4,5] considering surface condition effect. Viscous fluid flow along porous wall was studied by Zaturksa et al. [6] driven by suction. Vertical truncated cone was analyzed by Cheng [7] adopting the power law. Joneidi et al. [8] applied the Differential Transformation Method (DTM) to heat transfer problems of nonlinear equations while Hassan [9] adopted the DTM in solving Eigen value problems. Boundary layer flow problems were studied by Magyari and Keller [10] for permeable channels utilizing exact solutions. Murthy and Singh [11] presented the effect of thermal performance on surface mass flux under convection. Micropolar fluid transported through a permeable channel was studied using analytical method by Sheikholeslami et al. [12] considering flow and heat transfer. Kelson and Desseaux [13] presented flow of micropolar fluid on stretching surfaces while Mohamed and Abo-Dahab [14] studied thermal and chemical effect on Magnetohydrodynamic (MHD) mass and heat transfer on the micropolar flow. The study of micropolar fluid on flat plate was presented by Rees and Bassom [15]. Das et al. [16] studied MHD slip flow of micro polar fluid over a moving plate. Effects of pulsating micro polar fluid through bifurcated artery was studied by Srinivasacharya and Rao [17] while Rout et al. [18] investigated reaction effect of free convection on MHD fluid. Hassan et al. [19] presented their study on micro polar fluid flow over a moving boundary. Micro polar flow through porous medium with heat absorption was investigated by Bank et al. [20] considering heat absorption. Unsteady flow of micropolar fluid through porous flow channels under magnetic influence was analyzed by [21-23].

The system of equations describing flow and rotation of micropolar fluid are nonlinear, ordinary, higher order differential equations. Therefore numerical or analytical methods of solution are required in generating solutions to coupled equations. Hence numerical and analytical approximate solutions are applied by researchers [24-37] in analyzing nonlinear problems in engineering. Methods of solutions adopted include the Pertubation Method (PM),Homotopy Analysis Method (HAM), Homotopy Pertubation Method (HPM), differential transform method,Variational Iteration Method (VIM) , garlerkin method of weighted residuals and Adomian Decomposition Method (ADM). Methods such as PM requires the use of small perturbation parameter, which may be artificial making the solutions to problems linearly restrictive. The need to find initial condition or auxilliary parameter to satisfy the boundary condition makes method such as HAM more tedious, rigours

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of derivation of differential transforms for the DTM makes it less attractive to researchers. Computational tools are required for solving higher order problems for the HPM resulting to large computational cost and time [38] . The method of weighing residuals, an effective analytical approach which includes the Garlerkins method, Least square method and the Collocation method requires the weighing functions to satisfy weighted residual which may be arbitrary. The ADM makes it necessary to determine lagragian polynomials, which makes the method cumbersome for decomposed nonlinear coupled equations. In the search for convenient and relatively simple method of solution, the Variation of Parameters Method (VPM) is considered. Since it has the capacity to solve weakly and strongly dependent nonlinear equations. It as a rapid convergent rate without taking the highest order term into consideration as compared with VIM [34].

In past literatures, no study where non-Darcy effect on channel walls of micropolar fluid flow and rotation are examined. Hence this paper aim to investigate the effect of flow and rotation of micropolar fluids transported through non-Darcy porous channels with high mass transfer using the variation of parameters method.

2- Model Development and Analytical Solution

Flow of micropolar fluid though non-Darcy porous channel is described here. Fluid is said to be driven by suction or injection representing speed as q. The wall channel is parallel to the x axis having width of distance $2h$ and located at the reference $y=\pm h$. This is described using the Cartesian co-ordinate. The model is developed for the micropolar fluid with respect to the above conditions following the assumptions that the fluid is incompressible, flow is steady and laminar. Also radiation heat transfer is negligible. Therefore the governing equations of the channel flow are presented as [24]:

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

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial P}{\partial x}+(\mu+\kappa)\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\kappa\frac{\partial N}{\partial y} \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+(\mu+\kappa)\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\kappa\frac{\partial N}{\partial x} \tag{3}$$

$$\rho\left(u\frac{\partial N}{\partial x}+v\frac{\partial N}{\partial y}\right)=-\frac{\kappa}{j}(\mu+\kappa)\left(2N+\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}\right)+\frac{\mu_s}{j}\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right) \tag{4}$$

The governing equations, Eqs. (1) to (4) include material parameters and angular velocity or micro rotation whose

