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Numerical investigation on time-dependent flow of Williamson nanofluid along with heat and mass transfer characteristics past a wedge geometry

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A B S T R A C T

In the recent times, the nanofluid's thermal conductivity has become one of the most appealing topic for scientists and researchers due to its application in engineering and industry. So far, a large number of experimental and theoretical studies describing this issue has been presented in this field. These nanofluids have been explored with various volume divisions, different molecule sizes and distinctive production techniques. This paper presents findings from a theoretical study of magnetic-Williamson fluid flow in the presence of suspended nanoparticles. Further, heat and mass transfer properties of nanofluids flow over a wedge shape geometry with convective heating mode are examined. A mathematical model is proposed to narrate the two-dimensional flow problem for Williamson fluid with infinite shear rate of viscosity, to simulate and scrutinize the effects of enhanced heat flux. The time dependent conservation equations governing the flow fields are transformed to dimensionless form using the non-dimensional parameters. These converted equations are solved for non-dimensional velocity, temperature and concentration fields. Numerical computations are performed with the assistance of Nachtsheim-Swigert shooting iteration scheme alongside Runge-Kutta Fehlberg method. The physical behavior of obtained solution are investigated diagrammatically by considering the effects of various pertinent parameters. Numerical results reveal that a rise in fluid temperature is seen with higher convection parameter. A basic analysis further depicts that the rate of heat transfer is accelerated with the growth in Brownian motion and thermophoresis parameter. As well, a correlation is furnished in order to validate the result obtained in this analysis with earlier published works.

1. Introduction

In the recent couple of decades, the heat transfer enhancement is considered as one of the thrust area of research for engineers and scientists. The basic hurdle to enhance the heat transfer rate is the low thermal conductivity of usual liquids, like, air, water, oil, and ethylene glycol mixture. An innovative technique to improve this deficiency of usual fluids is the addition of some nano-scale particles in the base fluid, known as nanofluids. Nanofluid is a liquid containing nanometer-sized particles having diameter less than 100 nm, called nanoparticles. The study on nanofluids have gained much interest of the recent researchers due to their vital potential applications in industrial processes such as in power generation, bio-medicine, paper production, chemical reactions, heating or cooling and also in nanoscience and nanotechnology. It was Choi [1] who pioneered an experimentally study and revealed to the society about the enhancement of thermal conductivity of nanofluids. Later on, Kang and Choi [2] studied the convective instability and heat transfer analysis of nanofluids. Khan and Pop [3] are probably the pioneers who have investigated the laminar flow of nanofluids due to a stretching surface. Gorla and Chamkha [4] have analyzed the problem on flow of nanofluid with natural convective boundary layer by considering horizontal porous plate. They talk about the thermal and concentration properties of nanofluids by incorporating the impacts of Brownian motion and thermophoresis and computed the numerical solutions of governing problems. Gireesha et al. [5] have investigated the effect of dust particles suspended in a nanofluid flow past a stretching surface. In addition, Turkyilmazoglu [6] utilized the water-aluminum nanofluid to increase the performance of the direct absorption solar collector.

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Nomenclature

$\{O, x, y\}$	Cartesian coordinate system [m]
u, v	velocity components $[\text{m s}^{-1}]$
t	time [s]
a, b	stretching constants $[\text{s}^{-1}]$
T	temperature of fluid [K]
T_w	temperature at the surface [K]
T_∞	ambient temperature [K]
C	nanoparticles concentration
C_w	concentration at the surface
C_∞	ambient nanoparticles concentration
D_B	Brownian diffusion coefficient $[\text{m}^2/\text{s}]$
D_T	thermophoresis diffusion coefficient $[\text{m}^2/\text{s}]$
N_b	Brownian motion parameter
N_t	thermophoresis parameter
B_0	magnetic field strength [A/m]
T_0	initial reference temperature
U_w	stretching sheet velocity [m/s]
U_e	free stream velocity [m/s]
m, c	constant
C_{fx}	skin friction coefficient
Nu_x	local Nusselt number
Sh_x	Sherwood number
Pr	Prandtl number
Re	local Reynolds number
k	thermal conductivity [W/m K]
m	stretching parameter $[\text{s}^{-1}]$
f	dimensionless stream function
We	local Weissenberg number
Le	lewis number
Ha	Hartmann number
A	unsteadiness parameter
C_0	initial reference concentration
q_w	surface heat flux
q_m	surface mass flux
$(\rho c)_p$	heat capacity of nanofluid
$(\rho c)_f$	heat capacity of base fluid
c_p	specific heat $[\text{J kg}^{-1}\text{ K}^{-1}]$

