Results in Physics 8 (2018) 569–577

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

Three dimensional rotating flow of Powell-Eyring nanofluid with non-Fourier's heat flux and non-Fick's mass flux theory

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ARTICLE INFO

Article history:
Received 25 October 2017
Received in revised form 25 November 2017
Accepted 11 December 2017
Available online 30 December 2017

Keywords:
Three dimensional flow
Powell-Eyring nanofluid
Rotating flow
Non-Fourier flux theory

ABSTRACT

This article numerically examines three dimensional boundary layer flow of a rotating Powell-Eyring nanofluid. In modeling heat transfer processes, non-Fourier heat flux theory and for mass transfer non-Fick's mass flux theory are employed. This theory is recently re-initiated and it becomes the active research area to resolves some drawback associated with the famous Fourier heat flux and mass flux theory. The mathematical model of the flow problem is a system of non-linear partial differential equations which are obtained using the boundary layer analysis. The non-linear partial differential equations have been transformed into non-linear high order ordinary differential equations using similarity transformation. Employing bvp4c algorithm from matlab software routine, the numerical solution of the transformed ordinary differential equations is obtained. The governing equations are constrained by parameters such as rotation parameter λ, the non-Newtonian parameter N, dimensionless thermal relaxation and concentration relaxation parameters δ_t and δ_c. The impacts of these parameters have been discussed thoroughly and illustrated using graphs and tables. The findings show that thermal relaxation time δ_t reduces the thermal and concentration boundary layer thickness. Further, the results reveal that the rotational parameter λ has the effect of decreasing the velocity boundary layer thickness in both x and y directions. Further examination pinpoints that the skin friction coefficient along x-axis is an increasing and skin friction coefficient along y-axis is a decreasing function of rotation parameter λ. Furthermore, the non-Newtonian fluid parameter N has the characteristic of reducing the amount of local Nusselt numbers $-f''(0)$ and $-g''(0)$ both in x and y -directions.

Introduction

The study of the modified form of Fourier heat flux theory is the recent active research area in fluid heat transfer analysis. The theory is based on the addition of time relaxation term to Fourier heat flux model. The famous Fourier heat conduction theory has a limitation in that it doesn't have a room for time relaxation. Therefore, the recent modified model of the old heat conduction formula believed to be resolving the drawback associated with Fourier heat flux model. Many research activities have been carried out on non-Fourier heat flux model to come up with the possible solution to the drawback. Accordingly, Christove [1] give a new formulation of the Maxwell-Cattaneo model of heat conduction. Besides, Hayat et al. [2] have examined the rotating flow of Jeffery fluid with non-Fourier heat flux model. The finding reveals that the thermal relaxation time reduces the temperature. Further, Hayat et al. [3] studied the characteristics of thermal and concentration diffusion for three dimensional flow of nanofluid using non-Fourier heat flux model. The results of the study signify that thermal and concentration relaxation parameters have a reduction effect on temperature and concentration profiles. Furthermore, Hayat et al. [4] studied a double – diffusion flow of viscoelastic Nanofluids with Cattaneo-Christov model. Moreover, the impact of non-Fourier heat flux on the flow of Maxwell fluid past a stretching sheet with variable thickness was discussed by Hayat et al. [5]. The numerical solution for Sakiadis flow of upper-convected Maxwell fluid using Cattaneo-Christov heat flux model was analyzed by the researchers Mushtaq et al. [6]. Still further, Sui et al. [7] investigated the heat and mass diffusion with Cattaneoe-Christov model in upper-convected Maxwell nanofluid past a stretching sheet with slip velocity boundary condition.

The application of the non-Fourier heat flux model further extended to the more complex non-Newtonian fluid called Carreau fluid and analyzed by Hahim and Khan [8] considering slendering sheet. The numerical investigation of Cattaneo-Christov heat flux mode on the area of a non-Newtonian fluid has got a momentum. In line with this, Khan et al. [9] have examined the effect of

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https://doi.org/10.1016/j.rinp.2017.12.034
2211-3797/

Nomenclature

C_f	Skin friction coefficient
C_w	Concentration at the surface of the sheet
C_∞	Ambient concentration
D_B	Brownian diffusion coefficient
D_T	Thermophoresis diffusion coefficient
f	Dimensionless stream function
k	Thermal conductivity
k^*	Mean absorption coefficient
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
T	Temperature of the fluid inside the boundary layer
T_w	Temperature at the surface of the sheet
T_∞	Ambient temperature
u, v	Velocity component along x- and y-direction

