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Heat transfer in MHD nanofluid flow over a cone and plate in the presence of heat source/sink

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Abstract

In this study, a mathematical model is proposed for analyzing the heat source/sink effect on magnetohydrodynamic two-dimensional ferrofluid flow past a cone and a vertical plate in the presence of volume fraction of ferrous nanoparticles. The governing partial differential equations are transformed as ordinary differential equations by making use of similarity solutions and solved numerically with the aid of Runge-Kutta based shooting technique. The limiting case of the present results shows a good agreement with the published results. The solutions for the flow over a cone and a vertical plate cases are presented. The influence of dimensionless parameters on velocity and temperature profiles along with the friction factor coefficient and the heat transfer rate are analyzed with the help of graphs and tables. It is found that the rising value of the volume fraction of ferrous nanoparticles enhances the friction factor coefficient and heat transfer rate. It is also found that heat transfer performance of the flow over a plate is comparatively higher than the flow over a cone.

1. Introduction

The latest development of recent technologies has challenging applications in fluid flows past a cone. It has been demanded for the application in many of the real life situations like hospitality and healthcare management systems, energy storage systems, aeronautical, geosciences, micro-inverter chips, astrophysics, space technology, geology, automotive engine oil controlling systems, environment controlling factors and power management in nuclear safety systems. Owing to this importance, the flow past a cone was first originated by Tien [1] in 1960's. Further, Kumari et. al. [2] and Chamka [3] have studied the various flow dimensions and effects. Nadeem and Saleem [4] discussed an unsteady MHD flow of rotating cone in a rotating frame. Patrulescu et al. [5] investigated the mixed convection nanofluid flow past a vertically truncated cone. An unsteady nanofluid flow past a vertically rotating cone was illustrated by Saleem and Nadeem [6]. Rushikumar and Sivaraj [7] were considered the heat transfer analysis of viscoelastic fluid flow over a cone and plate in the presence of magnetic

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field and variable viscosity. Raju et al. [8] studied the Jeffery nanofluid flow past a permeable cone in the presence of radiation and chemical reaction effects. Heat and mass transfer characteristics of bio-convection flow past a rotating cone/plate in a rotating fluid were examined by Raju and Sandeep [9, 10]. They concluded that the buoyancy parameter enhances the Nusselt number and Sherwood number values.

Ferrofluids are the colloidal dispersion of magnetic particles that are nanometer in size. Based on the coating of the surface, the ferrofluids can be identified as the surfacted and ionic ferrofluids. In a surfacted ferrofluid, the coating is a surfactant molecule, and the ionic ferrofluid coating is filled with an electrical shell. Scherer and Figueiredo Neto [11] presented the engineering applications of the ferrofluids such as spacecraft propulsion, instrumentation, chemotherapy, petroleum industries, endoscopy, radiology treatment, doping of technological applications, printer inks, jet airway wings, sealing technology, magnetic hyperthermia, cells separation, MEMS, magnetic resonance imaging process etc. Raju et al. [12] analyzed the effect of radiation on ferrofluid flow past a flat plate in the presence of aligned magnetic field and non-uniform heat source/sink. An unsteady micropolar fluid flow over a porous vertical plate by using modified Boussinesq approximation model was studied by Animasun [13]. Khan et al. [14] studied the uniform heat flux effect on ferrofluid flow past a flat plate and concluded that the magnetite ferrous particle has higher heat transfer rate than kerosene-based cobalt ferrite particles. Raju et al. [15, 16] investigated the flow of a nanofluid past a permeable vertical plate in the presence of non-uniform heat source/sink. An external magnetic field effect on convection flow of a ferrofluid in a heated cavity was depicted by Sheikholeslami and Bandpy [17]. Sugunamma et al. [18] discussed the magnetohydrodynamic flow of dusty nano over a cone in the presence of chemical reaction and non-uniform heat source/sink. A three-dimensional non-Newtonian ferro and nanofluids towards a bidirectional stretching sheet was investigated by Raju and Sandeep [19]. They concluded that ferrous particles regulate the velocity profiles. Sandeep et al. [20] studied the non-uniform heat source/sink effect on an unsteady MHD flow of a nanofluid through a stretching surface in the presence of thermophoresis parameter and highlighted that an unsteadiness parameter reduces the velocity profiles. The heat and mass transfer characteristics of aviscoelastic fluid flow with nonlinear thermal radiation and an induced magnetic field were considered by Animasun et al. [21]. Ramanareddy et al. [22] illustrated the stagnation point flow of a magneto-nanofluid flow past a stretching surface in the presence of an induced magnetic field and concluded that the volume fraction of nanoparticle improves the temperature profiles. The magnetohydrodynamic flow of a nanofluid towards a non-linear stretching surface was investigated numerically by Mabood et al. [23]. Khan et al. [24] discussed the stagnation point flow of a ferrofluid over a stretching surface in the presence of magnetic field effect. Thermal radiation effect on heat transfer characteristics of flow over stretching surface filled with ferrous particles was examined by Rani Titus and Abraham [25]. Sandeep and Sulochana [26] examined the magnetohydrodynamic flow of a dusty nanofluid towards a stretching sheet filled with the volume fraction of dust particles and concluded that fluid particle interaction parameter due to temperature has tendency to boost up the thermal conductivity of fluid particle phase.

