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# Mathematical model of the micropolar fluid on continuous moving surface with suspended particles

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**Abstract**
We study the new mathematical model of micropolar fluid on continuous moving surface with suspended particles. The proposed model incorporates a thermal boundary condition known as Newtonian heating. We compared the numerical solution with previous work and examined the validity of the model.

**Keywords:** Micropolar fluid, suspended particles, model, moving surface

## 1. Introduction

The study of micropolar and viscoelastic fluid dynamics has emerged as a vital branch of fluid mechanics, particularly due to its ability to model complex fluids exhibiting microstructural behaviours. Unlike classical Newtonian fluids, micropolar fluids possess intrinsic angular momentum and micro-rotation effects, making them suitable for describing fluids with suspended particles, colloidal suspensions, polymers, and biological fluids such as blood. The foundational theories proposed by Eringen [10, 11] provided a mathematical framework for analyzed such fluids, where microelements can undergo both translational and rotational motion. These theories have since been expanded to account for various physical phenomena such as couple-stress, magnetic fields, porous media, and thermal gradients.

Boundary layer flow over stretching surfaces is a classical problem in fluid mechanics, with significant applications in industrial processes such as extrusion, fibre drawing, and wire coating. Sakiadis [18] first addressed the boundary layer development on a continuous solid surface, laying the groundwork for subsequent investigations. Ishak *et al.* [13] further extended this to the case of micropolar fluids on moving surfaces, emphasizing the influence of micro-rotation and spin-gradient viscosity. Qasim *et al.* [17] and Turkyilmazoglu [22] also investigated similar flows, considering Newtonian heating and porous stretching sheets, respectively, thereby enriching the understanding of heat transfer in micropolar systems.

In recent years, researchers have increasingly focused on incorporating additional complexities such as magnetic fields, rotation, and porous media into micropolar fluid models. For example, Ali-Sharifi *et al.* [1] performed a numerical investigation of Casson micropolar fluid flow over a stretching sheet under convective boundary conditions. Their results illustrated how the Casson parameter and convective effects influence velocity and temperature profiles, highlighting the importance of considering non-Newtonian and thermal boundary effects in realistic flow configurations.

Thermal convection and couple-stress effects are particularly relevant in micropolar and viscoelastic fluid dynamics. Couple-stress theory, which accounts for the size effects of fluid elements, enhances the modelling of microstructural stress distributions. Kumawat and colleagues have made significant contributions in this domain. Kumawat and Pankaj [2] investigated the thermal instability of couple-stress micropolar fluid flow, emphasizing the role of stress tensors in influencing the onset of convection. In another study, Kumawat and Mehta [3] examined the effects of suspended particles and rotation on micropolar fluid flow through a porous medium, revealing how such factors affect stability and thermal behaviour.

The integration of dust particles and electromagnetic forces further complicates the dynamics of micropolar flows. Kumawat *et al*. [4] studied the influence of dust particles and Hall current on micropolar fluid flow through a porous medium. Their findings suggest that dust concentration and magnetic parameters significantly modify the flow field and energy distribution. Similar themes were explored in Kumawat *et al*. [5–6], where couple-stress and Hall effects on viscoelastic fluid flows were analyzed, showing considerable alterations in velocity and temperature fields due to electromagnetic interactions.

Suspended particles, porous media, and rotation remain central topics in many studies, particularly in the context of industrial and geophysical applications. Kumawat *et al*. [7] proposed a mathematical model for micropolar fluids with suspended particles, offering insights into particle-fluid interaction mechanisms. In another investigation, Kumawat, Mehta, and Lal [8] analyzed the role of couple-stress in micropolar fluids under thermal convection, extending the applicability of such models in high-temperature and rotating systems. Their work was complemented by Kumawat *et al*. [9, 14, 15, 16, 23], who conducted numerical and analytical studies on the influence of magnetic fields, thermal instability, and rotating porous media, with a consistent focus on microstructural effects and energy transport.

Entropy generation and thermal conductivity variations further contribute to the complexity of heat and mass transfer in micropolar systems. Sharma and Khanduri [19] analyzed entropy generation in magnetohydrodynamic (MHD) flows with temperature-dependent properties, while Sharma *et al*. [20] studied soret effects and chemical reactions in magneto-micropolar fluids. These studies underscore the importance of considering thermal non-linearity and chemical interactions in advanced micropolar flow models.

