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The role of a convective surface in models of the radiative heat transfer in nanofluids

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HIGHLIGHTS

- The role of a convective surface in modelling with nanofluids is investigated over a wedge.
- Surface convection significantly controls the rate of heat transfer in nanofluid.
- Increased volume fraction of nanoparticles to the base-fluid may not always increase the rate of heat transfer.
- Effect of nanoparticles solid volume fraction depends on the types of constitutive materials.
- Higher heat transfer in nanofluids is found in a moving wedge rather than in a static wedge.

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ABSTRACT

Nanotechnology becomes the core of the 21st century. Nanofluids are important class of fluids which help advancing nanotechnology in various ways. Convection in nanofluids plays a key role in enhancing the rate of heat transfer either for heating or cooling nanodevices. In this paper, we investigate theoretically the role of a convective surface on the heat transfer characteristics of water-based nanofluids over a static or moving wedge in the presence of thermal radiation. Three different types of nanoparticles, namely copper Cu, alumina Al_2O_3 and titanium dioxide TiO_2 are considered in preparation of nanofluids. The governing nonlinear partial differential equations are made dimensionless with the similarity transformations. Numerical simulations are carried out through the very robust computer algebra software MAPLE 13 to investigate the effects of various pertinent parameters on the flow field. The obtained results presented graphically as well as in tabular form and discussed from physical and engineering points of view. The results show that the rate of heat transfer in a nanofluid in the presence of thermal radiation significantly depends on the surface convection parameter. If the hot fluid side surface convection resistance is lower than the cold fluid side surface convection resistance, then increased volume fraction of the nanoparticles to the base fluid may reduces the heat transfer rate rather than increases from the surface of the wedge to the nanofluid. This finding is new and has not been reported in any open literature.

1. Introduction

Nanofluids are a new class of nanotechnology-based heat transfer fluids consist of a suspension of very small (usually 1–100 nm) metallic like particles suspended in a carrier fluid. Typically these fluids are manufactured by using a suspension of solid particles into base liquids with low thermal conductivity such as water, ethylene glycol (EG), engine oil, etc. (Wange and Mujumdar, 2007). The nanoparticles can be made of metal (Cu, Al, Ti, Fe, Ag, Au, etc.), metal oxide (CuO, Al_2O_3, TiO_2, etc.), carbide, nitride (AlN) and even immiscible nano-scale liquid droplets (Chen and Ding, 2009). The shape of nanoparticles can be spherical, rod-like, tubular, etc. It seems that Choi (1995) was the first who has used the term nanofluid to describe this new class of fluid. The nanofluids are usually produced in two techniques namely: single-step and the two-step methods (see Akoh et al., 1978; Eastman et al., 1997). Both of these methods have advantages and disadvantages as discussed by Wange and Mujumdar (2007). There are many general applications of nanofluids such as: industrial cooling, vehicle cooling, generating new types of fuel, reducing fuel in electric power

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Nomenclature

a, A, b, D, E	constants defined in Eqs. (1), (13), (20), (22), and (23), respectively
Bi	Biot number
C_f	skin-friction coefficient
C_p	specific heat at constant pressure
f	dimensionless stream function
f_w	suction or injection parameter
h	convective heat transfer coefficient
m	Hartee pressure gradient parameter
Nu_x	local Nusselt number
p	pressure
Pr	Prandtl number
q_w	wall heat flux
R	radiation parameter
Re	Reynolds number
T	temperature of the nanofluid within the boundary layer
T_0	temperature of the fluid below the wedge
T_r	relative temperature ratio
T_∞	temperature of the ambient fluid
U_e	free stream velocity of the nanofluid
U_w	velocity of the wedge
u	velocity along the surface of the wedge
v	velocity normal to the surface of the wedge
(x, y)	Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	wedge angle parameter
δ	boundary layer thickness
λ	relative velocity parameter
ρ	density of the fluid
μ	dynamic viscosity
ν	kinematic coefficient of viscosity
κ	thermal conductivity
κ^*	Rosseland mean absorption coefficient
σ^*	Stefan-Boltzmann constant
θ	dimensionless temperature
ϕ	solid volume fraction of the nanoparticles
ψ	stream function
η	similarity variable

subscripts

bf	base fluid
nf	nanofluid
sp	solid particle
∞	conditions far away from the surface

superscripts

$'$	differentiation with respect to η

generation plant, cancer therapy, imaging and sensing etc. The details of nanofluid applications can be found in the work of Wong and Leon (2010).