Greek symbols

Γ	relaxation time [s]
μ	generalized Newtonian viscosity
μ_0	zero shear viscosity $[\text{N s/m}^2]$
μ_∞	infinite shear viscosity $[\text{N s/m}^2]$
$\dot{\gamma}$	rate of deformation
ν	kinematic viscosity $[\text{m}^2/\text{s}]$
ψ	stream function
τ_w	surface shear stress $[\text{N m}^{-2}]$
θ	dimensionless temperature
ϕ	dimensionless concentration
η	dimensionless variable
α	thermal diffusivity $[\text{m}^2\text{ s}^{-1}]$
τ	parameter defined by $\frac{(\rho c)_p}{(\rho c)_f}$
λ	velocity ratio parameter
β^*	ratio of viscosities
Ω	total wedge angle
γ	generalized Biot number
β	wedge angle parameter
σ	electrical conductivity $[S/m]$
ρ	fluid density $[\text{kg/m}^3]$

Hashim and Khan [7] performed a numerical analysis on the flow and heat transfer analysis of a non-Newtonian fluid in the presence of nanoparticles. They accomplished the solution of their leading problem by utilizing Runge-Kutta scheme. A theoretical endeavor to scrutinize the natural convection flow in a partially heated trapezoidal cavity filled with nanofluid is given by Haq et al. [8]. They employed the finite element method to simulate the flow analysis. Some recent theoretical studies on flow of nanofluids with effects of different physical phenomena are mentioned in the works of Sheikholeslami and Chamkha [9], Rashid et al. [10], Turkyilmazoglu [11], Khan et al. [12] and Garoosi and Rashidi [13], etc.

As elaborated earlier, the phenomenon of boundary layer flows with heat and mass transfer past a wedge shaped bodies has received much interest in past few years owing to its occurrence in engineering and industrial processes. It has applications in industrial processes, like, geothermal systems, thermal insulation, oil exploration, nuclear reactors, heat exchangers and the storage of nuclear waste, thermal insulation inside aircraft cabins, and so forth. Earlier in 1931, Falkner and Skan [14] presented a mathematical model for the boundary layer flow past a static wedge by considering the viscous fluid and give the Falkner-Skan equation. After that, various important features of flow and heat transfer analysis over a wedge shape geometry has been scrutinized by various researchers. The initial work of Falkner-Skan [14] has been extended by Rajagopal et al. [15]. They employed the non-Newtonian second grade fluid to explore the flow and heat transfer over a static wedge situated inside the fluid. Later on, Lin and Lin [16] have scrutinized the force convection flow and heat transfer past a wedge. They provided the exact results for wall heat transfer from either an isothermal or uniform flux wedge to fluids for any value of Prandtl number. The impact of thermal and concentration diffusions on a mixed convection MHD Falkner-Skan flow with convective boundary condition was studied by Khan et al. [17]. The Falkner-Skan equation by considering the velocity slip at the wedge's wall was studied by Turkyilmazoglu [18]. He utilized the analytical approach to obtain the exact multiple solutions for the momentum and thermal boundary layers. Later on, Khan and Hashim [19] has deliberated the flow of non-Newtonian fluid over a wedge shape geometry by taking into account the effects of multiple slips, chemical reaction and variable thermal conductivity.

This research intends to deliberate the time dependent flow of a non-Newtonian Williamson fluid past a wedge shaped geometry. The novelty of this work is to develop a mathematical model for two-dimensional flow by incorporating the non-zero infinite shear rate viscosity. To the ability of authors' knowledge, not much consideration have thus far been communicated in the literature with regard to convective heat transfer in the flow of Williamson fluid in presence of external magnetic field and nanoparticles. Because of that, we made an attempt to investigate the said situation here. Flow analysis is investigated through a wedge shape geometry which is imperiled to a transverse magnetic field normal to the wedge surface. The impacts of Brownian motion together with thermophoresis have been explored by practicing Buongiorno's model of nanofluids. A set of governing ordinary differential equations is achieve via compatible dimensionless variables and laws of conservation, which results in highly nonlinear ordinary differential equations. This arising mathematical modeling is numerically integrated with the implementation of Runge-Kutta Fehlberg scheme coupled with Nachtsheim-Swigert shooting method. The nanofluid velocity, thermal and nanoparticles concentration fields are demonstrated graphically and in tabular form in perspective of various active parameters. A detailed analysis is carried out to examine the plots for diverse parameters of interest such as: