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RESEARCH ARTICLE

Unsteady Falkner-Skan Flow of Hybrid Nanofluid Over a Nonlinear Moving Wedge

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Abstract The efficient heat transfer performance of hybrid nanofluid making the fluid crucial in many industrial applications like heat exchangers, nuclear reactors, automotive cooling systems, and most manufacturing processes. This research aims to uncover the properties of an unsteady Falkner-Skan hybrid nanofluid flows over a nonlinear moving wedge with the convective boundary condition. The water-based hybrid nanofluid that is considered in this research is composite nanoparticles of alumina (Al_2O_3) and copper (Cu). The governing nonlinear partial differential equations are transformed into nonlinear ordinary differential equations by incorporating similarity variables of appropriate types. A Keller-Box method is then used to solve the transformed equations numerically. The effects of various pertinent parameters such as unsteady flow, moving wedge, and angle wedge parameters on fluid flows and heat transfer are examined and graphically presented. The moving wedge parameter has enhanced the velocity profile and the heat transfer performance of the fluid. However, an opposite tendency is observed in temperature profiles for the increment of the angle wedge parameter.

Keywords: Unsteady flow, mixed convection, hybrid nanofluid, moving wedge, numerical solution.

Introduction

Numerous researchers have studied regular fluid with various physical properties, surfaces, plates, effects, and types. In recent years, researchers tried to produce nanofluids by dispersing nanoparticles in the base fluid. A nanofluid mixture is metal nanoparticles, oxides, carbides, or carbon nanotubes, with water, ethylene glycol, or oil as the base fluid. The earliest one who proposed the word nanofluid is Choi [1]. Choi et al. [2] showed that by adding a small number of nanoparticles, which is less than 1% by volume, the fluid thermal is conducting increased by approximately double. Kakac and Prmuanjaroenkij [3] then defined nanofluid as fluid particles in standard heat specific and nanometer size. Aladdin et al. [4] mentioned that many researchers carried out their research in nanofluid due to their comprehensive implementation in transport processes, optics, nanomedicine, chemistry, and electronic equipment.

Later on, nanofluids are truncated by hybrid nanofluid and become a potential topic among researchers. Turcu et al. [5] are one of the first researchers to study hybrid nanoparticles. Then Hemmat Esfe's team took the lead in developing hybrid nanofluids [6, 7, 8]. A proper hybridization may make the hybrid nanofluid promising for heat transfer enhancement. Sarkar et al. [9] mentioned that many research works are still needed to produce hybrid nanofluid stabilization, characterization, and practical applications. Researchers have identified alumina as a potential nanoparticle because of its chemical motionlessness and stability, although its thermal conductivity is lower than metal nanoparticles [10, 11, 12]. Silver, zinc, aluminum, and copper are other metal nanoparticles that receive excellent thermal conductivity. This research has characterized a water-based hybrid nanofluid as composite hybrid nanoparticles of alumina and copper. The idea of hybrid nanofluid is to improve the heat transfer capability of alumina due to its

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poor conductor compared to copper. Thus, we can reduce the conductor cost in the industry because aluminum is an inexpensive metal compared to copper.

Convection is the heat transfer by fluid movements, such as gas or liquid, between different area temperatures. There is two convection heat transfers which is natural or free convection and forced convection. Natural or free convection occurs when the fluid movement is caused by natural forces or buoyancy forces due to density variation caused by temperature differences. In contrast, the fluid motion that is affected by external resources is referred to as forced convection. The contact between pressure and buoyant forces is called mixed convection. Mixed convection flows occur when both natural and forced convection effects are significant. The flow has received full interest from the researcher due to their practical applications in real life, such as the design of chemical processing equipment, nuclear reactor safety, damage of crops, and solar collectors [13]. Three types of temperature distributions are applied to thermal boundary conditions: wall temperature, surface heat flux, and convective boundary condition. The importance of a convective boundary condition is when the heat transfer surface corresponds to surface temperature. Thus, convective heat between the surrounding and surface fluid cannot be neglected while heating and cooling the surface.

