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Nanofluid flow through a porous space with convective conditions and heterogeneous–homogeneous reactions

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A B S T R A C T

Present analysis deals with the nanofluid flow due to a cylinder. Heat transfer mechanism is inspected under the physically acceptable convective type conditions. A simple isothermal model of homogeneous–heterogeneous reactions is used to regulate the solute concentration. Thermodynamics processes of homogeneous–heterogeneous reactions analyze the effect of temperature phase changes, such as convection or evaporation. It is assumed that the base fluid (water) is essentially composed of single and multi walled carbon nanotubes. Uniformly valid convergent series expressions are obtained with the help of optimal homotopic approach. Impacts of embedded flow parameters are visualized through graphical illustrations. Fluid velocity displays decreasing trend near the cylinder as the curvature parameter is incremented. Interestingly, such result is not preserved far from the cylinder. The simulations predict that wall heat flux is inversely proportional to both curvature parameter and the convecting heating strength. However, value of heat flux is predicted to be larger in case of larger volume fraction of carbon nanotubes. Moreover heat transfer coefficient is more in single wall carbon nanotubes (SWCNTs) when compared with multi wall carbon nanotubes (MWCNTs). Heterogeneous and homogeneous reactions have opposite behaviors on nanoparticle concentration distribution. Drag coefficient at the cylinder enhances when larger curvature parameter is accounted. Comparison of present study with previous published work is given. The results are found in good agreement.

1. Introduction

It is known that nanofluids can overcome the issues associated with several materials of low thermal conductivity such as ethylene glycol, water, oil etc. Nanofluids consist of colloidal suspensions of nanoscale materials in liquid carrier. Nanofluids have fascinating applications in thermal engineering, heat exchangers, chemical processes, electronic devices, cancer therapy, bio medicine etc. Nanofluids are smart coolants which possess exceptional thermal performance at low particle concentrations. Researchers have shown that effective thermal conductivity for nanofluids is measurably elevated and hence potential applications of nanofluids to micro scale heat transfer are obvious. Especially, two phase flow problems have key role petroleum industries, waste water treatment, combustion and smoke emission from automobiles [1–5]. Choi [6] firstly used the terminology of nanofluids when he observed an anomalous rise thermal conductivity by filling water with copper nanoparticles. Solar energy is globally recognized as easily accessible as well as pollution free source of renewable energy. A device that converts solar radiation into heat energy is the solar collector. It has been demonstrated that replacement of water with nanofluid boosts the efficiency of these collectors [7]. The improved cooling capability of nanofluids is expected to meet the growing challenges of heat transfer in applications involving microchips in computer processors, hybrid-powered engines, refrigeration/air-conditioning, diesel engine oil etc. Rashidi et al. [8] carried out entropy generation analysis for nanofluid flow near a rotating disk with uniform suction. Sheikholeslami et al. [9] considered thermal energy transport in nanofluid flow across a porous stretchable wall. Bhattacharyya et al. [10] presented numerical approximations for nanofluid flow due to exponential shrinking surface. Free convection effect in nanofluid is reported by Sheikholeslami et al. [11] using two-phase model. Imtiaz et al. [12] discussed the effects of boundary slip on nanofluid flow subject to on-linear radiation. Turkyilmazoglu [13] addressed the time-dependent flow of nanofluid due to impulsive motion of

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vertical flat plate. Shehzad et al. [14] examined the flow of Jeffrey fluid containing nanoparticles using convective type conditions. Kameswaran et al. [15] examined the convective/radiative heat transfer for nanofluid flow past a permeable surface via convective conditions. Zheng et al. [16] analyzed the nanofluid flow in the regimes of variable heat flux and chemically reactive species. Magnetic field influence on buoyancy driven flow of CuO-water nanofluid in a cavity was presented by Sheikholeslami et al. [17]. Application of time-varying magnetic force on nanofluid flow confined between parallel flat surfaces was studied by Sheikholeslami et al. [18]. Onset of free convection in nanofluid flow through an eccentric semi annulus was described by Shekholeslami et al. [19]. Zeeshan et al. [20] studied the ferrofluid flow by a stretchable surface. Nanofluid flow comprising carbon nanotubes over a non-linearly deforming surface with variable thickness was reported by Hayat et al. [21]. Three dimensional natural convection of nanofluid has been studied by Sheikholeslami and Ellahi [22]. Hayat et al. [23] addressed nanofluid flow past a non-linearly deforming surface with chemically reactive species. Akbarzadeh et al. [24] investigated thermal and pumping power effects on nanofluid flow through a wavy channel. Hayat et al. [25] addressed nanofluid flow under the influence of homogeneous–heterogeneous reactions and melting heat transfer with CNTs. Sheikholesami et al. [26] analyzed radiative flow of nanofluid. Ellahi et al. [27] examined buoyancy effects on laminar flow of Al_2O_3-water nanofluid by a porous wedge. Ellahi et al. [28] addressed mixed convection flow of nanofluid by a permeable stretching sheet. Sheikholeslami et al. [29] addressed the buoyancy induced flow of nanofluid in three-dimensions. Sheikholeslami et al. [30] also considered two-phase model to examine energy transfer in magneto-nanofluid. Temperature variation and heat flux at the sheet are considered in numerous studies. Convective condition has been given little attention in the past in spite of its wide utilization in processes related to nuclear plants, material drying, thermal energy storage and others. Buoyancy effects on nanofluid flow driven by a power-law deforming surface were examined by Waqas et al. [31]. Hall effects on peristaltic motion of Carreau–Yasuda fluid with radially varying magnetic force and convective condition were analyzed by Hayat et al. [32]. Buoyancy assisting flow of Casson nanofluid driven by convectively heated boundary was explored by Rauf et al. [33]. Hayat et al. [34] examined the MHD flow of Sisko nanofluid induced by a convectively heated wall. Oyelakin et al. [35] reported effects of thermal radiation, convective and slip conditions on unsteady flow of Casson nanofluid near a deforming surface.