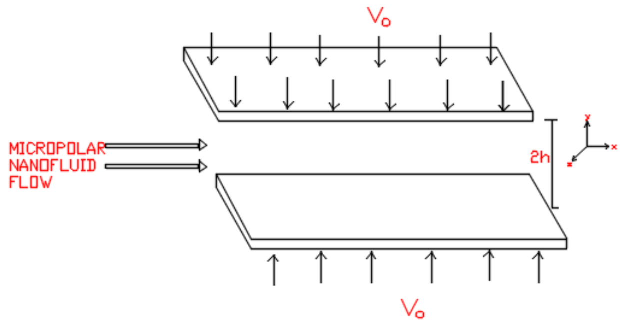

Fig. 1. Physical model diagram.

direction is consistent with the xy plane. Therefore in this study, material parameters are constant and independent [36].

$$u(x,\pm h)=0, v(x,\pm h)=\pm q, \quad N(x,\pm \mathrm{h})=-\mathrm{s}\left.\frac{\partial u}{\partial y}\right|_{x=\pm h} \tag{5}$$

Fluid flow is assumed symmetric about y equal zero [36].

$$\frac{\partial u}{\partial y}(x,0)=v(x,0)=0 \tag{6}$$

The flow situation of the micropolar fluid is represented by s. Where s=0, depicts inability of microelement close to the wall to rotate due to the no slip condition or fluid particle sticking at the inner surface of the channel while s=0.5 depicts fluid vorticity and microrotation is the same at the boundary due to weak concentration flows. Similarly injected or removed fluid from flow stream is depicted by the value of q. Given that suction is represented by q>0 and injection is the condition when q<0. The governing equation is therefore simplified by including micropolar effects assuming stream functions and micropolar adopting the similarity solution of Berman [25]:

$$\psi=-qxF(\eta) \tag{7}$$

$$N=\frac{qx}{h^2}G(\eta) \tag{8}$$

where

$$\eta=\frac{y}{h}, u=\frac{\partial\psi}{\partial y}=-\frac{qx}{h}F'(\eta), v=-\frac{\partial\psi}{\partial x}=qF(\eta) \tag{9}$$

Dimensionless micropolar parameters are introduced as

$$N_1=\frac{\kappa}{\mu}, N_2=\frac{v_s}{\mu h^2}, N_3=\frac{j}{h^2}, \quad Re=\frac{\rho q}{\mu}h, F_w=\frac{2C_f\sqrt{k_u}}{v} \tag{10}$$

Where dimensionless velocity components are taken as u and v for the x and y directions respectively, η is the dimensionless normal distance, F_w is the non-Darcy parameter measuring inertia effects on flow through porous medium and $N_{1,2,3}$ are the dimensionless micro rotation parameter which measures effect of particle rotating constituents on flow through the porous medium.

Utilizing Eqs. (7) to (10), the Eqs. (1) to (4) may be reduced to ordinary nonlinear equations of the differential type as stated below:

$$(1+N_1+F_w)\frac{d^4F}{d\eta^4}-N_1\frac{d^2G}{d\eta^2} -Re\left(F\frac{d^3F}{d\eta^3}-\frac{dF}{d\eta}\frac{d^2F}{d\eta^2}\right)=0 \quad (11)$$

$$N_2\frac{d^2G}{d\eta^2}+N_1\left(\frac{d^2F}{d\eta^2}-2G\right) -N_3Re\left(F\frac{dG}{d\eta}-G\frac{dF}{d\eta}\right)=0 \quad (12)$$

Symmetry of fluid flow through the porous channel is assumed therefore boundary condition takes the form

$$F(0)=F''(0)=F'(1)=0, F(1)=1$$
$$G(1)=sF''(1) \quad (13)$$

2- 1- Principles of variation of parameters method

The procedural concept or technique of the variation of parameters method for analysis of differential equation is expressed as follows. Nonlinear form of differential equation is in the operator form [34]:

$$Lf(\eta)+Rf(\eta)+N_uf(\eta)=g \quad (14)$$

Given

L is easily convertible and the derivative of the highest order

R is the linear operator remainder and is less compared with L

g is the system input or source term

u is the system output

N_u is the nonlinear equation terms

Decomposing Eq. (14) above into $L+R$ .Therefore the VPM can be defined as follows

$$f_{n+1}(\eta)=f_0(\eta) +\int_0^\eta \lambda(\eta s)(-Rf_n(s)-N_uf_n(s)-g(s)ds \quad (15)$$

where initial approximation $f_0(\eta)$ is given by

$$f_0(\eta)=\sum_{i=0}^{m}\frac{k_if^i(0)}{i!} \quad (16)$$

where

m is the order of the given differential equation

k_i is an unknown constant which could be obtained using initial/boundary conditions

