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Heat Generation Effects on Maxwell Nanofluid Passing Over an Oscillating Vertical Plate

Sidra Aman[1], Dennis Ling Chuan Ching[2], Mohd. Zuki Salleh[3], Zulkhibri Ismail[3,*]

[1] Department of Mathematics and Statistics, University of Haripur, KP, Pakistan
[2] Department of Fundamental and Applied Sciences, Universiti Teknologi Petronas, Seri Iskandar, 32610 Tronoh, Perak, Malaysia
[3] Centre for Mathematical Sciences, College of Computing and Applied Sciences, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Pahang, Malaysia

ABSTRACT

This article investigates the flow of Maxwell nanofluid over an oscillating plate with copper nanoparticles and kerosene oil as a base fluid. Novel aspects of heat generation, free convection and thermophysical properties of nanofluids are given special attention in this research. Revised model for passive control of nanoparticle volume fraction at the plate is used in this study. The formulated differential system is solved analytically using Laplace transform technique. The solutions acquired for momentum, temperature and shear stress are greatly influenced with the variation of the volume fraction and Maxwell parameter. The computational software MathCAD-15 has been used for plotting the graphs.

Keywords:
Maxwell nanofluid; Laplace transform method; heat generation; copper nanoparticles

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1. Introduction

Maxwell fluid model being the rate type fluid has gotten much consideration for being the first and one of the least complex fluid models. It is yet utilized generally exceptionally to depict the reaction of some polymeric fluids. Maxwell fluid model is the elementary rate type model used for fluid rheological effects initially introduced by Maxwell [1]. Fetecau and Fetecau [2] found "a new exact solution for Maxwell fluid flow past an infinite plate". Zierep and Fetecau [3] studied Rayleigh-Stokes problem for Maxwell fluid under various cases. Jordan *et al*., [4] analyzed Stokes' first problem for Maxwell fluids and obtained new exact solutions using integral transform method. In another study, Fetecau *et al*., [5] provided "a note on the second problem of Stokes for Maxwell fluid over an infinite plate oscillating in its plane". Later, this work was extended by Khan *et al*., [6] with taking MHD and porosity effects into account. Vieru and Rauf [7] examined slip conditions impact on Stokes flow of Maxwell fluid and acquired the exact solution via Laplace transform technique. They took two

[*] *Corresponding author.*
E-mail address: zulkhibri@ump.edu.my

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cases, sinusoidal oscillations and translation with constant velocity of the wall. In another study, the same two cases were inspected by for Couette flow of Maxwell fluid [8].

However, all these attempts were made for Maxwell fluid for momentum transfer only and the analysis of heat transfer due to convection was not considered. But most of the existing studies on convective flow of Maxwell fluid including Hayat *et al*., [10], Hayat *et al*., [11] and Shateyi and Marewo [9] are either solved numerically or analytically by using an approximate method and, exact solutions for such problems are rare. The area of nanofluid is quite attracting for the researchers due to its enormous implementations. Of course, the structure of nanofluid is not as simple as of regular fluid, because the suspended nanoparticles can be of different types, shapes and sizes. Afify and Elgazery (2016) analysed the influence of MHD boundary layer of Maxwell nanofluid over a stretching sheet.

Nanofluid flow in oscillating porous media rarely been a subject of thorough studies until their implementations in oil processing and natural gas. In the literature we can find some quality research work mostly done on Maxwell fluid flow in oscillating porous media without considering nanoparticles such as Hsiao [14], Khan *et al*., [15] acquired an exact solution for mixed convection for Maxwell fluid over an oscillating vertical plate with constant wall temperature. Ali et al. (2019) studied magnetohydrodynamic free convection flows with thermal memory over a moving vertical plate in porous medium. Thermal transport flow of Casson nanofluids with generalized Mittag–Leffler kernel of Prabhakar's type is studied by Wang *et al*., [13]. Yasin *et al*., [19] investigated the flow of ferrofluid with lower stagnation point over a solid sphere using Keller-Box technique. Mopuri *et al*., [20] studied unsteady MHD flow of a Newtonian fluid past an inclined plate with radiation absorption and Dufour effects. Numerical solution was obtained for unsteady free convective radiating nanofluid past a vertical moving porous plate by Chand [18].