In continuation of above studies, the present paper addresses the effect of heat source/sink on the flow of MHD ferrofluid, over a cone and plate. The transformed governing equations are solved numerically using Runge-Kutta based shooting technique. In this study, dual solutions are presented for the flow over a cone and plate. The influence of dimensionless parameters on velocity and temperature profiles along with the friction factor coefficient and the heat transfer rate are discussed with the help of graphs and tables.

2. Mathematical Formulation

Consider a steady, two-dimensional, incompressible flow of a ferrofluid over a cone and plate in the presence of heat source/sink. The physical system describes the x -axis is taken along the surface of the cone the y-axis is normal to the surface of the cone. The radius of the cone and the half angle are taken as $r$and γ , respectively. It is assumed that a variable magnetic field $B(x) = B_0 / x(Gr)^{-1/4}$ is acting along the x-

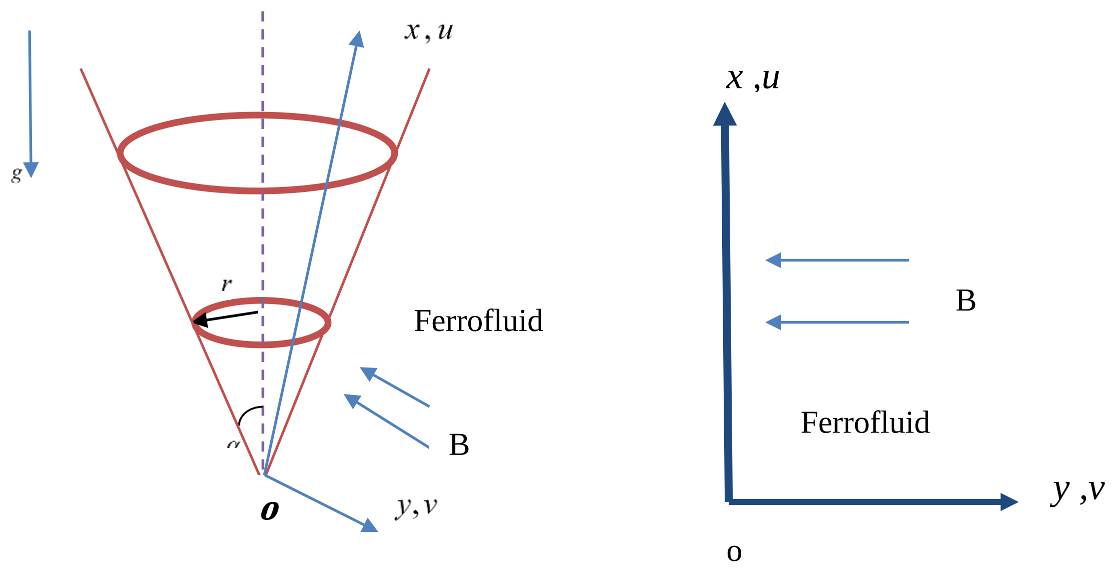

Fig.1. Schematic representation.