From a modelling and computational standpoint, the resolution of complex nonlinear differential equations often requires sophisticated analytical or numerical methods. Kumawat *et al*. [12] addressed this by applying the Kamal integral transform and Adomian decomposition to fractional differential equations, contributing to the mathematical toolbox used in modelling non-Newtonian fluid dynamics.

Finally, the influence of rotation and ferromagnetic properties has also been analyzed in studies such as that by Singh [21], who considered micropolar ferromagnetic dusty fluids in porous media. These investigations provide important insights into how magnetic and rotational forces shape the stability and motion of fluid layers, especially in rotating astrophysical or geophysical contexts.

Taken together, the body of literature reveals an increasing sophistication in modelling micropolar and viscoelastic fluid flows by incorporating microstructure, electromagnetic forces, thermal convection, and porous media effects. The present study seeks to build upon this extensive foundation, focusing on the coupled behaviour of micropolar fluids under the combined influence of suspended particles, couple-stresses, and thermal gradients in a porous medium. This work not only contributes to the theoretical understanding of such flows but also provides potential applications in chemical, mechanical, and environmental engineering.

In view of the above discussion, application of the work in geophysics, film lubrication, engineering science, chemical technology and industry. In this paper, we attempt to study the new mathematical model of the micropolar fluid on a continuous moving surface with suspended particles. To the best of our knowledge, the Boussinesq approximations model has not yet been used to study this problem.

## 2. Model

We considered the new model of the micropolar fluid on continuous moving surface with suspended particles. We governing the equations of continuity, momentum, angular momentum, and temperature using the boundary layer and the Boussinesq approximation.

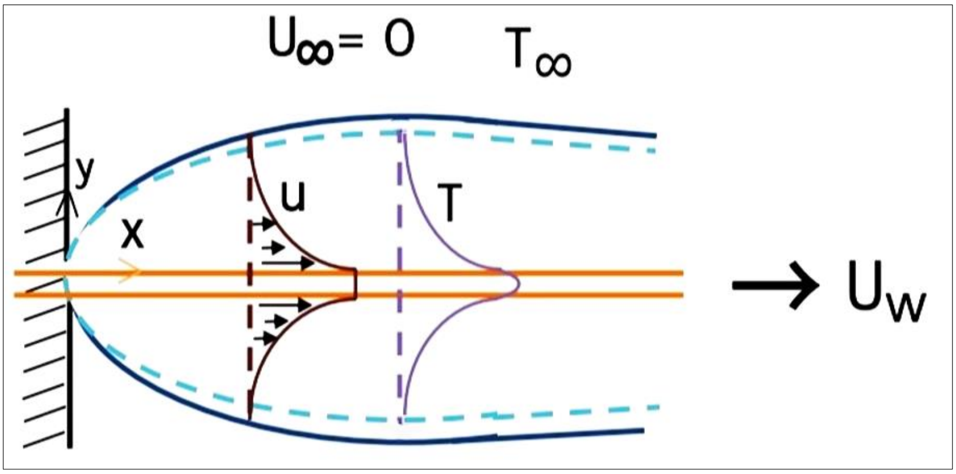


**Fig 1:** Governing equations for micropolar fluid with suspended particles

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\left(\mu+\frac{\kappa}{\rho}\right)\frac{\partial^2 u}{\partial y^2}+\frac{\kappa}{\rho}\frac{\partial N}{\partial y}+\frac{\rho_s}{\rho\tau_m}\left(u_s-u\right) \tag{2.2}$$

$$\rho j\left(v\frac{\partial N}{\partial y}+u\frac{\partial N}{\partial x}\right)=-\kappa\left(2N+\frac{\partial u}{\partial y}\right)+\gamma\frac{\partial^2 N}{\partial y^2} \quad (2.3)$$

$$v\frac{\partial T}{\partial y}+u\frac{\partial T}{\partial x}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\rho_s C_v}{\tau_T \rho C_s}(T_s-T) \quad (2.4)$$