However, some recent work in this domain has been reported such as a revise model of Maxwell nanofluid flow over a stretching sheet with thermal effects [17]. They considered zero mass flux of nanoparticles on the surface. Wang *et al*., [21] examined natural bio-convective flow of Maxwell nanofluid over an exponentially stretching surface with slip effect and convective boundary condition.

Due to complicated Maxwell equation for nanofluids, a very rare study can be seen in the literature for Maxwell nanofluid which is tackled for exact solutions. According to authors' knowledge, no study has been reported yet in the literature for heat transfer Maxwell fluid containing CNTs nanoparticles, where the exact solution is obtained via Laplace transform technique.

2. Methodology

Consider a vertical plate located in the x and y plane at $y = 0$ and incompressible Maxwell fluid with cobalt nanoparticles and the fluid occupies the porous medium $y > 0$. The fluid is electrically conducting under the magnetic field $B = (0, B_0, 0)$. Initially, both the plate and fluid were at rest with constant wall temperature T_∞. At time $t = 0^+$, the temperature of the plate is raised to a constant value T_w. The temperature approaches to a constant value T_∞ as shown in Figure 1. The fluid flow is induced by the buoyancy force and kerosene oil is considered as base fluid.

The equation for momentum, shear stress and heat for MHD free convection flow of Maxwell nanofluid in a porous medium are as

$$\rho_{nf}\left(1+\lambda_1\frac{\partial}{\partial t}\right)\frac{\partial u}{\partial t} = \mu_{nf}\frac{\partial^2 u}{\partial y^2} - \sigma_{nf}B_0^2\left(1+\lambda_1\frac{\partial}{\partial t}\right)u(y,t) - \frac{\mu_{nf}\varphi}{k_1}u(y,t) + \left(1+\lambda_1\frac{\partial}{\partial t}\right)(\rho\beta)_{nf}g(T-T_\infty), \quad (1)$$

$$\left(1+\lambda_1\frac{\partial}{\partial t}\right)\tau(y,t) = \mu_{nf}\frac{\partial u(y,t)}{\partial y} \quad (2)$$

$$(\rho c_p)_{nf}\frac{\partial T}{\partial t} = k_{nf}\frac{\partial^2 T}{\partial y^2} + Q_0(T - T_\infty) \tag{3}$$

where ρ_{nf} is the density, σ_{nf} the electrical conductivity, μ_{nf} the dynamic viscosity, $(\rho\beta)_{nf}$ are the thermal expansion, $(\rho c_p)_{nf}$ and k_{nf} denote heat capacitance and thermal conductivity of the nanofluids while Q_0 is the heat generation constant.

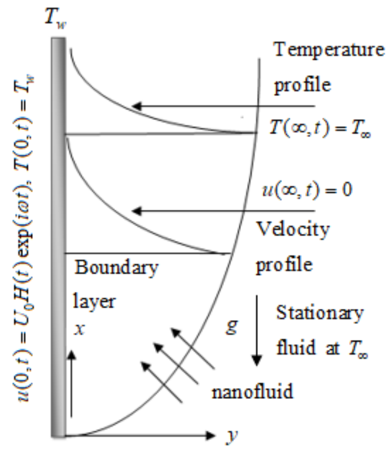

Fig. 1. Geometry of the flow over a vertical plate

The following initial and boundary conditions will be used for this problem.

$$\begin{aligned} u(y,0) = 0, u(0,t) = U_0 H(t) \cos\omega t, u(\infty,t) = 0, \\ T(y,0) = T_\infty, T(0,t) = T_w, T(\infty,t) = T_\infty. \end{aligned} \tag{4}$$