Many aspects of convective boundary layer flow past different types of geometries have been studied. The wedge flow is one of the most exciting phenomena to explore, whether static or moving with different liquid directions. The wedge is a metal, wood, or any thin material at one end and thick at the other end. Primarily, the wedge is being used for the separation of two objects in contact. In the aerodynamic field, Falkner-Skan flow has long been known. Falkner and Skan [14] initially proposed the wedge flow, and the flow is named Falkner-Skan flow after their excellent study in the earliest case. Based on the boundary layer theory, they had developed a model that was not parallel to flow direction. In real life, we can apply these principles to the bow of a ship, the wingtips of an airplane, and the shapes of Formula One cars. Then, the thermal boundary layer of a wedge with uniform force flow was analyzed by Watanabe [15] with injection or suction. Kumari et al. [16] explored mixed convection flowing through a vertical wedge embedded in highly porous media. Ishak et al. [17] studied the Falkner-Skan equation with the presence of injection or suction. Ganapathirao et al. [18] studied the many effects of heat generation in the presence of injection or suction on an unsteady mixed convection boundary layer flow using the Falkner-Skan model. Ullah et al. [19] investigated the mixed convection flow of Casson fluid using the Falkner-Skan model with heat transfer.

Based on the discussions, the study of the moving wedge impact on the fluid field and heat transfer in a mixed convection hybrid nanofluid flow under the influence of Newton boundary condition or convective boundary condition has not been established in the literature. Therefore, the objective of the present study is to theoretically investigate the thermal performance of a Falkner-Skan hybrid nanofluid flows over a nonlinear moving wedge. Besides, the effect of the convective boundary condition is also taken into consideration. Nonlinear partial differential equations are transformed into nonlinear ordinary differential equations using a similarity transformation technique. Following the conversion, the Keller Box method is used to solve the governing equations [20]. The fluid velocity and temperature variation due to the various value of the embedded parameters are discussed and graphically manifested. The physical quantities of the hybrid nanofluid, like the skin friction coefficient and Nusselt number, are also analyzed.

Mathematical formulation

A two-dimensional unsteady mixed convection Falkner-Skan flow of hybrid nanofluid over a moving wedge is studied. Thermal equilibrium and no-slip conditions are considered. The physical model under consideration is shown in Figure 1, where the wedge is moving with the velocity, $U_w = \frac{ax^m}{(1-\varepsilon t)^{\frac{1}{2}}}$, and the free stream velocity, $U = \frac{bx^m}{(1-\varepsilon t)^{\frac{1}{2}}}$, where m is the angle wedge parameter, *a*, *b,* and $\varepsilon \geq 0$ are constants, and t is time. In this system, the fluid flow is utilized at $x, y \geq 0$, where the x-axis takes place on the wedge's surface and the y-axis points in the direction of outward fluid flow. The Hartree pressure gradient parameter, $\lambda = \frac{2m}{m+1}$ is significant to $\lambda = \frac{\Omega}{\pi}$ for the sum of angle Ω of the wedge [19]. The temperature, T, at the wedge is T_f, and the ambient fluid temperature is set as T_∞. It is crucial to consider buoyancy in the momentum equation because of temperature differences within the fluid.

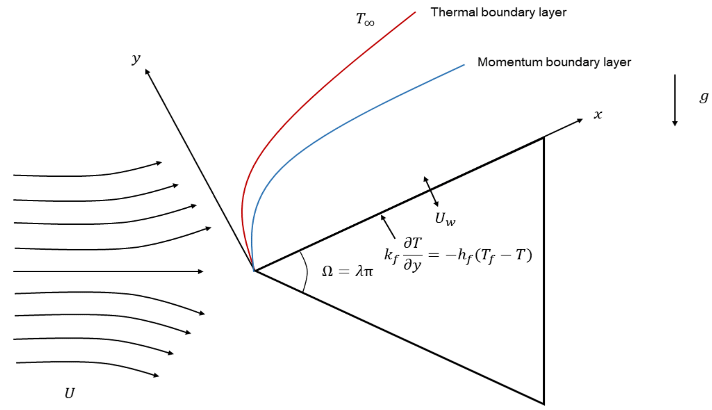

Figure 1. Physical model and coordinate system.

Table 1. The physical properties of hybrid nanofluid are referred to [4, 19].