**The equations of continuity, momentum and temperature for the suspended particles are**

$$\frac{\partial u_s}{\partial x}+\frac{\partial v_s}{\partial y}=0 \quad (2.5)$$

$$u_s\frac{\partial u_s}{\partial x}+v_s\frac{\partial u_s}{\partial y}=-\frac{1}{\tau_m}(u_s-u) \quad (2.6)$$

$$u_s\frac{\partial T_s}{\partial x}+v_s\frac{\partial T_s}{\partial y}=-\frac{1}{\tau_T}(T_s-T) \quad (2.7)$$

where, $u,v$ – Fluid velocity, $u_s,v_s$ – Particles velocity components of x and y directions, $\kappa$ – Vortex viscosity, $\rho$ – Density, $\rho_s$ – Density of particles, N – Micro rotation, $\tau_m$ – Velocity relaxation time of particles, $\tau_T$ – Thermal velocity relaxation time of particles, j – Micro inertia, $\gamma$ – Spin (micro rotation), T – Temperature, $T_s$ – Temperature of particles, $\alpha$ – Thermal diffusivity, $C_v$ – Specific heat and $C_s$ – Specific heat of particles.

**Boundary Condition**

$$u=U_w(x),\ v=V_w(x)=0,\quad N=-n\frac{\partial u}{\partial y},\ \frac{\partial T}{\partial y}=-h_sT \quad \text{at } y=0,$$

$$u\to 0,\ N\to 0,\ u_s\to 0,\ v_s\to v,\ T\to T_\infty,\ T_s\to T_\infty \quad \text{at } y\to\infty. \quad (2.8)$$

**3. Mathematical Formulation**
**The similarity transformations are**

$$u=2U_w x f'(\eta),\ v=-(2U_w v)^{\frac{1}{2}} f(\eta),\ u_s=2U_w xF'(\eta),\ v_s=-(2U_w v)^{\frac{1}{2}} F(\eta),$$

$$\eta=\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} y,\quad \psi=(2U_w v)^{\frac{1}{2}} xf(\eta),\quad N=2U_w x\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} h(\eta),\ \theta=\frac{T-T_\infty}{T_\infty},\ \theta_s=\frac{T_s-T_\infty}{T_\infty} \quad (3.1)$$

Where, $\psi$ -Stream function defined as $u=\frac{\partial \psi}{\partial y}$ and $v=\frac{\partial \psi}{\partial x}$.

Using the above transformations in equations (2.1) to (2.7), we have

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=\frac{\partial}{\partial x}\{2U_w xf'(\eta)\}+\frac{\partial}{\partial y}\left\{-(2U_w v)^{\frac{1}{2}} f(\eta)\right\}=0 \quad (3.2)$$

**It is clear that the equation of continuity is satisfy**

$$u\frac{\partial u}{\partial x}=2U_w x\ f'(\eta)\times 2U_w\ f'(\eta)=(2U_w)^2 x\left[f'(\eta)\right]^2 \quad (3.3)$$

$$v\frac{\partial u}{\partial y} = -\left(2U_w v\right)^{\frac{1}{2}} f(\eta)\times 2U_w x\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} f''(\eta) = -\left(2U_w v\right)^2 x f(\eta) f''(\eta) \tag{3.4}$$

$$\frac{\partial^2 u}{\partial y^2} = \frac{\partial}{\partial y}\left[2U_w x\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} f''(\eta)\right] = \left(2U_w x\right)^2 \frac{x}{v} f'''(\eta) \tag{3.5}$$

$$\frac{\partial N}{\partial y} = \frac{\partial N}{\partial \eta}\frac{\partial \eta}{\partial y} = 2U_w x\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} h'(\eta)\times\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} = \left(2U_w\right)^2 \frac{x}{v} h'(\eta) \tag{3.6}$$

$$u_s - u = 2U_w x F'(\eta) - 2U_w x f'(\eta) = 2U_w x\left[F'(\eta) - f'(\eta)\right] \tag{3.7}$$

**Putting the value of equations (3.3) to (3.7) in equation (2.2), we obtained**

$$f'^2(\eta) - f(\eta) f''(\eta) - \left(\mu + \frac{\kappa}{\rho}\right)\frac{1}{v} f'''(\eta) - \frac{\kappa}{\rho}\frac{1}{v} h'(\eta) - \frac{\rho_s}{2U_w \rho \tau_m}\left\{F'(\eta) - f'(\eta)\right\} = 0 \tag{3.8}$$

$$(1+K) f'''(\eta) + f(\eta) f''(\eta) - f'^2(\eta) + K h'(\eta) + \beta L\left\{F'(\eta) - f'(\eta)\right\} = 0 \tag{3.9}$$