$\lambda(\eta,s)$ is a multiplier which reduces the equation order of integration, which is determined adopting the Wronskian technique stated as Sobamowo et al. [34]

$$\lambda(\eta,s)=\sum_{i=0}^{m}\frac{(-1)^{i-1}s^{i-1}\eta^{m-1}}{(i-1)!(m-i)!}=\frac{(\eta-s)^{m-1}}{(m-1)!} \quad (17)$$

2- 2- Application of the variation of parameters method

Applying the standard procedure of the VPM the Eq. (17). The Eqs. (11) and (12) is presented as

$$F_{n+1}(x)=k_1+k_2s+k_3\frac{s^2}{2}+k_4\frac{s^3}{6}- \int_0^\eta\left(\frac{\eta^3}{3!}-\frac{\eta^2s}{2!}+\frac{\eta s}{2!}-\frac{s^3}{3!}\right)\left[\begin{array}{l}N_1\frac{d^4F}{d\eta^4}+F_w\frac{d^4F}{d\eta^4}-\\ N_1\frac{d^2G}{d\eta^2}-Re\\ \left(F\frac{d^3F}{d\eta^3}-\frac{dF}{d\eta}\frac{d^2F}{d\eta^2}\right)\end{array}\right]ds \quad (18)$$

$$G_{n+1}(x)=k_1+k_2s -\int_0^\eta(\eta-s)\left[\begin{array}{l}\frac{N_1}{N_2}\left(\frac{d^2F}{d\eta^2}-2G\right)\\ -\frac{N_3}{N_2}Re\left(F\frac{dG}{d\eta}-G\frac{dF}{d\eta}\right)\end{array}\right]ds \quad (19)$$

Here k_1, k_2, k_3 and k_4 are constant. They are derived by taking the highest order in the linear term Eqs. (18) and (19) which is integrated, to generate the scheme final form. Applying the boundary condition Eq. (13). The above equation can be written as

$$F_{n+1}(x)=k_1+k_3\frac{s^2}{2}-\int_0^\eta\left(\frac{\eta^3}{3!}-\frac{\eta^2s}{2!}+\frac{\eta s}{2!}-\frac{s^3}{3!}\right)\left[\begin{array}{l}N_1\frac{d^4F}{d\eta^4}+F_w\frac{d^4F}{d\eta^4}-N_1\frac{d^2G}{d\eta^2}\\ -Re\left(F\frac{d^3F}{d\eta^3}-\frac{dF}{d\eta}\frac{d^2F}{d\eta^2}\right)\end{array}\right]ds \quad (20)$$

$$G_{n+1}(x)=k_1-\int_0^\eta(\eta-s)\left[\begin{array}{l}\frac{N_1}{N_2}\left(\frac{d^2F}{d\eta^2}-2G\right)-\\ \frac{N_3}{N_2}Re\left(F\frac{dG}{d\eta}-G\frac{dF}{d\eta}\right)\end{array}\right]ds \quad (21)$$

Following the iterative scheme, it can be easily shown that

$$F_0=-\eta^2(2\eta-3) \quad (22)$$

$$G_0=0 \quad (23)$$

$$F_1 = \left(\eta^2 \begin{pmatrix} 7560N_1 + 13\,\mathrm{Re} + 7560F_w - 5060\eta - 66\,\mathrm{Re}\,\eta \\ -5040N_1\eta - 16Re\eta - 5040F_w\eta + 126Re\eta^2 - \\ 96Re\eta^3 + 9Re\eta^6 - 10Re\eta^7 + 4Re\eta^8 - \\ 108Re\eta^7 + 84Re\eta^7 + 36Re\eta^8 - 24Re\eta^8 \\ +86Re\eta^2 \\ -180Re\eta^3 + 162Re\eta^4 - 54Re\eta^6 + 54Re\eta^7 \\ -20Re\eta^8 + 7560 \end{pmatrix} \right) / \left(N_1 + F_w + 1\right) \tag{24}$$

$$G_1 = -\frac{\left(N_1\eta(\eta-1)\left(\eta^2 - 2\eta^2 + \eta\right)\right)}{N_2} \tag{25}$$