direction as displayed in Fig. 1. The flow is considered along the *x*-direction, and suction/injection velocity and induced magnetic field are neglected in this study. T_w and T_∞ are used to represent the temperature near and far away from the cone/plate, respectively. In view of the above assumption, the flow can be modeled using the following equations (see [7]).

2.1 .Flow analysis

$$\frac{\partial}{\partial x}(r^h u)+\frac{\partial}{\partial y}(r^h v)=0, \qquad (1)$$

$$\rho_{nf}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\left(\begin{array}{c}\mu_{nf}\dfrac{\partial^2 u}{\partial y^2}+g(\rho\beta)_{nf}(T-T_\infty)\cos\gamma\\ -\sigma B_0^2 u\end{array}\right), \qquad (2)$$

with the boundary conditions:

$$\left.\begin{array}{l}u=0, v=0, \quad \text{at } y=0,\\ u\to 0, \ \text{as } y\to\infty,\end{array}\right\} \qquad (3)$$

where $h=1$ denotes the flow over a vertical cone and $h=\gamma=0$ represents the flow over a vertical plate, u and v are the velocity components along the x and y directions, respectively. ρ_{nf} is the density of the nanofluid, μ_{nf} is the viscosity coefficient, g is the acceleration due to gravity, $(\rho\beta)_{nf}$ is the thermal expansion coefficient due to temperature difference, σ is the electric conductivity, and ν is the kinematic viscosity. To convert the nonlinear coupled partial differential equations into ordinary nonlinear differential equations the self-similarity transformations are used as follows:

$$\left.\begin{array}{l}u=\dfrac{\nu_f}{x}(Gr)^{1/2}f'(\eta), \eta=\dfrac{y}{x}(Gr)^{1/4},\\ v=\dfrac{\nu_f}{x}(Gr)^{1/4}\left(\dfrac{\eta}{4}f'(\eta)-\dfrac{1}{2}f(\eta)\right),\\ T=T_\infty+(T_w-T_\infty)\theta(\eta),\\ Gr=\dfrac{\rho g x^3\beta_T(T_w-T_\infty)}{\nu^2},\end{array}\right\} \qquad (4)$$

where u and v satisfy the continuity equation and the nanofluid constants are given by:

$$\left.\begin{array}{l}\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s, \mu_{nf}=\dfrac{\mu_f}{(1-\phi)^{2.5}},\\ \dfrac{k_{nf}}{k_f}=\dfrac{(k_s+2k_f)-2\phi(k_f-k_s)}{(k_s+2k_f)+\phi(k_f-k_s)},\\ (\rho c_p)_{nf}=(1-\phi)(\rho c_p)_f+\phi(\rho c_p)_s,\end{array}\right\} \qquad (5)$$

By making use of Eqs. (4 and 5), the transformed Eq. (1) to Eq. (2) as follows:

$$\left(\frac{1}{(1-\phi)^{2.5}}\right)f''' + \left(\frac{ff''}{4}-\frac{f'^2}{2}\right)\left((1-\phi)+\phi\left(\frac{\rho_s}{\rho_f}\right)\right) - Mf' + \left((1-\phi)+\phi\frac{(\rho\beta)_s}{(\rho\beta)_f}\right)\lambda\theta = 0, \tag{6}$$