Nanofluids have higher thermal conductivity (Das et al., 2007), can flow smoothly through micro-channels without blocking them because nanoparticles are small enough to behave similar to liquid molecules (Khanafer et al., 2003), and induce a very small pressure drop. In addition, nanoparticles resist sedimentation, as compared to larger particles, due to Brownian motion and inter-particle forces and possess much higher surface area (1000-time) which enhances the heat conduction of nanofluids since heat transfer occurs on the surface of the fluid. Three properties that make nanofluids promising coolants are: (i) increased thermal conductivity, (ii) increased single-phase heat transfer, and (iii) increased critical heat flux. Research has shown that relatively small amounts of nanoparticles (5% or less volume fraction), can enhance thermal conductivity of the base fluid to a large extent. Therefore, exploiting the unique characteristics of nanoparticles, nanofluids are created with two features very important for heat transfer systems: (i) extreme stability, and (ii) ultra-high thermal conductivity. These facts have attracted many researchers such as Abu-Nada (2008), Tiwari and Das (2007), Maiga et al. (2005), Polidori et al. (2007), Singh (2008), Oztop and Abu-Nada (2008), Nield and Kuznetsov (2009), Straughan (2011), Rahman et al. (2012, 2014a,b,c), Rahman and Eltayeb (2013), Rahman and Aziz (2012), Kuznetsov and Nield (2010), Kuznetsov and Nield (2014), Rosca and Pop (2014) to investigate the heat transfer characteristics in nanofluids, and they found that the presence of nanoparticles in the conventional base fluid increases appreciably the effective thermal conductivity of the base fluid and consequently enhances the heat transfer characteristics.

Due to many engineering applications in aerodynamics, geothermal systems, crude oil extractions, ground water pollution, thermal insulation, heat exchanger, storage of nuclear waste, etc., convective flows over wedge shaped bodies have been extensively studied since the early formulation of the problem in 1931 by Falkner and Skan. They first studied two-dimensional flow of viscous incompressible fluid over a wedge. Similarity transformation technique was developed which reduced the governing partial differential boundary layer equation to an ordinary differential equation which could then be solved numerically. Since then many investigators have studied and reported results on wedge flow considering various flow conditions. Lin and Lin (1987) studied two-dimensional steady laminar forced flow and heat transfer from a wedge. They proposed similarity solutions for an isothermal surface for a wide range of Prandtl numbers. Yih (1998) presented an analysis of forced convection boundary layer flow over a wedge with uniform suction and injection. Anjali Devi and Kandasamy (2001) analyzed the effects of thermal stratification on the laminar boundary layer flow over a wedge with suction (or injection). Pantokratoras (2006) studied the Falkner-Skan flow of a viscous incompressible fluid with constant wall temperature and variable viscosity. Martin and Boyd (2010) studied the Falkner-Skan flow over a wedge with slip boundary conditions. Rahman and Eltayeb (2011) studied convective slip flow of rarefied fluids over a wedge. Rahman and Al-Hadhrami (2012) studied nonlinear slip flow with variable transport properties over a wedge with convective surface. These studies confirmed that strong rarefaction and increased angle of wedge significantly controls the growth of the hydrodynamic and thermal boundary layer thicknesses. Muhaimin et al. (2013) studied effect of thermophoresis particle deposition and chemical reaction on unsteady MHD mixed convective flow over a porous wedge in the presence of temperature-dependent viscosity.

In recent years, heat transfer due to surface convection over various geometries has received considerable attention for its potential applications in several engineering and industrial processes like transpiration cooling process, material drying, etc. The use of the convective boundary condition at the surface of the body is more general and realistic to apply. Several authors, Bataller (2008), Rahman (2011), Makinde and Aziz (2011), Rahman et al. (2012, 2014a), and Rahman and Eltayeb (2013), Makinde (2013), etc., discussed the effect of convective boundary conditions on the forced convection flow past a flat plate, stretching surface and past a wedge.

In view of the above discussion the objective of the present study is to investigate the role of a convective surface on the flow dynamics and radiative heat transfer characteristics of a water-based nanofluids over a static or moving wedge. For a moving wedge its