The coefficient for order two of $F(\eta)$ and $G(\eta)$ in Eqs. (20) and (21) were too voluminous to be stated analytically in the text but it has been expressed in the plots and results validation, Table 1. Therefore flow and rotation profile can be expressed finally as:

$$F(\eta) = F_0(\eta) + F_1(\eta) + F_2(\eta) \tag{26}$$

$$G(\eta) = G_0(\eta) + G_1(\eta) + G_2(\eta) \tag{27}$$

3- Results and Discussion

The result obtained from the analytical solutions using the variation of parameters method is discussed in this section. As observed the validity of results when compared with solutions obtained in literature for the simplified case, forms satisfactory agreement as depicted in Table 1. Effect of important parameters such as Reynolds number (Re), non-Darcy parameter and micro-rotation parameters are reported graphically. Quantifying parameters at various values on the velocity and rotation profile, results are presented as Figs. 2 to 7. The Fig. 2 depicts the Reynolds number effect on axial component of dimensionless velocity, as depicted from the plot increasing Re causes increase in velocity profile towards the lower plate during injection while towards (as η=0.57, not determined accurately) the upper plate fluid motion is decreased during suction. This occurs as a result of decreasing fluid viscosity due to increased viscose heating as micro-constituent collides against each other during flow.

The effect of numerical increase of the non-Darcy parameter (F_w) is demonstrated in Fig. 3. It is observed that axial velocity profile decreases with increasing F_w towards the lower plate during injection flow due to decreasing porous medium permeability which tends to increase fluid motion resistance while as fluid approaches upper plate during suction flow velocity increases due to decrease in fluid motion resistance. Reynolds number effect on rotation profile is clearly illustrated in Fig. 4 which shows quantitative increase in *Re* result in increasing rotation distribution during suction and decreasing rotation distribution during injection which is as a result of increased mass transfer during injection and reverse during suction.

Table 1. Comparison of numerical and variation of parameters solution. When N_1=N_2=N_3=1, F_w =0 and *Re*=-1.

η	$F(\eta)$ Numerical Solution [36]	Present work	$G(\eta)$ Numerical Solution [36]	Present work
0	0	0	0	0
0.05	0.07518206173	0.075181	-0.020190328	-0.020190
0.1	0.14998590360	0.149986	-0.040103308	-0.040103
0.15	0.22403298656	0.224033	-0.059460011	-0.059461
0.2	0.29694421863	0.296944	-0.077978446	-0.077979
0.25	0.36833980248	0.368339	-0.095372128	-0.095372
0.3	0.43783919066	0.437839	-0.111348747	-0.111349
0.35	0.50506115802	0.505062	-0.125608933	-0.125609
0.4	0.56962399728	0.569624	-0.137845116	-0.137845
0.45	0.63114584762	0.631146	-0.147740487	-0.147741
0.5	0.68924516577	0.689245	-0.154968072	-0.154968
0.55	0.74354134489	0.743541	-0.159189909	-0.159189
0.6	0.79365548778	0.793656	-0.160056339	-0.160057
0.65	0.83921133966	0.839211	-0.157205409	-0.157206
0.7	0.87983638200	0.879837	-0.150262384	-0.150262
0.75	0.91516309029	0.915163	-0.138839370	-0.138839
0.8	0.94483035438	0.944831	-0.122535036	-0.122535
0.85	0.96848505804	0.968485	-0.100934437	-0.100935
0.9	0.98578381378	0.985784	-0.073608923	-0.073609
0.95	0.99639484474	0.996395	-0.040116126	-0.040116
1.00	1	1.000000	0	0

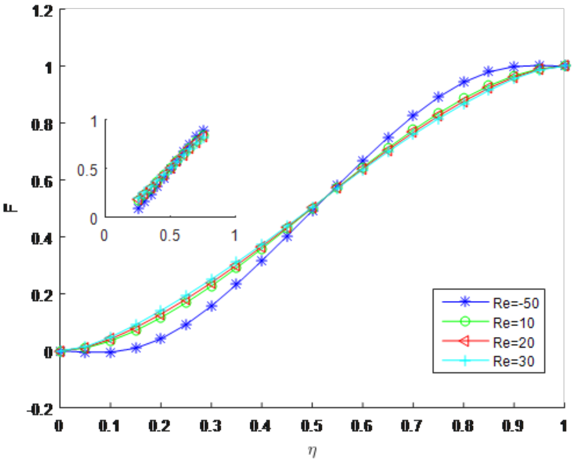

Fig. 2. Effect of Reynolds number on velocity profile when N_1=N_2=F_w =1, N_3=0.1.