The natural processes of chemical reactions connect mutually with homogeneous and heterogeneous reactions. A number of the reactions progress gradually or instantly in absence of a catalyst. The relations between the homogeneous and heterogeneous reactions are very composite. Hayat et al. [36] investigated chemical reaction effects on three dimensional flow of couple stress fluid due to unsteady deforming sheet. Rashidi et al. [37] studied mixed convective heat/mass transfer in chemically reactive flow across a horizontal surface. Bhattacharyya [38] analyzed the aspect of chemical reaction for laminar flow past a shrinking boundary. Merkin et al. [39] analyzed homogeneous–heterogeneous reactions in boundary-layer flow governed by a simple isothermal model.

Our main interest here is to discuss the heterogeneous–homogeneous chemical reaction for nanofluid flow past a stretching cylinder. The behavior of base fluid with single and multi-wall carbon nanotubes observed. Convective boundary conditions are employed to inspect the heat transfer. Optimal Homotopy Analysis (OHAM) approach [40–49] is utilized to achieve the convergent series solutions of momentum, energy and concentration equations. Skin friction coefficient and Nusselt number corresponding to various physical parameters are calculated and analyzed graphically.

Nomenclature

k_f	thermal conductivity of fluid
l	characteristics length
k_{CNT}	thermal conductivity of carbon nanotubes
A, **B**	chemical species
D_A, D_B	Diffusion coefficients of chemical species
f	dimensionless stream function
T_f	temperature of hot fluid
C_f	skin friction coefficient
q_w	surface heat flux
Re_z	local Reynolds number
γ	curvature parameter
h_f, h_θ, h_φ	auxiliary parameters
k^*	permeability of porous medium
U_0	reference velocity
Sc	Schmidt number
Ks	heterogeneous reaction parameter
δ	ratio of diffusion coefficients
OHAM	optimal homotopy analysis method
MWCNT	multi wall carbon nanotube

Greek symbols

μ_f	dynamic viscosity of fluid
ν_f	kinematic viscosity of fluid
$(c_p)_{nf}$	specific heat at constant pressure of nanofluid
ν_{nf}	kinematic viscosity of nanofluid
$(c_p)_{CNT}$	specific heat at constant pressure of carbon nanotubes
ρ_{nf}	density of nanofluid
θ	dimensionless temperature
η	similarity variable
k_{nf}	thermal conductivity of nanofluid
h_f	heat transfer coefficient
a, b	concentrations of chemical species **A**, **B**, respectively
k_s, k_r	rate constants
T	temperature of fluid
T_∞	ambient temperature of fluid
Nu_z	local Nusselt number
τ_w	surface shear stress
R	radius of cylinder
u, w	velocity components in $r-$ and $z-$ directions, respectively
r, z	cylindrical coordinates along the surface and normal to it respectively
w_e	velocity of stretching cylinder
k_1	porous medium parameter
Pr	Prandtl number for base fluid water
K	homogeneous reaction parameter
B_i	Biot number
SWCNT	single wall carbon nanotube
CNT	carbon nanotube
ρ_f	density of fluid
c_p	specific heat at constant pressure
μ_{nf}	dynamic viscosity of nanofluid
α_{nf}	thermal diffusivity of nanofluid
$(\rho)_{CNT}$	density of carbon nanotubes
ϕ	volume fraction of nanoparticle
φ	dimensionless concentration

We have employed the well-known Tiwari and Das model for investigation of thermal energy transport in nanofluids. It should be emphasized that particle size, volume fraction, thermal conductivity and temperature contribute to the improved thermal behavior of nanofluids. Besides this, Brownian motion and