Thermophysical	Hybrid nanofluids
Density	$\rho_{hnf} = (1-\phi_2)[(1-\phi_1)\rho_f + \phi_1\rho_{s_1}] + \phi_2\rho_{s_2}$
Heat capacity	$(\rho C_p)_{hnf} = (1-\phi_2)[(1-\phi_1)(\rho C_p)_f + \phi_1(\rho C_p)_{s_1}] + \phi_2(\rho C_p)_{s_2}$
Viscosity	$\mu_{hnf} = \mu_f/(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}$
Thermal conductivity	$k_{hnf} = [(k_{s_2} + 2k_{nf} - 2\phi_2(k_{nf} - k_{s_2}))/(k_{s_2} + 2k_{nf} + \phi_2(k_{nf} - k_{s_2}))]k_{nf}$
	$k_{nf} = [(k_{s_1} + 2k_f - 2\phi_1(k_f - k_{s_1}))/(k_{s_1} + 2k_f + \phi_1(k_f - k_{s_1}))]k_f$
Thermal diffusivity	$\alpha_{hnf} = k_{hnf}/(\rho C_p)_{hnf}$
Electrical conductivity	$\sigma_{hnf} = [(\sigma_{s_2} + 2\sigma_{nf} - 2\phi_2(\sigma_{nf} - \sigma_{s_2}))/(\sigma_{s_2} + 2\sigma_{nf} + \phi_2(\sigma_{nf} - \sigma_{s_2}))]\sigma_{nf}$
	$\sigma_{nf} = [(\sigma_{s_1} + 2\sigma_f - 2\phi_1(\sigma_f - \sigma_{s_1}))/(\sigma_{s_1} + 2\sigma_f + \phi_1(\sigma_f - \sigma_{s_1}))]\sigma_f$
Thermal expansion coefficient	$(\rho\beta)_{hnf} = (1-\phi_2)[(1-\phi_1)(\rho\beta)_f + \phi_1(\rho\beta)_{s_1}] + \phi_2(\rho\beta)_{s_2}$

Table 2. The nanoparticles and base fluids' thermophysical properties are referred to [4].

Thermophysical properties	$k(W/mK)$	$C_\rho(J/kgK)$	$\rho(kg/m^3)$
Copper (Cu)	400	385	8933
Alumina (Al_2O_3)	40	765	3970
Water	0.613	4179	997.1

The hybrid nanofluid is formed by considering the dispersing of Cu and Al_2O_3 nanoparticles in water. In this research, we use $\phi_1 = \phi_2 = 0.04$ for volume solid fraction of Cu and Al_2O_3 nanoparticles to investigate the performance of hybrid nanofluid Cu - Al_2O_3/water [21]. The physical properties of hybrid nanofluid can be observed in Table 1. Throughout the table, the subscript of f, nf, and hnf represents fluid, nanofluid, and hybrid nanofluid respectively. While ϕ_1 and ϕ_2 represent Cu and Al_2O_3, respectively. Further, $C_p, \alpha, k, \rho, s_1$ and s_2 represent the specific heat at constant pressure, thermal diffusivity, thermal conductivity, density, Cu nanoparticles and Al_2O_3 nanoparticles, respectively. The thermophysical attributes of hybrid nanofluids are presented in Table 2. The primary governing equations can be expressed as [4, 19, 22] with the assumption of Boussinesq approximations and boundary layer approximation.

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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}= \frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+\frac{\mu_{hnf}}{\rho_{hnf}}\frac{\partial^2 u}{\partial y^2}\pm g\sin\frac{\Omega}{2}\beta_{hnf}(T-T_\infty), \tag{2}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y} =\alpha_{hnf}\frac{\partial^2 T}{\partial y^2}, \tag{3}$$

subjected to the following convective boundary conditions,

$$\begin{gathered} u=U_w \quad ,v=0,-k_f\frac{\partial T}{\partial y}=h_f(T_f-T) \quad \text{at} \quad y=0, \\ u=U,T\to T_\infty \quad \text{when} \quad y\to\infty, \end{gathered} \tag{4}$$

where,

$$T_f=T_\infty+\frac{T_0x^{2m-1}}{(1-\varepsilon t)^2},h_f=\frac{h_0x^{\frac{m-1}{2}}}{(1-\varepsilon t)^{\frac{1}{2}}},k_f=\frac{k_0(1-\varepsilon t)}{x^{m-1}}. \tag{5}$$

