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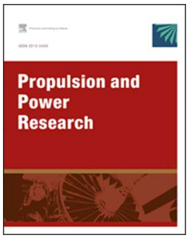

ORIGINAL ARTICLE

Melting and second order slip effect on convective flow of nanofluid past a radiating stretching/shrinking sheet

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Abstract A mathematical model is presented for forced convective slip flow of a nanofluid past a radiating stretching/shrinking sheet. Melting boundary condition is taken into account. The nanofluid model involves the Brownian motion and thermophoresis effects. Lie group transformation is used to the transport equations as well as the boundary conditions to develop the similarity equations, before being solved numerically using the Runge-Kutta-Fehlberg fourth-fifth order numerical method. To show the effects of the controlling parameters on the dimensionless velocity, temperature, nanoparticle volume fraction, skin friction factor, local Nusselt, and local Sherwood numbers, numerical results are presented both in graphical and tabular forms. It is found that the friction factor decreases with slip and melting parameters for both stretching/shrinking sheets. It is also found that the Nusselt number decreases with the first order slip while it increases with melting and radiation parameters in both cases. Also, the Sherwood number decreases with the melting parameter both for radiating and non-radiating stretching/shrinking sheets. An excellent agreement is found between the present numerical results and published results.

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Nomenclature

a	first order momentum slip parameter
a_0	positive constant
A	parameter of the group
b	second order momentum slip parameter
c	positive constant characterizing stretching intensity.
c_s	heat conducted to the melting surface
C	dimensional nanoparticle volume fraction (unit: kg·m^{-3})
D_B	Brownian diffusion coefficient (unit: m^{2}·s^{-1})
D_T	thermophoretic diffusion coefficient (unit: m^{2}·s^{-1})
f	dimensionless free stream function
k	thermal conductivity of fluid (unit: W·m^{-1}·K^{-1})
k_1	Rosseland mean absorption coefficient (unit: m^{-1})
Le	Lewis number
Me	melting parameter
n	power law index
Nb	Brownian motion parameter
Nr	buoyancy ratio parameter
Nt	thermophoresis parameter
Nur	reduced Nusselt number
$Nu_{\bar{x}}$	local Nusselt number
R	radiation parameter
$Ra_{\bar{x}}$	local Rayleigh number
Shr	reduced Sherwood number
$Sh_{\bar{x}}$	local Sherwood number
T	dimensional temperature (unit: K)
T_o	dimensional solid temperature (unit: K)
T_m	dimensional melting temperature (unit: K)
$\bar{u}$	dimensional fluid velocity in the $\bar{x}$ direction (unit: m·s^{-1})
$\bar{u}_e$	velocity of the external flow (unit: m·s^{-1})
$\bar{v}$	dimensional fluid velocity in the $\bar{y}$ direction (unit: m·s^{-1})
$\bar{x}, \bar{y}$	coordinates along and normal to the plate (unit: m)

Greek symbols

α	thermal diffusivity (unit: m^{2}·s^{-1})
ε	stretching/shrinking parameter
η	similarity independent variable
θ	dimensionless temperature
λ	latent heat of the fluid (unit: kJ·kg^{-1})
μ	dynamic viscosity of the fluid (unit: kg·m^{-1}·s^{-1})
ν	kinematic viscosity (unit: m^{2}·s^{-1})
ρ	fluid density (unit: kg·m^{-3})
$(\rho C)_f$	heat capacity of the fluid (unit: J·K^{-1})
$(\rho C)_p$	effective heat capacity of the nanoparticles material (unit: J·K^{-1})
σ_1	Stefan-Boltzmann constant (unit: W·m^{-2}·K^{-4})
τ	parameter defined as, $\tau = (\rho C)_p/(\rho C)_f$
ϕ	dimensionless nanoparticles volume fraction
ψ	dimensionless stream function

Subscripts

w	conditions at the wall
∞	ambient condition

Superscript

$'$	prime denotes the derivative with respect to η

1. Introduction

Melting effects on flow, heat and mass transfer have received the attention ofresearchers since melting is important in frozen ground thawing, permafrost, silicon water process etc. [1]. Cho and Epstein [2] studied the laminar film condensation of flowing vapor past a horizontal surface with melting effects. Walker [3] has pointed out the relationship between permafrost phenomenon degradation in Arctic Alaska and global warming. Many investigators studied melting phenomenon with heat/mass transfer past various flow configurations. Kazmierczak and coworkers [4] studied melting phenomenon from a vertical plate in porous medium whilst Hassanien and Bakier [5] studied the melting effect in mixed convective flow past a horizontal flat plate. Cheng and Lin [6] investigated the convective heat transfer from a vertical plate with melting effects. Bakier and colleagues [7] illustrated hydromagnetic heat transfer due to mixed convection around a vertical plate. Chamkhaand co-workers [8] considered the effects of melting on steady mixed convection from a radiating plate. Bachoket al. [9] studied the melting heat transfer effects on boundary layer for a steady two-dimensional flow past a stretching/shrinking sheet. They found multiple solutions for shrinking sheet.Heat transfer from a flowing warm, laminar liquid to a melting surface moving parallel to a constant free stream was investigated by Ishak et al. [10]. It was found that the melting phenomenon decreases the local Nusselt number at the solid-fluid interface. Khan et al. [11] investigated the influence of melting, thermal dispersion as well as thermo-diffusion effect on unsteady mixed convection heat and mass transfer from a vertical flat plate in a non-Darcy porous medium. Das and Zheng [12] studied melting effects on the stagnation point flow of a Jeffrey fluid in the presence of magnetic field. The melting heat transfer effects on the boundary layer flow of a micropolar fluid near a stagnation point in a porous medium was investigated by Mahmoud and Waheed [13]. They used the Chebyshev spectral method and found that the local skin-friction coefficient decreases, while the local Nusselt number increases as the melting parameter increases. Gorla et al. [14] discussed melting heat transfer past a permeable continuous moving surface in a nanofluids flow.

Conventional heat transfer fluids have poor thermal conductivity due to their low heat transfer capacity. The enhanced heat transfer performance of the fluid will reduce operating costs. One way of enhancing heat transfer is to add nanoparticle to the base fluid. Nanofluid is a suspension

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