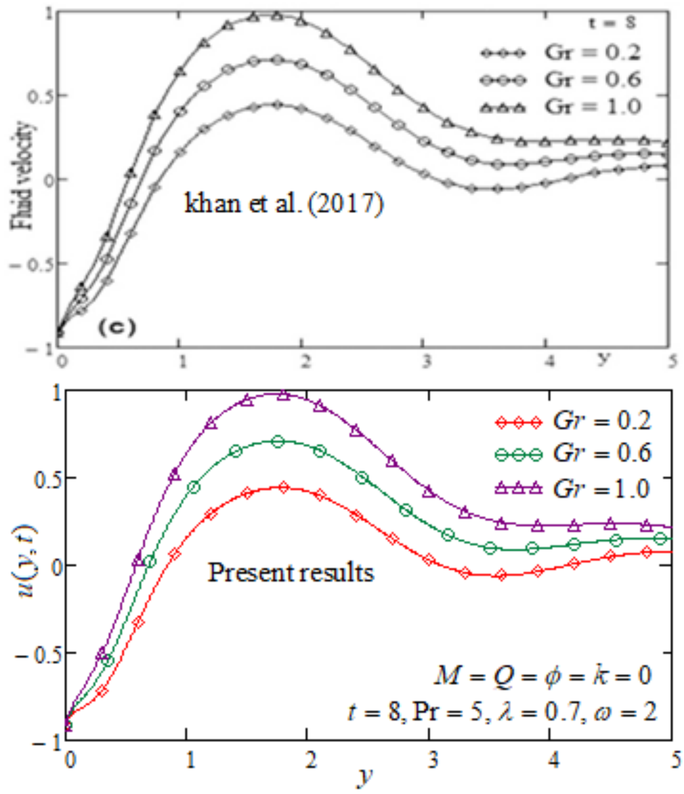

Fig.2. Comparison of present velocity result with previous published results Source: Khan *et al.*, [15]

3. Solution of the Problem

In this analysis, the following non-dimensional variables are introduced

$$u^* = \frac{u}{U_0}, y^* = \frac{yU_0}{\nu}, t^* = \frac{tU_0^2}{\nu}, \tau^* = \frac{\nu\tau}{\mu U_0^2}, \theta = \frac{T - T_\infty}{T_\infty}.$$

Substituting the above non-dimensional variables into Equation 1, Equation 2, and Equation 3, we get

$$A_2 \frac{\partial^2 u(y,t)}{\partial y^2} - A_1\left(1 + \lambda\frac{\partial}{\partial t}\right)\frac{\partial u(y,t)}{\partial t} = A_3\left(1 + \lambda\frac{\partial}{\partial t}\right)Mu(y,t) + A_2\gamma u(y,t) - A_4\left(1 + \lambda\frac{\partial}{\partial t}\right)Gr\theta(y,t), \quad (5)$$

$$\left(1 + \lambda\frac{\partial}{\partial t}\right)\tau(y,t) = A_2\frac{\partial u(y,t)}{\partial y}, \quad (6)$$

$$A_6\frac{\partial^2\theta(y,t)}{\partial y^2} - A_5 Pr\frac{\partial\theta(y,t)}{\partial t} + Q\theta(y,t) = 0, \quad (7)$$

with the corresponding initial and boundary conditions in non-dimensional form

$$u(y,0) = 0, \theta(y,0) = 0, y > 0$$
$$u(0,t) = H(t)\cos\omega t; \theta(0,t) = 1; y > 0 \quad (8)$$
$$u(\infty,t) = 0; \theta(\infty,t) = 0,$$

where

$$\lambda = \frac{\lambda_1 u^2{}_0}{\nu},\ M = \frac{\sigma_f B_0^2\nu}{\rho_f U^2{}_0}, k = \frac{\mu_f\varphi\nu}{\rho_f k_1 U^2{}_0}, Gr = \frac{\nu g\beta_f(T_w - T_\infty)}{U^3{}_0},\ Br = \frac{\mu_f c_p}{k_f},$$

are Maxwell parameter, magnetic parameter, porosity parameter, Grashof number and Prandtl number. While other constants introduced are

$$A_1 = (1-\phi) + \phi\left(\frac{\rho_s}{\rho_f}\right), A_2 = \frac{1}{(1-\phi)^{2.5}}, A_3 = \sigma_f\left(1 + \frac{3(\sigma_f - 1)\phi}{(\sigma_f + 2) - (\sigma_f - 1)}\right),$$

$$A_4 = (1-\phi) + \phi\left(\frac{\rho_s\beta_s}{\rho_f\beta_f}\right), A_5 = (1-\phi) + \phi\frac{(\rho c_p)_s}{(\rho c_p)_f}, A_6 = \frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s - 2k_f) + \phi(k_f - k_s)},$$

