Advanced Powder Technology 27 (2016) 2448–2456

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Enhanced heat transfer in liquid thin film flow of non-Newtonian nanofluids embedded with graphene nanoparticles

N. Sandeep [a], A. Malvandi [b,*]

[a] Department of Mathematics, VIT University, Vellore 632014, India
[b] Department of Mechanical Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran

ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form 10 August 2016
Accepted 29 August 2016
Available online 9 September 2016

Keywords:
Graphene nanoparticles
MHD
Liquid film flow
Non-uniform heat source/sink
Non-Newtonian nanofluid

ABSTRACT

Recent days, graphene is emanating as one of the most encouraging nanomaterials due to its continuous electrical conducting behaviour even at zero carrier concentrations. Heat transfer in non-Newtonian fluids plays a major role in technology and in nature due to its stress relaxation, shear thinning and thickening properties. With this incentive, we investigate the flow and heat transfer characteristics of electrically conducting liquid film flow of water based non-Newtonian nanofluids dispensed with graphene nanoparticles. For this investigation, we proposed a mathematical model for the flow of Jeffrey, Maxwell and Oldroyd-B nanofluids past a stretching surface in the presence of transverse magnetic field and non-uniform heat source/sink. Numerical results are carried out by employing Runge-Kutta-Felhberg integration scheme. The influence of pertinent parameters on reduced Nusselt number, friction factor, flow and heat transfer is discussed with the assistance of graphs. Embedding the graphene nanoparticles effectively enhances the thermal conductivity of Jeffrey nanofluid when compared with the Oldroyd-B and Maxwell nanofluids. Deborah number in terms of relaxation time plays a major role in convective heat transfer.

1. Introduction

Nowadays, heat transfer of liquid film flow plays a major role in understanding the heat exchangers design, paper production, wire coating, cooling process, etc. Heat transfer of non-Newtonian flows has wide range of applications in design of industrial equipment, polymer sheet manufacturing, food stuffs, etc. To increase the thermal conductivity of the base fluids, nanometer sized high thermal conductivity nano-materials are suspended in base fluids and named it as nanofluid. Recent days, nanofluids are playing important role in cooling and heating applications. Graphene is one of the most encouraging nanomaterials due to its continuous electrical conducting behaviour even at zero carrier concentration. The electron movement in graphene is very high when compared with the other existing materials. External magnetic fields are capable to set the thermal and physical properties of magnetic-nanofluids and regulate the flow and heat transfer characteristics. This is very helpful in metallurgical and controlling process. Heat transfer process is non-uniform in the nature. It is depends on the temperature and the existed space differences. The space and temperature dependent heat source/sink helps to regulate the heat transfer performance of the existed phenomena.

In view of all the above mentioned applications, the study of flow and convective heat transfer in electrically conducting liquid film flow of water based non-Newtonian nanofluids dispensed with graphene nanoparticles in the presence of non-uniform heat source/sink have a great importance in industry as well as in engineering applications. But Navier-Stokes equations are not enough to elaborate the rheological properties of the fluids. The boundary layer behaviour of MHD flow over a stretching surface was initially discussed by Sakiadas [1]. Wang [2] was the first person who discussed about the thin film flow over a stretching sheet. Further, Andersson et al. [3,4] developed the Wang's work by considering the power-law fluid under variable physical properties. Later on Wang and Pop [5] proposed a homotopy analysis method to analyze the heat transfer characteristics of liquid film flow of power-law fluid. In all the above existed nanofluid flow models, nanoparticles are passively involved in enhancing the thermal conductivity of the flow. In 2006, Buongiorno [6] proposed a mathematical model for active participation of the nanoparticles to enhance the effective thermal conductivity of the nanofluid. Further, the researchers [7–9] discussed the heat transfer characteristics of the liquid film flow of Newtonian and non-Newtonian

* Corresponding author.
E-mail address: amirmalvandi@aut.ac.ir (A. Malvandi).

http://dx.doi.org/10.1016/j.apt.2016.08.023
0921-8831/

Nomenclature

u, v	velocity components along x and y directions (m s^{-1})
$u_w(x)$	stretching velocity of the sheet (m s^{-1})
c_p	specific heat capacitance
B_0	applied magnetic field strength
A^*, B^*	non-uniform heat source/sink parameters
S	unsteadiness parameter
C_{fx}	skin friction coefficient
f	dimensionless velocity
k	thermal conductivity (W m^{-1} K^{-1})
M	magnetic field parameter
Nu_x	local Nusselt number
Pr	Prandtl number
Re_x	local reynolds number
T	temperature of the fluid (K)
T_∞	temperature of the fluid in the free stream (K)

Greek symbols

ϕ	solid volume fraction of the nanoparticles
λ	dimensionless film thickness
γ_1	relaxation time
γ_2	ratio of the relaxation and retardation times
γ_3	retardation time
δ_1	Deborah number with respect to relaxation time
δ_2	Deborah number with respect to ratio of relaxation and retardation time
δ_3	Deborah number with respect to retardation time
ξ	stream function
ζ	similarity variable
σ	electrical conductivity (m Ω m^{-1})
θ	dimensionless temperature
ρ	fluid density (kg m^{-3})
μ	dynamic viscosity (Pa S)
υ	kinematic viscosity (m^2 s^{-1})
ε_1 to ε_5	nanofluid constants

Subscripts

f	base fluid
nf	nanofluid
s	solid nanoparticle

flows over a stretching sheet by considering the various physical properties. The non-Newtonian fluid properties for modeling the engineering problems were studied by Chhabra [10].