Where, $\mu = v\rho$ – Dynamic viscosity, $K = \frac{\kappa}{\mu}$ – Material parameter, $L = \frac{\rho_s}{\rho}$ – Mass concentration of suspended particles, $\beta = \frac{1}{2U_w \tau_m}$ – Fluid particles parameter.

$$u\frac{\partial N}{\partial x} = 2U_w x f'(\eta)\times 2U_w\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} h(\eta) = \left(2U_w\right)^2\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} x f'(\eta) h(\eta) \tag{3.10}$$

$$v\frac{\partial N}{\partial y} = -\left(2U_w\right)^2\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} x f(\eta) h'(\eta) \tag{3.11}$$

$$\frac{\partial^2 N}{\partial y^2} = \frac{\partial}{\partial y}\left[\left(2U_w\right)^2 \frac{x}{v} h'(\eta)\right] = \left(2U_w\right)^2\left(\frac{2U_w}{v}\right)^{\frac{1}{2}} \frac{x}{v} h''(\eta) \tag{3.12}$$

**Putting the value of equations (3.10) to (3.12) in equation (2.3), we have**

$$\frac{\gamma}{\rho j v} h''(\eta) - f'(\eta) h(\eta) + f(\eta) h'(\eta) - \frac{\kappa}{\rho j U_w} h(\eta) - \frac{\kappa}{2\rho j U_w} f''(\eta) = 0$$

$$\left(1 + \frac{K}{2}\right) h''(\eta) - f'(\eta) h(\eta) + f(\eta) h'(\eta) - K\left\{2h(\eta) + f''(\eta)\right\} = 0 \tag{3.13}$$

Where, $K = \frac{\kappa}{\mu}$ – Material parameter, $\gamma = \left(\mu + \frac{\kappa}{2}\right) j$ – Spin viscosity, $j = \frac{v}{2U_w}$ – Micro inertia density.

$$u\frac{\partial T}{\partial x} = 2U_w x f'(\eta)\frac{\partial}{\partial x}\left[T_\infty\left\{\theta(\eta) + 1\right\}\right] = 2U_w x f'(\eta)\left[T_\infty \frac{\partial \theta}{\partial \eta}\frac{\partial \eta}{\partial x}\right]$$

$$u\frac{\partial T}{\partial x} = 2U_w x f'(\eta) T_\infty \theta'(\eta).0 = 0 \tag{3.14}$$

$$v\frac{\partial T}{\partial y}=-\left(2U_w v\right)^{\frac{1}{2}}f(\eta)\left[T_\infty\frac{\partial\theta}{\partial\eta}\frac{\partial\eta}{\partial x}\right]=-\left(2U_w v\right)^{\frac{1}{2}}f(\eta)T_\infty\theta'(\eta)\left(\frac{2U_w}{v}\right)^{\frac{1}{2}}=-2U_wT_\infty f(\eta)\theta'(\eta) \tag{3.15}$$

$$\alpha\frac{\partial^2T}{\partial y^2}=\alpha\frac{\partial}{\partial y}\left[T_\infty\theta'(\eta)\left(\frac{2U_w}{v}\right)^{\frac{1}{2}}\right]=\alpha\frac{2U_w}{v}T_\infty\theta''(\eta) \tag{3.16}$$

$$T_s-T=T_\infty\left[\theta_s(\eta)+1\right]-T_\infty\left[\theta(\eta)+1\right]=T_\infty\left[\theta_s(\eta)-\theta(\eta)\right] \tag{3.17}$$

**Putting the value of equations (3.15) to (3.17) in equation (2.4), we obtained**

$$\frac{\alpha}{v}\theta''(\eta)+f(\eta)\theta'(\eta)+\frac{\rho_sC_v}{2U_w\tau_T\rho C_s}\left\{\theta_s(\eta)-\theta(\eta)\right\}=0$$

$$\frac{\theta''(\eta)}{P_r}+f(\eta)\theta'(\eta)+\frac{2}{3}\beta L\left\{\theta_s(\eta)-\theta(\eta)\right\}=0 \tag{3.18}$$

where, $L=\frac{\rho_s}{\rho}$ – Mass concentration of suspended particles, $\beta=\frac{1}{2U_w\tau_m}$ – Fluid particles parameter, $P_r=\frac{v}{\alpha}$ – Prandtl number and $\tau_T=\frac{3}{2}\gamma\tau_mP_r$.