To solve the Equation 5, Equation 6, and Equation 7, we use the Laplace transform technique. Thus, employing Laplace transform to the mentioned equations and using Equation 8, we obtain

$$\frac{\partial^2\bar{u}(y,q)}{\partial y^2} - \beta_0(1 + \lambda q)q\bar{u}(y,q) = \beta_1(1 + \lambda q)M\bar{u}(y,q) + k\bar{u}(y,q) - \beta_2(1 + \lambda q)Gr\bar{\theta}(y,q), \quad (9)$$

$$(1 + \lambda q)\bar{\tau}(y,q) = A_2\frac{\partial\bar{u}(y,q)}{\partial y}, \quad (10)$$

$$A_6\frac{\partial^2\bar{\theta}(y,q)}{\partial y^2} - A_5\, Pr\, q\,\bar{\theta}(y,q) + Q\bar{\theta}(y,q) = 0, \quad (11)$$

with the transformed boundary conditions

$$\bar{\theta}(0,q) = \frac{1}{q}, \bar{\theta}(y,q) \to 0 \text{ as } y \to \infty.$$
$$\bar{u}(0,q) = \frac{q}{q^2+\omega^2}, \bar{u}(y,q) \to 0, \text{ as } y \to \infty.$$

The solution of Equation 9 and Equation 11 subject to above conditions, is given as

$$\bar{\theta}(y,q) = \frac{1}{q}exp\left(-y\sqrt{b_0}\sqrt{q - b_2}\right). \quad (12)$$

$$\bar{u}(y,q) = \frac{q}{q^2+\omega^2}exp\left(-y\sqrt{\{(\lambda q + 1)(\beta_0 q + \beta_1 M) + k\}}\right) + \frac{\beta_2(1 + \lambda q)Gr}{q\left[b_0(q - b_2) - \{(\lambda q + 1)(\beta_0 q + \beta_1 M) + k\}\right]}$$

$$\left[exp\left(-y\sqrt{\{(\lambda q+1)(\beta_0 q+\beta_1 M)+k\}}\right)-exp\left(-y\sqrt{b_0}\sqrt{q-b_2}\right)\right], \quad (13)$$

where $\beta_0=\frac{A_1}{A_2},\beta_1=\frac{A_3}{A_2},\beta_2=\frac{A_4}{A_2},b_0=\frac{A_5 Pr}{A_6},b_1^2=\frac{QPr}{A_6},b_2=\frac{b_1^2}{b_0}$.

Taking the inverse Laplace transform of Equation 12, we obtain

$$\theta(y,t)=\frac{1}{2}\left[e^{-y\sqrt{b_0 b_2}}erfc\left(\frac{y\sqrt{b_0}}{2\sqrt{t}}-\sqrt{b_2 t}\right)+e^{y\sqrt{b_0 b_2}}erfc\left(\frac{y\sqrt{b_0}}{2\sqrt{t}}+\sqrt{b_2 t}\right)\right]. \quad (14)$$

Equation 13 can be written as

$$\bar{u}(y,q)=\frac{q}{q^2+\omega^2}exp\left(-y\sqrt{\{(\lambda q+1)(\beta_0 q+\beta_1 M)+k\}}\right)+\frac{\beta_2(1+\lambda q)Gr}{q\left[b_0(q-b_2)-\{(\lambda q+1)(\beta_0 q+\beta_1 M)+k\}\right]}$$
$$exp\left(-y\sqrt{\{(\lambda q+1)(\beta_0 q+\beta_1 M)+k\}}\right)-\frac{\beta_2(1+\lambda q)Gr}{q[b_0(q-b_2)-\{(\lambda q+1)(\beta_0 q+\beta_1 M)+k\}]}exp\left(-y\sqrt{b_0}\sqrt{q-b_2}\right), \quad (15)$$