The transformed boundary conditions are:

$$\left.\begin{array}{ll} f = 0, f' = 0, & at \quad \eta = 0, \\ f' \to 0, & as \quad \eta \to \infty, \end{array}\right\} \tag{7}$$

where ϕ is the volume fraction of nanoparticles, M is the magnetic field parameter, ρ_f and ρ_s are the densities of the fluid and solids, respectively, λ is the buoyancy parameter, $(T_w - T_\infty) > 0$ is for assisting flow, $(T_w - T_\infty) < 0$ is for restricting flow, and

$$\left. M = \frac{\sigma x^2 B_0^2}{(Gr)^{1/2}\rho_f}, \lambda = \frac{g\,\beta_f\,(T_w - T_\infty)\cos\gamma}{v^2 Gr} \right\} \tag{8}$$

2.2. Heat Transfer analysis

The boundary layer energy equation with non-uniform heat source/sink and heat source parameters is given by:

$$(\rho c_p)_{nf}\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k_{nf}\frac{\partial^2 T}{\partial y^2} - Q_0(T - T_\infty), \tag{9}$$

The corresponding boundary conditions are:

$$T = T_w, \ at \ y = 0, \ T \to T_\infty, \ as \ y \to \infty, \tag{10}$$

where $(\rho c_p)_{nf}$ is the heat capacity of the nanofluid, T is the fluid temperature, T_w and T_∞ are the near and the far away temperature, respectively, k_{nf} is the thermal conductivity of the nanofluid, c_p is the specific heat capacitance at constant pressure, c_s is the concentration susceptibility, and Q_0 is the heat source/sink parameter.

By using self-similarity transformations, Eqs. (4 and 5), the Eq. (9) is reduced to

$$\frac{k_{nf}}{k_f}\theta'' + \Pr f\,\theta'\left((1-\phi)+\phi\frac{(\rho c_p)_s}{(\rho c_p)_f}\right) + \Pr Q_H\theta = 0, \tag{11}$$

The corresponding transformed boundary conditions are:

$$\theta(0) = 1, \ \theta(\infty) = 0, \tag{12}$$

where $\Pr$ is the Prandtl number and Q_H is the non-dimensional the heat source/sink parameter which are given by

$$\Pr = \frac{k_f}{(\mu c_p)_f}, Q_H = \frac{Q_0 x^2}{Gr}, \tag{13}$$

For physical quantities of interest, the friction factor coefficients and the rate of heat transfer is given by

$$C_{fx}\,\mathrm{Re}^{1/2} = \frac{1}{(1-\phi)^{2.5}}f''(0), \tag{14}$$

$$\mathrm{Re}^{-1/2}\,Nu_x = -\frac{k_{nf}}{k_f}\theta'(0), \tag{15}$$

where $\mathrm{Re} = \frac{x u_w(x)}{v}$ is the Reynolds number.

3. Results and discussion

The set of nonlinear coupled ordinary differential Eqs. (6 and 11) subjected to the boundary conditions (7) and (12) are solved numerically using Runge-Kutta based shooting method. The influence of pertinent parameters on velocity and temperature profiles along with the friction factor coefficient and local Nusselt numbers are discussed and presented through graphs and tables. The non-dimensional parameter values as $M = 0.3, \lambda = 0.1, K = 0.3, Q_H = 0.4, \Pr = 6.72$ are taken for the numerical computation. These values are kept as constant in the entire study except the variations in the corresponding figures and tables.

The variations of velocity and temperature fields against magnetic field parameter are plotted in Figs. 2 and 3 for both geometries (the flow over a cone and a plate). It shows that an increase in the magnetic field parameter weakens the velocity field and strengthens the temperature field in both cases. Physically, increasing values of the magnetic field parameter creates a resistive type drag force (Lorentz's force) that dominates the velocity profiles. Figures 4 and 5 depict the variations in velocity and temperature profiles against nanoparticle volume fraction for both cases. It is noticed that the velocity profiles are enhanced and temperature profiles are depreciated for higher values of the nanoparticle volume fraction. Physically, increasing values of volume fraction of nanoparticles decreases their size. This leads to enhance the momentum and reduce the thermal boundary layers.