Now,

$$\frac{\partial u_s}{\partial x}+\frac{\partial v_s}{\partial y}=\frac{\partial}{\partial x}2U_wxF'(\eta)+\frac{\partial}{\partial y}\left\{-\left(2U_wv\right)^{\frac{1}{2}}F(\eta)\right\}=0 \tag{3.19}$$

**It is clear that the equation of continuity for suspended particles is satisfy.**

$$u_s\frac{\partial u_s}{\partial x}=2U_wxF'(\eta)\times 2U_wF'(\eta)=\left(2U_w\right)^2xF'^2(\eta) \tag{3.20}$$

$$v_s\frac{\partial u_s}{\partial y}=-\left(2U_wv\right)^{\frac{1}{2}}F(\eta)\times\frac{\partial}{\partial y}\left\{2U_wF'(\eta)\right\}=-\left(2U_w\right)^2xF(\eta)F''(\eta) \tag{3.21}$$

$$u_s-u=2U_wxF'(\eta)-2U_wxf'(\eta)=2U_wx\left[F'(\eta)-f'(\eta)\right] \tag{3.22}$$

**Putting the value of equations (3.20) to (3.22) in equation (2.6), we have**

$$\left(2U_w\right)^2xF'^2(\eta)-\left(2U_w\right)^2xF(\eta)F''(\eta)+\frac{1}{\tau_m}2U_wx\left\{F'(\eta)-f'(\eta)\right\}=0$$

$$F'^2(\eta)-F(\eta)F''(\eta)+\beta\left\{F'(\eta)-f'(\eta)\right\}=0 \tag{3.23}$$

**Now,**

$$u_s\frac{\partial T_s}{\partial x}=2U_wxF'(\eta)\times\frac{\partial}{\partial x}\left[T_\infty\left\{\theta_s(\eta)+1\right\}\right]=0 \tag{3.24}$$

$$v_s\frac{\partial T_s}{\partial y}=-\left(2U_wv\right)^{\frac{1}{2}}F(\eta)\times\frac{\partial}{\partial y}\left[T_\infty\left\{\theta_s(\eta)+1\right\}\right]=-2U_wT_\infty F(\eta)\theta_s'(\eta) \tag{3.25}$$

$$T_s(\eta)-T(\eta)=T_\infty\left\{\theta_s(\eta)-\theta(\eta)\right\} \tag{3.26}$$

**Putting the value of equations (3.24) to (3.26) in equation (2.7), we obtained**

$$\theta_s'(\eta)F(\eta)+\frac{2}{3}\frac{\beta}{\gamma P_r}\{\theta(\eta)-\theta_s(\eta)\}=0 \tag{3.27}$$

Where, $\beta=\frac{1}{2U_w\tau_m}$ – Fluid particles parameter, $P_r=\frac{v}{\alpha}$ – Prandtl number and $\tau_T=\frac{3}{2}\gamma\tau_m P_r$.

**Boundary conditions (2.8), become**

$$f(0)=S,\ f'(0)=1,\ h(0)=-nf''(0),\ \theta'(0)=-b\{1+\theta(0)\}\ \text{at}\ \eta=0$$

$$f'(\eta)\to 0,\ h(\eta)\to 0,\ F(\eta)\to f(\eta),\ \theta(\eta)\to 0,\ \theta_s(\eta)\to 0\ \text{at}\ \eta\to\infty \tag{3.28}$$

**We obtained the following equation using the above model**

$$(1+K)f'''(\eta)+f(\eta)f''(\eta)-f'^2(\eta)+Kh'(\eta)+\beta L\{F'(\eta)-f'(\eta)\}=0$$

$$(2+K)h''(\eta)-f'(\eta)h(\eta)+f(\eta)h'(\eta)-K\{2h(\eta)+f''(\eta)\}=0$$

$$\frac{\theta''(\eta)}{P_r}+f(\eta)\theta'(\eta)+\frac{2}{3}\beta L\{\theta_s(\eta)-\theta(\eta)\}=0$$

$$F'^2(\eta)-F(\eta)F''(\eta)+\beta\{F'(\eta)-f'(\eta)\}=0$$

$$\theta_s'(\eta)F(\eta)+\frac{2}{3}\frac{\beta}{\gamma P_r}\{\theta(\eta)-\theta_s(\eta)\}=0$$

## 4. Validation and Numerical Analysis of the Work

Now, we the comparison of $-\left(1+\frac{K}{2}\right)f''(0)$ for different values of the K is displayed in Table 1, when $n=\frac{1}{2}$, $\gamma\to\infty$ and the effect of suspended particles are neglected i.e. $S=\beta=N=0$.

$$f''(\eta)=-\lambda e^{-\eta\lambda}$$

$$\lambda=\frac{S+\sqrt{4+2K+S^2}}{2+K},\ n=\frac{1}{2}$$

$$\lambda=\frac{\sqrt{2}}{\sqrt{2+K}},\ n=\frac{1}{2}$$

In this part, we verify the work done with [17] and [22].