Here, u and v are the velocity components along x, and y directions, $\alpha_{hnf},\rho_{hnf},\mu_{hnf}$, are thermal diffusivity, density, the viscosity of hybrid nanofluid, respectively, ‘$-$’ is for opposing flow, ‘$+$’ sign for assisting flow, g is the gravitational force due to acceleration, T is the fluid temperature, β_{hnf} is the thermal expansion coefficient of hybrid nanofluid, T_f is the temperature of the wedge wall, h_f is the convective heat transfer and k_f is the thermal conductivity of the body where T_0, k_0 and h_0 denotes as constant. The following similarity transformations are introduced as follows:

$$\psi=\sqrt{\frac{2x\nu_f U}{(1+m)(1-\varepsilon t)}}f(\eta),\eta=y\sqrt{\frac{U(1+m)}{2x\nu_f(1-\varepsilon t)}},\theta(\eta)=\frac{T-T_\infty}{T_f-T_\infty}, \tag{6}$$

where the stream function, ψ is defined as follows:

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

Equation (1) is automatically satisfied, and the partial differential equations (2) and (3) are then transformed into non-dimensional ordinary differential equations,

$$\begin{gathered} \frac{\mu_{hnf}}{\rho_{hnf}}\frac{\rho_f}{\mu_f}f'''(\eta)+f(\eta)f''(\eta)+\lambda(1-f'(\eta)^2)+\lambda_T\theta(\eta) \\ -A(\frac{2}{m+1}f'(\eta)+\frac{1}{m+1}\eta f''(\eta)-\frac{2}{m+1})=0, \end{gathered} \tag{8}$$

$$\begin{gathered} \frac{1}{\Pr}\frac{\alpha_{hnf}}{\alpha_f}\theta''(\eta)+f(\eta)\theta'(\eta)-2\lambda f'(\eta)\theta(\eta) \\ -A\left(\frac{4m}{m+1}\theta(\eta)+\frac{1}{m+1}\eta\theta'(\eta)\right)=0, \end{gathered} \tag{9}$$

and the transformed boundary conditions,

$$f(\eta)=0, f'(\eta)=\gamma, \theta'(\eta)=-\sqrt{\frac{2}{m+1}}\mathrm{Bi}(1-\theta(\eta)) \quad \text{at} \quad \eta=0, \qquad (10)$$
$$f'(\eta)\to 1, \theta(\eta)\to 0 \quad \text{when} \quad \eta\to\infty.$$

In equation (8)-(10), a prime denotes partial differentiation with respect to η. Here, Pr is Prandtl number, γ is moving wedge parameter, λ_T is thermal buoyancy parameter, Gr_x is Grashof number, Re_x is Reynolds number, A is an unsteady parameter and Bi is Biot number are defined as

$$Pr=\frac{\nu_f}{\alpha_f}, \lambda_T=\pm\frac{Gr_x}{{Re_x}^2} \quad , Gr_x=\frac{2g\sin\frac{\Omega}{2}\beta_{hnf}(T_w-T_\infty)x^3}{{\nu_f}^2(m+1)}, Re_x=\frac{Ux}{\nu_f},$$
$$A=\frac{\varepsilon}{1-\varepsilon t}\frac{x}{U}, \mathrm{Bi}=\frac{h_f}{k_f}Re_x^{-\frac{1}{2}}. \qquad (11)$$

Skin friction coefficient Cf_x and the Nusselt number Nu_x are significant physical quantities in this problem. These quantities are defined as

$$Cf_x=\frac{\tau_w}{\rho_f U^2}, Nu_x=\frac{xq_w}{k_f(T_w-T_\infty)}, \qquad (12)$$

where, $\tau_w=\mu_{hnf}\left(\frac{\partial u}{\partial y}\right)_{y=0}$ is the shear stress at the surface of the wedge, and the heat flux from the surface of the wedge is $q_w=-k_{hnf}\left(\frac{\partial T}{\partial y}\right)_{y=0}$. Thus, the local skin friction and Nusselt number can be written as

$$(Re_x)^{\frac{1}{2}}Cf_x=\sqrt{\frac{(m+1)}{2}}\frac{\mu_{hnf}}{\mu_f}f''(0), \qquad (13)$$
$$(Re_x)^{-\frac{1}{2}}Nu_x=-\sqrt{\frac{(m+1)}{2}}\frac{k_{hnf}}{k_f}\theta'(0). \qquad (14)$$

The equations (8) and (9), together with the transformed boundary conditions (10), are then solved by using the Keller-Box method. The numerical solution is attained by the following steps:

1. Reduce the higher order of differential equations (ODEs) into the system of first-order ODEs by introducing new dependent variables,
2. Finite differences formulation of transformed first-order ODEs formed using the central difference scheme,
3. Apply Newton's method to linearize the nonlinear algebraic system,
4. Utilize the block elimination technique to solve the linear system.