Figures 6 and 7 depict the effect of buoyancy parameter on velocity and temperature fields for both cases. It is obvious that increasing values of the buoyancy parameter causes to decrement in the thermal boundary layer thickness and increment in the momentum boundary layer thicknesses. This may be due to the fact that the buoyancy forces are less dominant in the flow and causes an enhancement in the flow velocity. The influence of heat source/sink parameter on velocity and temperature profiles is displayed in Figs. 8 and 9. This shows that rising values of the heat source/sink parameter depreciates both the velocity and temperature profiles of the flow. This concludes that Q_H acts like heat absorption parameters. Table 1 demonstrates the thermophysical properties of the base and ferrofluid. Table 2 compares the limiting cases of the present results with the published results and suggests a good agreement in supportive of the present study.

Tables 3 and 4 depict the variations in the friction factor coefficients and the Nusselt number for the flow over the cone and plate cases for different values of non-dimensional governing parameters. It is observed that increasing the ferroparticle volume fraction improves the friction factor coefficients as well as Nusselt number. The quite similar results are observed in the presence of buoyancy parameter. The magnetic field parameter depreciates the friction factor coefficient and Nusselt number in both cases. It is interesting to mention that the friction factor coefficient is reduced and the rate of heat transfer is improved when values of the heat source/sink parameter are increased.

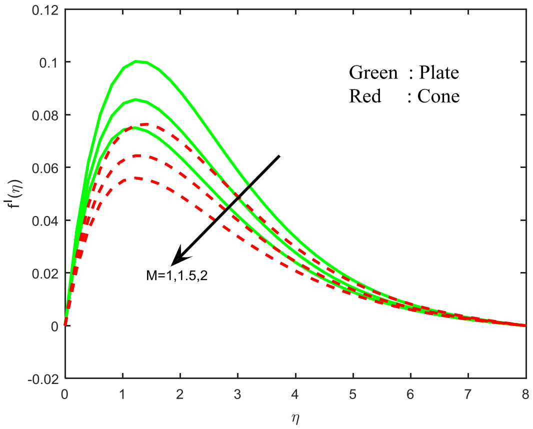

Fig. 2. Velocity profile for different values of magnetic field parameter.

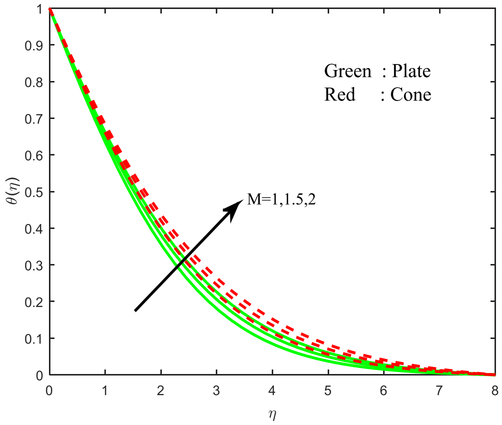

Fig. 3. Temperature profiles for different values of magnetic field parameter.

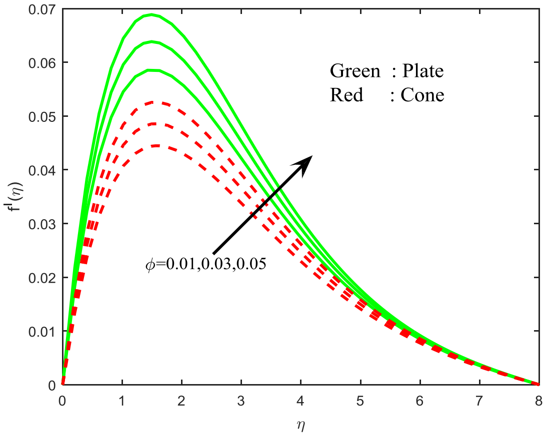

Fig. 4. Velocity profiles for different values of the nanoparticle volume fraction.