Let

$$F(y,q)=exp\left(-y\sqrt{\lambda q^2+q}\right)=exp\left(-y\sqrt{\lambda}\sqrt{\left(q+\frac{1}{2\lambda}\right)^2-\left(\frac{1}{2\lambda}\right)^2}\right),$$

$$\bar{H}_1(y,q)=exp\left(-y\sqrt{a_0\lambda}\sqrt{q}\right),G(q)=\frac{a\lambda-1}{a^2}\frac{1}{q}+\frac{1}{a}\frac{1}{q^2}+\frac{1-a\lambda}{a^2}\frac{1}{q+a},$$

$$h_1(y,t)=L^{-1}\{\bar{H}_1(y,q)\}=\begin{cases}\dfrac{y\sqrt{a_0\lambda}\,exp\left(-\frac{y^2\lambda a_0}{4t}\right)}{2t\sqrt{\pi t}};y>0.\\ \delta(t);y=0\end{cases}$$

Applying the inverse Laplace transform to Equation 15, and using convolution product, we obtain

$$u(y,t)=-\frac{a_1}{a_0\lambda}\int_0^t g(t-s)f(y,s)ds+\frac{a_1}{a_0\lambda}\int_0^t g(t-s)h(y,s)ds, \quad (16)$$

where

$$f_1(y,t)=\left[h_1(y,t)+\frac{1}{2\lambda}\int_0^t h_1(y,z)\frac{z}{\sqrt{t^2-z^2}}I_1\left(\frac{1}{2\lambda}\sqrt{t^2-z^2}\right)dz\right]exp\left(-\frac{1}{2\lambda}t\right)$$
$$=\begin{pmatrix}\dfrac{y\sqrt{a_0\lambda}}{2t\sqrt{\pi t}}exp\left(-\dfrac{y^2 a_0\lambda}{4t}-\dfrac{1}{2\lambda}t\right)\\ +\dfrac{1}{2\lambda}exp\left(-\dfrac{1}{2\lambda}t\right)\displaystyle\int_0^t\frac{y\sqrt{a_0\lambda}}{2z\sqrt{\pi z}}exp\left(-\frac{y^2 a_0\lambda}{4z}\right)\frac{z}{\sqrt{t^2-z^2}}I_1\left(\frac{1}{2\lambda}\sqrt{t^2-z^2}\right)dz\end{pmatrix},$$

$$f(y,t)=L^{-1}\{F(y,q)\}=\begin{cases}f_1(y,t);y>0\\ \delta(t);y=0\end{cases},$$

$$g(t)=\frac{a\lambda-1}{a^2}H(t)+\frac{1}{a}t+\frac{1-a\lambda}{a^2}exp(-at),$$

$$h(y,t)=L^{-1}\left\{exp\left(-y\sqrt{b_1}\sqrt{q}\right)\right\}=\begin{cases}\dfrac{y\sqrt{b_1}\,exp\left(-\frac{y^2 b_1}{4t}\right)}{2t\sqrt{\pi t}};y>0,\\ \delta(t);;y=0\end{cases}$$

Differentiate Equation 10

$$\frac{\partial \bar{u}(y,q)}{\partial y} = \frac{a_1(\lambda q+1)\sqrt{a_0 q(\lambda q+1)}\, exp\left(-y\sqrt{a_0 q(\lambda q+1)}\right)}{q^2\left(a_0\lambda q+(a_0-b_1)\right)} - \frac{a_1(\lambda q+1)\sqrt{Pr\, q}\, exp\left(-y\sqrt{Pr\, q}\right)}{q^2\left(a_0\lambda q+(a_0-b_1)\right)}. \tag{17}$$

Incorporating Equation 17 into Equation 10, we obtain

$$\bar{\tau}(y,q) = \frac{a_4(q+\lambda_0)\, exp\left(-y\sqrt{a_0 q(\lambda q+1)}\right)}{q(q+a_2)\sqrt{a_0 q(\lambda q+1)}} + \frac{a_3\sqrt{b_1 q}\, exp\left(-y\sqrt{b_1 q}\right)}{q(q+a_2)\sqrt{q}}, \tag{18}$$