Results and discussion

The variation of the velocity, $f'(\eta)$, and temperature profiles, $\theta(\eta)$ due to the different value of the unsteady parameter, A, the moving wedge parameter, γ and the angle wedge parameter, m, are presented. By comparing the present results with previous findings, the validity of the present findings is verified, as shown in Table 3. A correlation between the current results and the results of Watanabe [15], Kumari et al. [16], Ishak et al. [17], Ganapathirao et al. [18], and Ullah et al. [19] by concerning local skin friction coefficient with different values of m are found to be excellent.

Table 3. The skin friction coefficient for different values of m with $Pr = 0.73, A = \gamma = Bi = 0$, where $\lambda = 2m/(m+1)$.

m	Watanabe [15]	Kumari *et al.* [16]	Ishak *et al.* [17]	Ganapathirao *et al.* [18]	Ullah *et al.* [19]	Present results
0	0.46960	0.46975	0.4696	0.46972	0.4696	0.46960
0.0141	-	0.50472	0.5046	0.50481	0.5046	0.50462
0.0435	0.56898	0.56904	0.5690	0.56890	0.5690	0.56898
0.0909	0.65498	0.65501	0.6550	0.65493	0.6550	0.65498
0.1429	0.73200	0.73202	0.7320	0.73196	0.7320	0.73200
0.2000	0.80213	0.80214	0.8021	0.80215	0.8021	0.80213
0.3333	0.92765	0.92766	0.9277	0.92767	0.9277	0.92766

It is observed that as m increases, the local friction coefficient increases, leading to the resistance force exerted on a moving wedge in a fluid. A more relevant analogy of the model in this problem can be drawn to airfoils that flow over an airfoil's top surface faster than its bottom surface. For example, the streamlines of a fluid approach one another as the fluid passes over a solid body, causing the flow velocity to increase. As a result, a pressure difference occurs between the top and bottom surfaces because the average pressure on the top surface is less than the average pressure on the bottom surface. An airfoil gets a lift from this source, where the lift is defined as the force exerted on an airfoil due to its motion in a direction normally opposite to its motion. On the other hand, drag on an airfoil refers to the force acting on it due to movement in a given direction. In other words, the skin friction coefficient or drag force slows any object's movement.

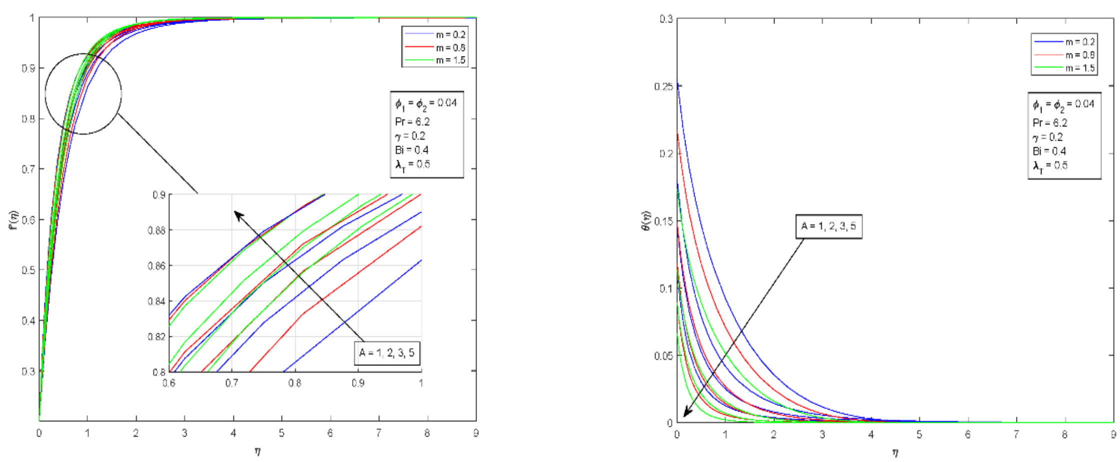

Figure 2. The effect of A on $f'(\eta)$ and $\theta(\eta)$ for different values of m.