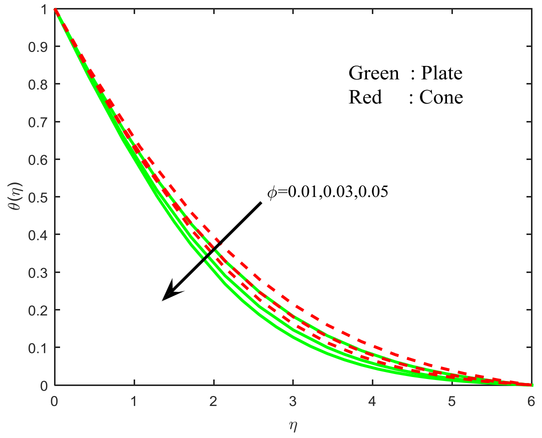

Fig. 5. Temperature profiles for different values of the nanoparticle volume fraction.

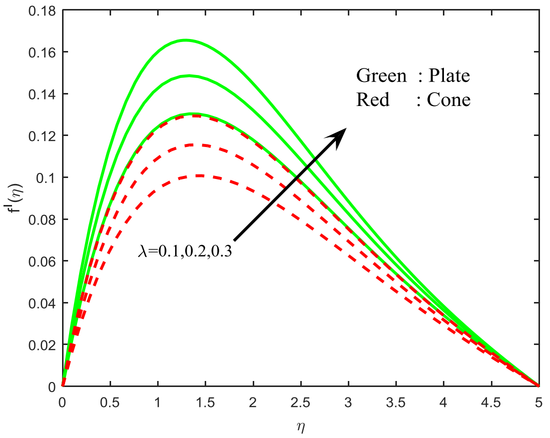

Fig. 6. Velocity profiles for different values of the buoyancy parameter.

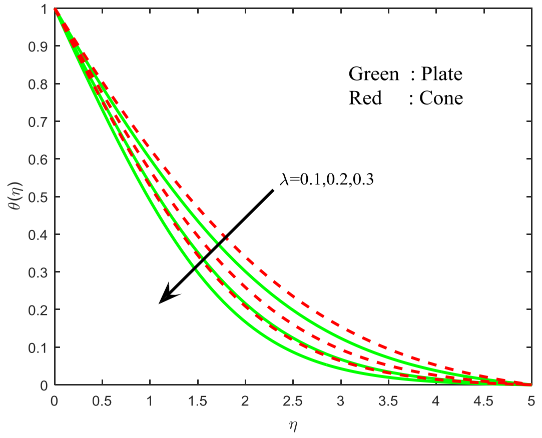

Fig. 7. Temperatureprofile for different values of the buoyancy parameter.

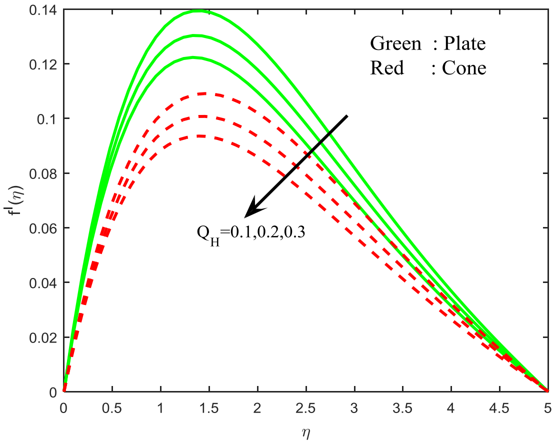

Fig. 8. Velocity profiles for different values of heat source parameter.