To enhance the cyclic performance of lithium ion batteries Wu et al. [11] used graphene doped Co_3O_4 nanoparticles and found the enhanced reversible life of the battery. Further, the researchers [12–14] used graphene based composites for energy storage in tribological and electronics applications. Deborah and Erickson number predictions for non-Newtonian flow models were studied by Kelin et al. [15]. Liquid film flow over a graphene-mica slit pore was experimentally investigated by Severin et al. [16]. The thermal properties of graphene and its applications were experimentally studied by the researchers [17–19]. The flow and heat transfer characteristics of chemically reacting couple stress, Power-Law and Maxwell fluids are respectively studied by the researchers [20–22]. Flow boiling characteristics of water-graphene nanofluid and graphene thin film flow with chemical deposition was illustrated by the authors [23,24]. Flow and heat transfer characteristics of Jeffrey, Maxwell and Oldroyd-B fluids over a stretching/shrinking sheet was individually studied by the researchers [25–28]. The heat transfer in magnetohydrodynamic thin film flow of a second grade fluid past a vertical belt was numerically studied by Gul et al. [29]. Applications and properties of graphene doped materials was experimentally studied by Rao et al. [30]. Effect of variable thermal conductivity on Maxwell fluid flow over a stretching sheet in porous medium was numerically elaborated by Singh and Agarwal [31].

Unsteady thin film flow of Newtonian and non-Newtonian magnetic-flows over a stretching sheet by considering the viscous dissipation, internal heat generation, thermal radiation and variable thermal conductivity effects was studied by the researchers [32–35]. Recently, the researchers [36–38] analyzed the heat and mass transfer in Newtonian and non-Newtonian flows past uniform/non-uniform thickness stretching sheet by considering the various physical effects and presented dual solutions for each case. Adegbie et al. [39] studied the heat and mass transfer in Maxwell nanofluid flow over a melting surface with variable thermophysical properties. Further, the researchers [40–42] continued their research on analyzing the heat and mass transfer characteristics of MHD flows by considering the Oldroyd-B fluid. Recently, Malvandi et al. [43–45] studied the film boiling of magnetic nanofluid over a vertical plate by considering the thermophoresis and Brownian motion effects.

Raju et al. [46] developed a mathematical model for the flow of thee different types of non-Newtonian fluids over a cone. Very recently, Yadav et al. [47–50] studied the free convective heat transfer in rotating nanofluid layer by considering the rotating porous medium with variable physical aspects. Effect of magnetic field on the free convection of onset of nanofluid was numerically investigated by Yadv et al. [51]. Further, the researchers [52–55] studied the natural convection of magnetohydrodynamic flow in vertically orientated Hele-Shaw cell suspending with the nanoparticles. Nanoparticle migration effect on heat transfer enhancement of nanofluid over a vertical cylinder was numerically studied by Malvandi et al. [56–58]. The researchers [59–62] studied the effect of various physical parameters on MHD flow of nanofluid by considering the uniform and non-uniform thickness stretching surfaces, upper paraboloid of revolution and film flow over a stretching surface.

In all the above investigations, authors discussed the heat or heat and mass transfer characteristics of either Newtonian or non-Newtonian flows over a steady or unsteady stretching sheet with one or more physical aspects. But to the author's best knowledge no studies has been reported yet on analyzing the flow and heat transfer characteristics of electrically conducting liquid film flow of water based non-Newtonian nanofluids dispensed with graphene nanoparticles. For this investigation, we proposed a combined model for the flow of Jeffrey, Maxwell and Oldroyd-B nanofluids past a stretching surface in the presence of transverse magnetic field and non-uniform heat source/sink. Numerical results are carried out by enforcing Runge-Kutta-Felhberg integration scheme. Obtained results are discussed with the help of graphs.

2. Mathematical formulation

Consider an unsteady, electrically conducting liquid film flow of magnetohydrodynamic Jeffrey, Maxwell and Oldroyd-B nanofluids past a stretching surface. The elastic sheet starts from a narrow slit, which is located at the origin of a coordinate system (x, y). Here x-axis is measured along the stretching surface with stretched velocity $u_w(x, t) = bx/(1 - \alpha t)$, where b, α constants and y-axis is