**Table 1:** Comparison of numerical results for micropolar fluid flow with suspended particles

| K | $\lambda$ | Present | Qasim *et al.* | Turkyilmazoglu |
|---|---|---|---|---|
| 0 | 1.0000000 | 1.00000000 | 1.000000 | 1.00000000 |
| 1 | 0.8164965 | 1.22474487 | 1.224741 | 1.22474487 |
| 2 | 0.7071067 | 1.41421356 | 1.414218 | 1.41421356 |
| 4 | 0.57735026 | 1.73205080 | 1.733052 | 1.73205081 |

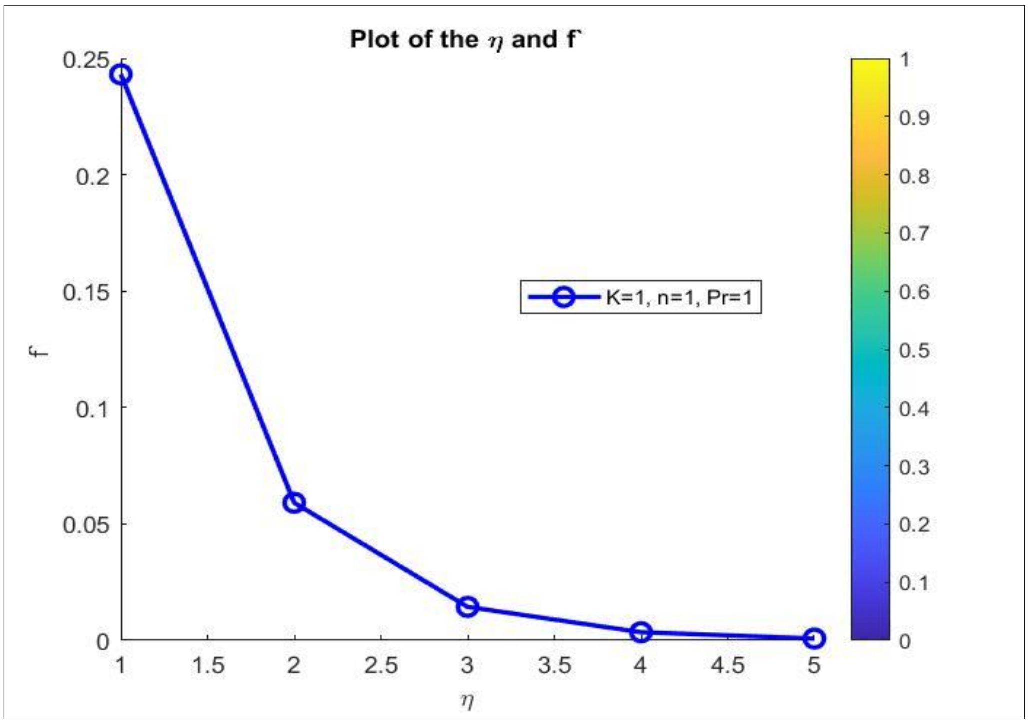


**Fig 2:** Analytical solution under fixed parameter configuration

To illustrate, the specific set of fixed parameter values shown in Fig.1, where all variables intersect at a single point is given by $K = 1$, $S = \frac{1}{\sqrt{2}}$, $n = 1$, $\Pr = 1$, and $\lambda = \sqrt{2}$. Under this configuration, the analytical solution is $f'(\eta) = e^{-\sqrt{2}\eta}$

## 4. Conclusion

In this paper, we have studied the new mathematical model of the micropolar fluid on continuous moving surface with suspended particles. In order to reduce the solver equations to a non-linear ordinary differential equation, the model of the micropolar fluid and suspended particles was used. This resulting equation is valid compared to previous study and will provide researchers, especially mathematicians and fluid mechanics, advance understanding of micropolar fluids on a continuously moving surface with models of suspended particles.

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