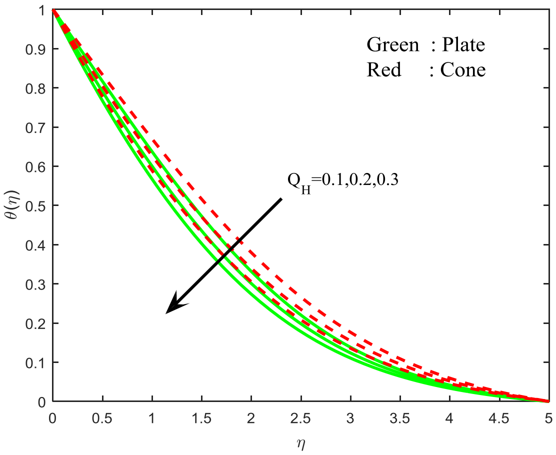

Fig. 9. Temperature profiles for different values of heat source parameter.

Table 1. Thermo physical properties kerosene and Fe_3O_4.

Thermophysical properties	Keresone	Fe_3O_4
ρ (Kg/m^3)	783	5180
C_p (J/Kg K)	2090	670
k (W/m K)	0.15	9.7
β X 10^{-5}(1/K)	9.9	2.1

Table 2. Validation of the present results when $M = A^* = B^* = K = Q_H = \phi = 0$.

	$\Pr = 0.7$			$\Pr = 1$			$\Pr = 10$		
λ $\downarrow$	$-\theta'(0)$ Anilkumar and Roy [16]	$-\theta'(0)$ Raju et al. [8]	$-\theta'(0)$ Present	$-\theta'(0)$ Anilkumar & Roy [16]	$-\theta'(0)$ Raju et al.[8]	$-\theta'(0)$ Present	$-\theta'(0)$ Anilkumar & Roy [16]	$-\theta'(0)$ Raju et al. [8]	$-\theta'(0)$ Present study
0	0.4305	0.47697	0.4299	0.557294	0.5180	0.5570	1.4042	1.6359	1.4952
1	0.6127	0.60041	0.6020	0.721982	0.7005	0.7005	1.5885	2.0911	2.0912
10	1.0175	0.99523	1.0175	1.170983	1.1494	1.1709	2.3528	2.7734	2.7735

Table 3. The physical parameter values of skin friction coefficient and local Nusselt number.

M	ϕ	λ	Q_H	Skin friction coefficient		Nusselt number	
				Cone	Plate	Cone	Plate
1				0.116341	0.159440	0.375841	0.402855
1.5				0.105614	0.145666	0.362430	0.387356
2				0.097467	0.135037	0.352445	0.375457
	0.01			0.072642	0.099678	0.379573	0.399252
	0.03			0.078834	0.107994	0.382814	0.403635
	0.05			0.084659	0.115799	0.385751	0.407599
		0.1		0.137480	0.186572	0.409918	0.437828
		0.2		0.251698	0.337767	0.470708	0.508588
		0.3		0.354910	0.473788	0.515522	0.559264
			0.1	0.143936	0.194043	0.333604	0.367939
			0.2	0.137480	0.186572	0.409918	0.437828
			0.3	0.131805	0.179849	0.479418	0.502457

4. Conclusions

This study deals with the numerical investigation of heat source/sink effect on magnetohydrodynamic ferrofluid flow past a cone and plate in the presence of volume fraction of ferrous nanoparticles. The following conclusions are derived:

- Thermal boundary layer thickness is high for the flow over a cone when compared with the flow over a plate.
- Suspension of ferrous nanoparticles improves the thermal conductivity of the flow.
- Increase in the magnetic field parameter depreciates both the friction factor and rate of heat transfer.
- The buoyancy parameter and the volume fraction of nanoparticles enhance the flow as well as the heat transfer rate.
- Increasing values of the heat source/sink parameter improves the Nusselt number and suppresses the skin friction coefficient.

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