Hence

$$\bar{\tau}(y,q) = G(q)H(y,q) + g(q)h(y,q), \tag{19}$$

Where $\lambda_0 = \frac{1}{\lambda}, a_2 = \frac{a_0-b_1}{a_0\lambda}, a_4 = \phi_2 a_1, a_3 = \frac{a_1\sqrt{b_1}}{a_0\lambda}, G(q) = \frac{a_4}{(q+a_2)} + \frac{\lambda_0 a_4}{q(q+a_2)}, g(q) = \frac{a_3}{q(q+a_2)}.$

Applying the inverse Laplace transform to Equation 19, we obtain

$$\tau(y,t) = \int_0^t G_1(t-s) * H_1(y,t)ds + \int_0^t g_1(t-s) * h_1(y,t)ds, \tag{20}$$

And

$$G_1(t) = a_5\, exp(-a_2 t) + a_6, g_1(t) = a_7[1 - exp(-a_2 t)],$$

$$h_1(t) = \frac{e^{-y^2\frac{b_1}{4t}}}{\sqrt{\pi t}}, H_1(t) = \begin{cases} 0;\ 0 < t < yc \\ e^{-b_0 t} I_0\left(b_0\sqrt{t^2-(yc)^2}\right);\ t > yc \end{cases}$$

3. Limiting Case

The present solution for oscillating boundary conditions can be reduced to a limiting case in the absence of solutal grashof number and nanoparticles. The published results of Khan *et al.*, [15] have been recovered when $Gm = 0, \phi = 0$ are taken in Equation 16 of the present solution. The solution acquired in this case is same as the velocity solution in Equation 28 of Khan *et al.*, [15].

$$u(y,t) = \int_0^t cos(t-s)f(y,s)ds - \frac{Gr}{\lambda}\int_0^t g(t-s)f(y,s)ds + \frac{Gr}{\lambda}\int_0^t g(t-s)h(y,s)ds, \tag{21}$$

4. Discussion

Thermophysical properties of base fluid kerosene oil and copper nanoparticles are given in Table 1. The variation of dimensionless temperature and velocity for different values of embedded parameter such as Maxwell parameter λ, and nanoparticles volume fraction φ has been illustrated in Figures 3-5 for Maxwell nanofluid. Moreover, all profiles are plotted versus y, with varying a specific parameter at a time. Prandtl number is taken $Pr = 21$ for Kerosene oil [22].

Table 1
Thermophysical properties of base fluid and nanoparticles
Source: Zin *et al.*, [22]

Physical Properties	Kerosene oil	Copper
ρ/kgm^{-3}	783	8933
$c_p/Jkg^{-1}K^{-1}$	2090	385
$k/Wm^{-1}K^{-1}$	0.149	401
$\beta \times 10^{-5}K^{-1}$	99	1.67
Pr	21	

Figure 3 presents the temperature profiles for different values of nanoparticles volume fraction ϕ and constant heat generation $Q = 2.4$ at time $t = 4$. The results are plotted for the range $\phi = 0, 0.02, 0.06, 0.09$ and $Pr = 21$. The fluid temperature exhibits a gradual increase with increasing number of cobalt nanoparticles which leads to an enhancement in the thermal conductivity. Figure 4 depicts that increasing the volume fraction ϕ of cobalt nanoparticles, a gradual decrease is observed in the Maxwell fluid flow velocity though the velocity has sinusoidal behavior due to oscillatory motion of the plate. These results are plotted for the range $0.01 \leq \phi \leq 0.04$ and constant parameters $Q = 4, M = 0.01, \lambda = 0.01, k = 0.02, Gr = 3, Pr = 21$ at time $t = 3$. It is known that the convection flow is always affected by buoyancy forces thus the influence of Gr is very essential to consider in the flow and heat transfer problems.