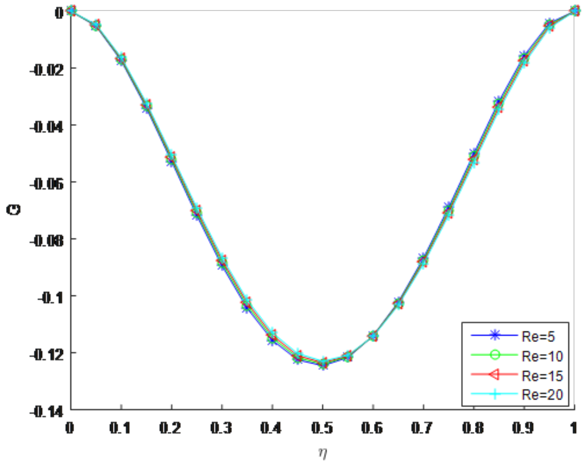

Fig. 4. Effect of Reynold's number on rotation profile when N_1=N_2=F_w =1, N_3=0.1.

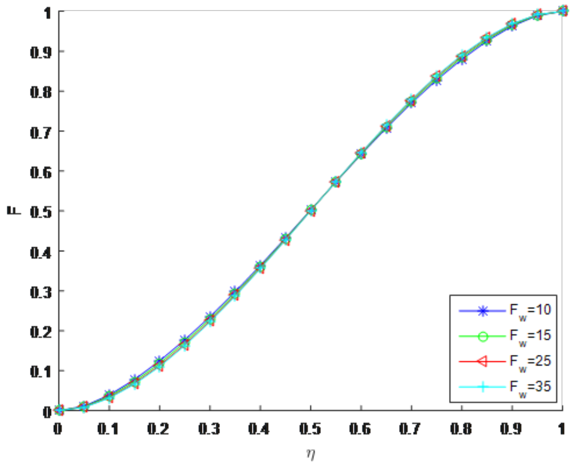

Fig. 3. Effect of non-Darcy parameter (F_w) on velocity profile when Re=N_1=N_2=1, N_3=0.1.

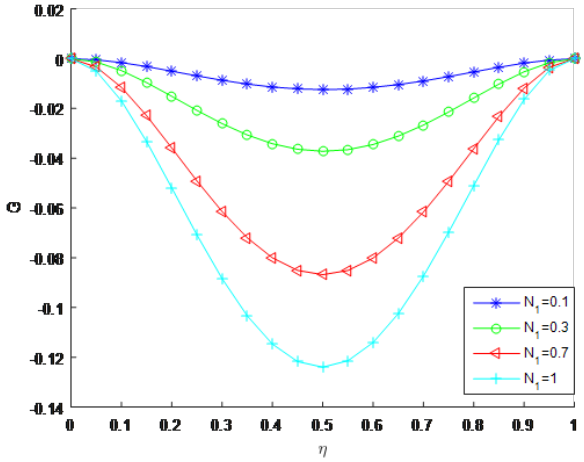

Fig. 5. Effect of microrotation parameter (N_1) on rotation profile when when Re=N_1=N_2= F_w =1.

Micro rotation parameter (N_1) effect on rotation profile is observed in Fig. 5. It is observed that at increasing N_1, rotation profile decreases due to decrease in fluid viscosity caused by increasing friction of rotating constituents during flow. Though micro-constituent rotation effect is maximum around the midplate (η=0.5, not accurately determined). Effect of micro rotation parameter (N_2) on rotation profile is demonstrated in Fig. 6 which depicts increasing rotation distribution with increasing N_2 parameter. This is physically explained as a result of increasing fluid particle rotation. Fig. 7 illustrates the effect of increasing micro rotation parameter (N_3) on rotation profile. As observed increasing values of N_3 leads to increased density of fluid inertia which results in increasing rotation profile during suction while during injection rotation profile decreases.

Fig. 8 demonstrates the Reynolds parameter effect which depicts increase in flow for injection flow (0<η<0.6, not accurately determined), during suction slight decrease in velocity component is observed (i.e. a reverse trend).