Greeks

λ_E	The thermal relaxation time
λ_C	The concentration relaxation time
η	Dimensionless similarity variable
ϕ	Dimensionless concentration function
δ_t	thermal relaxation parameter
δ_c	concentration relaxation parameter
μ	Dynamic viscosity of the fluid
υ	Kinematic viscosity of the fluid
$(\rho)_f$	Density of the basefluid
$(\rho c)_f$	Heat capacity of the base fluid
$(\rho c)_p$	Effective heat capacity of a nanoparticle
λ	rotation parameter
ψ	Stream function
θ	Dimensionless tempreture
Γ	The extra stress tensor
Ω	Angular velocity
Λ	Parameter defined by $\frac{(\rho c)_p}{(\rho c)_f}$

Subscripts

∞	Condition at the free stream
w	Condition at the surface

non-Fourier heat flux model on viscoelastic fluid. Furthermore, Abbasi et al. [10] have examined the non-Newtonian Oldroyed-B fluid with variable thermal conductivity employing the Cattaneo-Christove heat flux model. Also, Hayat et al. [11] have applied the Cattaneo-Christov heat flux model on the study of Maxwell fluid with Darcy-Forchheimer flow and variable thermal conductivity. The result reveals that the porosity enhances the velocity and inhibits the temperature. Furthermore, Kahansa and Mustafa [12] have examined MHD three-dimensional flow of upper-convected Maxwell fluid over a bi-directional stretching surface by considering the Cattaneo-Christov heat flux model. Nadeem and Muhammed [13] are also examined the influence of stratification and Cattaneo-Christov heat flux in the flow saturated with porous medium. The findings indicate that an increase in thermal relaxation parameter outcomes in the reduction of the temperature field. Hayat et al. [14] have discussed on doubly stratified chemically reactive flow of non-newtonian fluid called Powell-Eyring liquid subject to time relaxation term on Fourier heat flux theory.It is indicated that thermal and concentration stratification parameters reduces the concentration and concentration graphs. Further, very recently, Liu et al. [15] analyzed heat conduction with fractional Cattaneo-Christov upper-convective derivative flux model. The outcome shows that temperature profiles are monotonically decreases with time fractional parameter with time relaxation parameter. Further examination of the thermal convection with the Cattaneo Christov model has been examined by Straughan [16]. Moreover, the study of Cattaneo-Christove heat flux model was applied to the non-Newtonian fluid called Williamson fluid past a stretching sheet with variable thickness by Salahuddin et al. [17].

The rotating flow of a fluid past a stretching surface has been presented by many scholars. Accordingly, the pioneering study on a rotation flow was discussed by Wang [18]. Later, Kumari and Pop [19] also examined the rotating flow of a non-Newtonian fluid called power-law fluid. The analysis of the study comes up with the result both the x and y-direction skin friction coefficients are reduced by rotation parameter. Further, Shafiq et al. [20] have examined the heat and mass transfer effects of a rotating flow of Maxwell fluid due to stretching surface. Still further, Mustafa [21] examined heat and mass transfer of the rotating flow of Maxwell fluid using Catteneo-Christove heat flux model. The impact of Cattaneo-Christove model on the peristalsis flow was analysed by Tanveer et al. [22]. The stagnation point flow of of Eyring-Powell liquid towards a nonlinear stretched surface with Cattaneo-Christove model was reported by Hayat et al. [23]. Very recently Hayat et al. [24] further examined the effect of the Cattaneo-Christove model on Powell-Eyring fluid with variable thermal conductivity. Again recently, Xiaoqin and Shumei [25] have utilized Cattaneo-Christov heat flux to explore the heat transfer characteristic of Marangoni boundary layer flow in a copper water nanofluid. The comprehensive review of three dimensional flow of different kinds of fluids are given in the references [26–33].

The study of Powell-Eyring nanofluid has not be given wide coverage. Few literatures are available about Powell-Eyring. To list some of them Hayat et al. [34] studied the effect of magnetic field on Powell-Eyring nanofluid past a stretching non-uniform thickness. Javed et al. [35] have discussed the flow of an Eyring-Powell non-Newtonian fluid over a stretching sheet However, the effect of rotation on Powell-Eyring nanofluid with non-Fourier heat flux theory and non-Ficks mass flux theory not yet studied. Therefor, the investigator of the present study aimed to fill the knowledge gape.

Powell-Eyring fluid

In this analysis non-Newtonian fluid called Powell-Eyring fluids is studied. Mathematical modeling of the Powell-Eyring fluid is given by [35]

$$A = -PI + \Gamma \tag{1}$$

where P is the principal stress tensor and Γ is the extra stress tensor and Γ is defined as:

$$\Gamma = \mu A_1 + \frac{1}{\beta\dot{\gamma}} sinh^{-1}\left(\frac{1}{d}\dot{\gamma}\right)A_1 \tag{2}$$

by the same author. Here μ is dynamic viscosity, β and C are the rheological Powell- Eyring fluid model parameters. Using Taylor