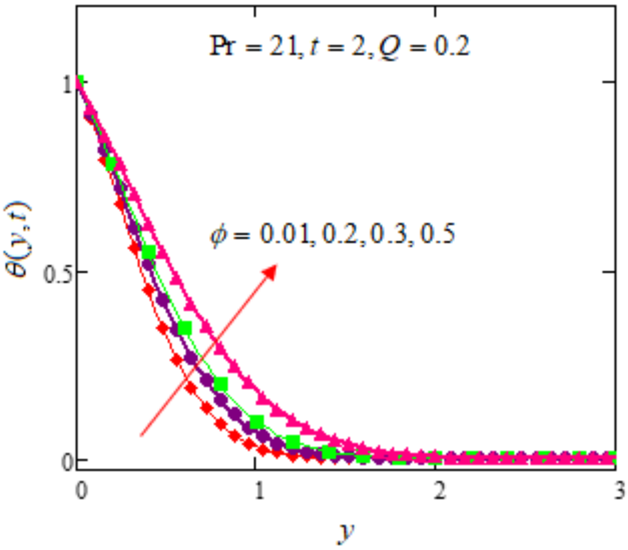

Fig. 3. Temperature profile for various values of volume fraction ϕ

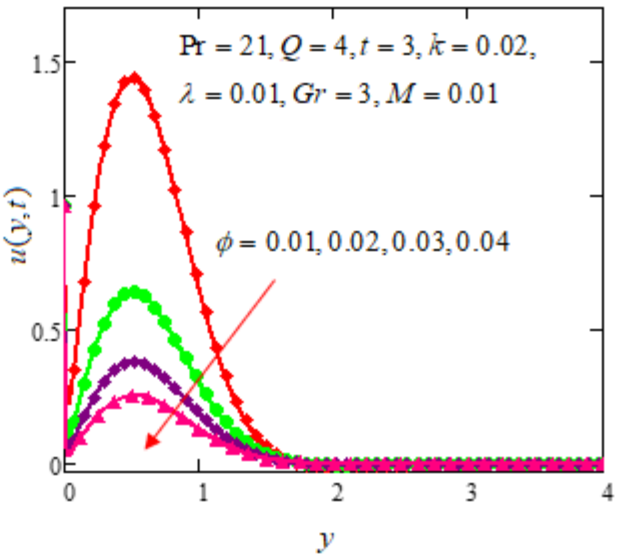

Fig. 4. Velocity profile for different values of volume fraction ϕ

Figure 5 present the effect of Maxwell parameter λ on the flow of kerosene-oil based Maxwell nanofluid. The fluid flow is sinusoidal and increases with increasing Maxwell parameter λ. The figure is portrayed for the range $\lambda = 0.1, 0.3, 0.5, 0.9$ and the fluid velocity is plotted for $Gr = 3$ with parameters $Q = 4, M = 0.01, k = 0.02$, $\phi = 0.02, t = 3, Pr = 21$. Near the plate the fluid is static at the beginning but further away from the plate it increases with greater values of velocity and oscillations due to the plate.

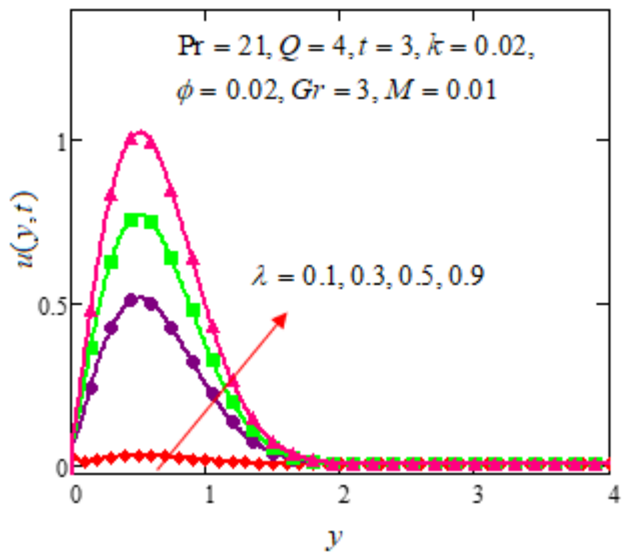

Fig. 5. Velocity profile for different values of Maxwell parameter λ

4. Conclusions

In this attempt, the exact solutions for MHD unsteady free convection problem of Maxwell nanofluid in a porous medium are obtained via Laplace transform method. The effect of volume fraction ϕ of nanoparticles was evaluated on velocity and temperature. From the plotted results it is found that temperature increases with increasing ϕ. Velocity decreases with increasing ϕ because the fluid becomes more viscous whereas a sinusoidal behaviour is observed for Maxwell parameter λ.

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