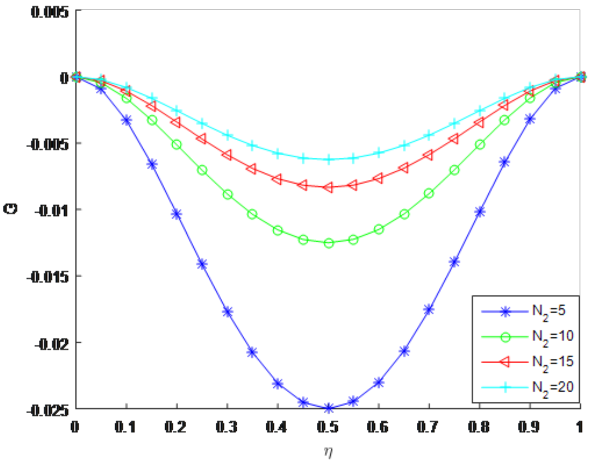

Fig. 6. Effect of microrotation parameter (N_2) on rotation profile when Re=N_1=N_2= F_w =1.

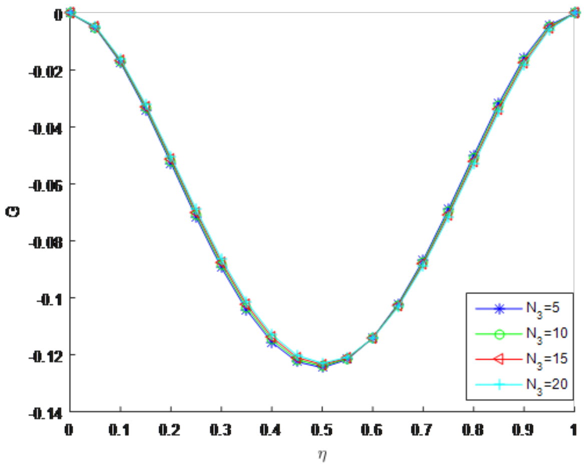

Fig. 7. Effect of micro rotation parameter (N_3) on rotation profile when $Re=N_1=N_2=F_w=1$.

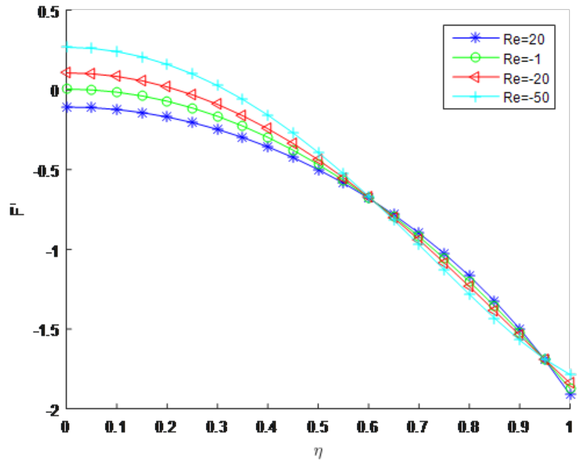

Fig. 8. Effect of Reynolds number on F' when $N_1=N_2=N_3=F_w=1$.

4- Conclusions

This present study analyses micropolar fluid flow through non-Darcy porous medium driven by high mass transfer. The mechanics of fluid arising from the rotation of micro-constituent during flow of micropolar fluid is described by higher order coupled system of nonlinear equations; these are solved analytically adopting the variation of parameters method of solution. Effects of various pertinent parameters such as non-Darcy parameter and Reynolds number on flow and rotation were observed. Results reveal that increasing effect of non-Darcy parameter shows decrease in flow velocity towards the lower plate while increasing Reynolds number also shows slight decrease in fluid rotation but towards the upper plate. This study proves useful in the advancement of flow processes such as micro channel and flow in capillaries amongst other applications.

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Nomenclature

F	dimensionless stream function
G	dimensionless microrotation
H	width of channel (m)
j	micro-inertia density
C_f	Forchheimer empirical constant
F_w	dimensionless non-Darcy parameter
N	microrotation/angular velocity (s^{-1})
$N_{1,2,3}$	dimensionless parameter
K	Permeability of porous medium
p	embedding parameter
q	Mass transfer parameter (ms^{-1})
Re	Reynolds number
s	microrotation boundary condition
u, v	Cartesian velocity components (ms^{-1})
x, y	Cartesian coordinate parallel and normal to channel (m)
Greek Symbols	
η	Dimensionless normal distance
μ	Dynamic viscosity ($kgm^{-1}s^{-1}$)
κ	Coupling coefficient ($kgm^{-1}s^{-1}$)
ρ	Fluid density (kgm^{-3})
ψ	Stream function (m^2s^{-1})
ν_s	Microrotation/spin gradient viscosity (m kg s^{-1})

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