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ORIGINAL ARTICLE

Magnetohydrodynamic (MHD) boundary layer stagnation point flow and heat transfer of a nanofluid past a stretching sheet with melting

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Abstract The paper examines the melting heat transfer in magnetohydrodynamic (MHD) stagnation point flow of a nanofluid past a stretching sheet. Boundary layer theory is employed to simplify the system of partial differential equations of motion, energy and concentration to three coupled non-linear ordinary differential equations. The non-linear ordinary differential equations and their boundary conditions are changed into dimensionless form by using suitable similarity variables before numerically solved using fourth order Runge-Kutta-Fehlberg method along with shooting technique. The effect of pertinent parameters on different flow fields are determined and discussed in detail through several plots and tables.
The numerical results are obtained for velocity, temperature and concentration profiles. It is found that the skin friction coefficient and Sherwood number decrease with an increase in B and M parameters. However, the local Nusselt number $-\theta'(0)$ increases with an increase in B and Nt. Then, the results are compared and found to be in good agreement with the previously published results in limiting cases of the problem.

1. Introduction

The examination of boundary layer flow and heat transfer over stretching sheet has a significant importance on industrial and manufacturing processes. Crane [1] was a forerunner in examining the similarity solution for laminar

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Nomenclature

A	velocity ratio
B	melting heat transfer
B_0	magnetic field parameter
C_f	skin friction coefficient
C_∞	ambient concentration
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
f	dimensionless velocity stream function
k	thermal conductivity
Le	Lewis number
M	magnetic parameter
Nb	Brownian motion parameter
Nt	thermophoresis parameter
Nu_x	local Nusselt number
Pr	Prandtl number
Re_x	local Reynolds number
Sh_x	local Sherwood number
T	temperature of the fluid inside the boundary layer
TM	melting temperature
T_0	solid temperature
T_∞	ambient temperature
u,v	velocity component along x- and y-direction

Greek letters

α	thermal diffusivity
η	dimensionless similarity variable
μ	dynamic viscosity of the fluid
υ	kinematic viscosity of the fluid
$(\rho)_f$	density of the fluid
$(\rho c)_f$	heat capacity of the fluid
$(\rho c)_p$	effective heat capacity of a nanoparticle
ψ	stream function
σ	electrical conductivity
ϕ_w	dimensionless concentration function at the surface
ϕ_∞	dimensionless concentration function at large values of y
θ	dimensionless temperature
τ	parameter defined by $(\rho c)_p/(\rho c)_f$

Subscripts

∞	condition at the free stream
w	condition at the surface

boundary layer flow and heat transfer over a stretching surface. Later, many researchers, such as Carragher and Crane [2], Dutta [3], Grubka and Bobba [4], Elbashbeshy [5], Elbashbeshy and Bazid [6] and Mahapatra and Gupta [7] have analyzed the problem of stretching sheet by including different aspects, such as heat flux, permeability and unsteadiness characteristics, etc.

Melting heat transfer has wide industrial applications, such as casting, welding and magma solidification, permafrost melting and thawing of frozen ground, etc. Many research papers have been published on the effect of melting heat transfer. Accordingly, Tien and Yen [8] have examined the effect of melting on convective heat transfer between a melting body and surrounding fluid. Their study indicates that melting retards the rate of heat transfer. Then after, Epstein and Cho [9] have studied melting heat transfer in steady laminar flow over a flat surface. The result shows that melting inhibits the heat transfer rate and reduces the local Nusselt number.

Further, Ishak et al. [10] examined melting heat transfer in steady laminar flow over a moving surface. They indicated that melting decreases the local Nusselt number at the solid-liquid interface. Moreover, Hayat et al. [11] and Yacob et al. [12] extended the study of melting heat transfer to non-Newtonian fluid, and they examined melting heat transfer in the stagnation point flow of couple stress and micropolar fluid. The results show that the velocity boundary layer thickness is a decreasing function of the couple stress parameter. Still further, Gorla et al. [13] and Ahmad and Pop [14] have analyzed the effect of melting on mixed convection boundary layer about vertical surfaces in a fluid-saturated porous medium. The result indicates that the melting diminishes the local Nusselt number at the solid-liquid interface and enhances the boundary layer separation.

Melting heat transfer of upper-convected Maxwell fluid over stretching sheet was discussed by Hayat et al. [15]. They indicate that the local Nusselt number is a diminishing function of melting parameter. Similarly, Abdel-Rahman et al. [16] investigated melting heat transfer in magnetohydro dynamic over a moving surface. Their study shows that an incremental in melting parameter causes an increment in the boundary layer thickness and the velocity.

The boundary layer flow and heat transfer characteristics in nanofluid was studied by Buongiorno [17]. He sketched a model were the influences of Brownian motion and thermophoresis parameters were taken into consideration. Following him, many papers have been published on nanofluid by employing the model. For example, scholars, Khan and Aziz [18], Kuznetsov and Nield [19], Khan and Pop [20], Yacob et al. [21], Makinde and Aziz [22] examined the flow of a nanofluid past a stretching surface under different circumstances. All the above studies signify that both Brownian motion and thermophoresis reduces the heat transfer rate of the laminar flow.

Besides, Olanrewaju and Makinde [23], Khan and Reddy [24], Vajravelu et al. [25] analyzed the stagnation point flow of a nanofluid past stretching surface with convective boundary condition. The findings reveal that the momentum and energy boundary layer thickness are antagonistic. Moreover, Wubshet and Shanker [26–29] and Wubshet and Makinde [30], Wubshet and Rizwan [31] have analyzed the boundary layer flow and heat transfer of a nanofluid towards stretching surface under different conditions, such as permeability, slip, variable surface temperature, stratified

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