The effect of unsteady parameter, A on the hybrid nanofluid flow is illustrated in Fig. 2 by using three different values of m. It is observed that as A increases, the velocity profile increases, whereas the dimensionless temperature decreases due to the dimensions of the molecules, which become more significant under unsteady flow. In this way, the rate of cooling of the fluid can be improved. It is, therefore, crucial to sufficiently consider the unsteady parameter for practical matters. For various values of m, Fig. 3 illustrates the effect of moving wedge parameter, γ on velocity and temperature profiles. The wedge can move in three different directions; $\gamma < 0$ moves in the opposite direction from the fluid motion where the momentum boundary layer thickness is more than $\gamma = 0$, no moving, and $\gamma > 0$ moves in the same direction the fluid movement. The velocity profiles show an increase with increasing γ. It is also observed that in all cases of γ, when m increases, the temperature increases and then slowly decreases. The skin friction coefficient and Nusselt number variation are influenced by the governing parameters presented in Table 4. From this table, the following results were obtained where the skin friction coefficient is higher for increasing values of γ because the momentum boundary layer thickness is higher when $\gamma < 0$. It is also observed that the variation of skin friction coefficient and Nusselt number are higher for all various values considered parameters.

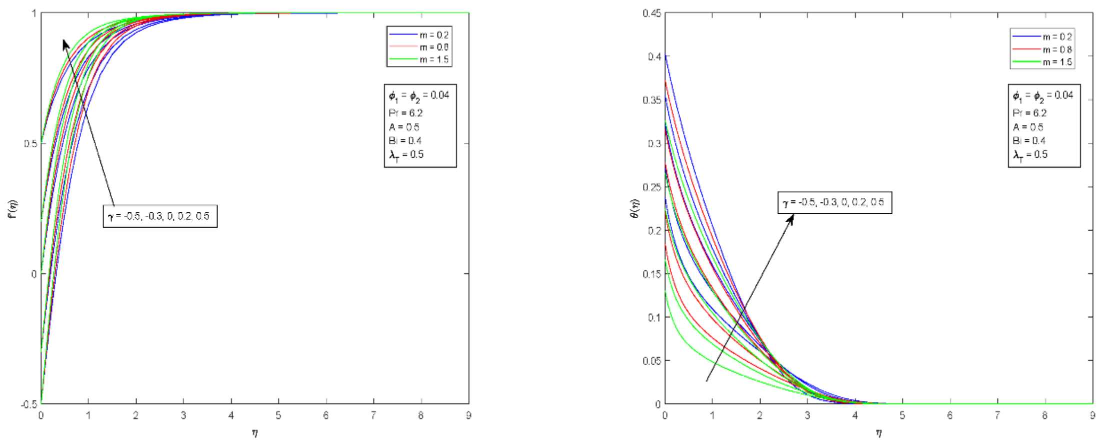

Figure 3. The effect of γ on $f'(\eta)$ and $\theta(\eta)$ for different values of m.

Table 4. For different values of A, m, and γ, numerical results of skin friction coefficient and Nusselt number are presented.

A	m	γ	$(Re_x)^{\frac{1}{2}}Cf_x$	$(Re_x)^{-\frac{1}{2}}Nu_x$
0.2	0.5	0.3	1.1915	0.2960
0.4			1.3790	0.3763
0.8			1.6114	0.4478
	0.6		1.2666	0.2944
	0.8		1.6144	0.3387
		0	1.5934	0.3360
		-0.3	1.8324	0.3808

Conclusions

The unsteady flow of hybrid nanofluid over a moving wedge has been numerically analyzed. A conclusion can be drawn from this study:

1. When $A, m,$ and γ are increased, hybrid nanofluid flow velocity increases,
2. As A is increased, the distribution of temperature decreases, but as the γ is increased, the distribution begins to rise and slowly decrease with different values of m,
3. The skin friction coefficient or drag force is increased with an increase of m,
4. The skin friction coefficient and Nusselt number are higher for the greater value of A, m and γ.

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