Journal of Molecular Liquids 220 (2016) 200–207

Contents lists available at ScienceDirect

Journal of Molecular Liquids

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

Heterogeneous-homogeneous reactions and melting heat transfer effects in flow with carbon nanotubes

T. Hayat [a,b], Zakir Hussain [a,*], A. Alsaedi [b], B. Ahmad [b]

[a] Department of Mathematics, Quaid-I-Azam University, Islamabad 44000, Pakistan
[b] Nonlinear Analysis and Applied Mathematics (NAAM) Research Group, Department of Mathematics, Faculty of Science, King Abdulaziz University, P. O. Box 80257, Jeddah 21589, Saudi Arabia

ARTICLE INFO

Article history:
Received 21 February 2016
Accepted 6 April 2016
Available online xxxx

Keywords:
Heterogeneous-homogeneous reactions
Carbon nanotubes
Porous medium
Melting heat

ABSTRACT

The communication here addresses the impact of heterogeneous-homogeneous reactions in boundary layer flow of nanofluid saturating porous medium. The stretching cylinder caused the flow in presence of melting heat transfer. Analysis for single-wall carbon nanotubes (SWNTs) and multi-wall carbon nanotubes (MWNTs) is explored. Water is taken as the base fluid. Auto catalyst and reactant both have same diffusion coefficient. Boundary layer problems are computed for the velocity, temperature and concentration. Resulting differential systems are evaluated for the convergent series solutions. Outcomes for the velocity $f'(\eta)$, temperature $\theta(\eta)$ and concentration $\varphi(\eta)$ are examined. The skin friction coefficient $f''(0)$ and Nusselt number $\theta'(0)$ are also explored. It is found that temperature $\theta(\eta)$ and velocity $f'(\eta)$ have reverse effects for melting parameter M. Concentration distribution $\varphi(\eta)$ is decreasing function of homogeneous reaction parameter K while opposite influence of heterogeneous reaction appears. Maximum heat transfer and minimum thermal resistance are noticed for MWCNTs than SWNTs.

1. Introduction

Recent scientists and engineers are stimulated in discovering new energy resources and energy technologies to make use of solar energy. Clearly the global energy consumption is 2000 times less when compared with solar energy. The concept of nanofluid arose for the thermal enhancement of traditional fluids like water, ethylene glycol and oil. It is now recognized fact that the thermal characteristics can be improved by advancing nanoparticles with low volume fraction and high thermal characteristics. Metals, carbides, oxides, carbon nanotubes (CNTs) are the typical nanoparticles. The carbon nanotubes due to its integrally special chemical and physical characteristics can be marked as an auspicious materials in nanomaterials. Single-walled carbon nanotubes and multi-wall carbon nanotubes are frequently utilized CNTs. There is only single layer of graphene cylinder in SWNTs and many layers in the MWNTs. The carbon nanotubes have exceptional mechanical properties and thermal conductivity. Mechanical behavior of base materials and thermal characteristics enhance effectively by mixing them in solid or fluid. The first experimental observation is performed by Choi et al. [1] using multi walled nanotubes for the enhancement of thermal conductivity. It is concluded that MWNTs dissolved in oil increase 160 (percentage) the thermal conductivity. Bakhshan [2] investigated Al_2O_3, diamond and MWCNTs as the base fluids. Rashidi et al. [3] investigated magnetohydrodynamic flow of nanofluid induced by a rotating porous disk with entropy generation. Sheikholeslami et al. [4] observed heat transfer analysis in stretched flow of nanofluid saturating porous medium. Bhattacharyya et al. [5] investigated flow analysis of nanofluid past an exponentially permeable sheet. Natural convection flow of nanofluid with thermal management is studied by Sheikholeslami et al. [6]. Imtiaz et al. [7] analyzed magnetohydrodynamics and velocity slip effects in three dimensional flow of nanofluid. Turkyilmazoglu [8] examined unsteady boundary layer flow of nanofluid by a vertical flat plate. Hayat et al. [9] addressed boundary layer flow of second grade nanofluid in presence of magnetic field. Mabood et al. [10] numerically studied the boundary layer flow of viscous nanofluid over a stretching surface. Rida et al. [11] presented numerical solution for MHD flow of nanofluid by an exponentially stretching sheet without variable thickness. Magnetohydrodynamic flow of nanofluids in the presence of porous medium with variable surface heat flux and chemical reaction is studied by Zheng et al. [12]. Mustafa et al. [13] examined Bodewadt flow of second grade nanofluids by a stretching stationary disk. Hayat et al. [14] analyzed nonlinear thermal radiation in magnetohydrodynamic flow of viscoelastic nanofluid. Melting heat transfer in Falkner-Skan wedge flow of second grade nanofluid is studied by Hayat et al. [15].

Melting characteristics phenomenon has received much attention by its widespread utilization in industries and technologies. Recently scientists have given full attention to develop more sustainable, efficient and low cost energy storage technologies. Such technologies are interconnected with solar energy, waste heat recovery and plants of heat and power. Mainly three methods are used for the storage of energy

* Corresponding author.
E-mail address: zakir.qamar@yahoo.com (Z. Hussain).

http://dx.doi.org/10.1016/j.molliq.2016.04.012
0167-7322/

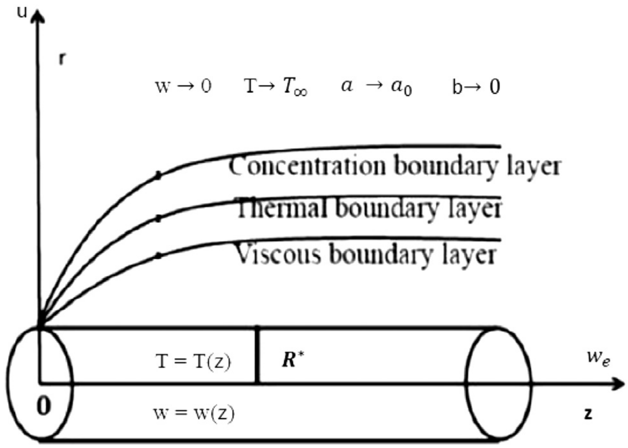

Fig. 1. Geometry of problem.

i.e., sensible heat energy storage, latent heat energy storage and chemical thermal energy storage. However economically more suitable and efficient way of energy storage is the latent heat by changing the phase of materials. Thermal energy is stored in a material through latent heat by melting and again recovered by freezing it. The involvement of such utilization is in freezing of soil in ground based pump, magma solidification, the freeze treatment of sewage, the preparation of semiconductor material, the casting and welding of manufacturing process. Rahman et al. [16] examined melting phenomenon in magnetohydrodynamic (MHD) steady flow and heat transfer over a moving surface with thermal radiation. Melting heat phenomenon of ice slab placed in the stream of hot air is studied first time by Robert [17]. Das [18] explored thermal radiation and melting effects in magnetohydrodynamic boundary layer flow by a surface. Hayat et al. [19] analyzed melting heat characteristics in boundary layer flow of second grade fluid over a surface with Soret and Dufour effects. Farooq et al. [20] studied melting heat transfer in the stagnation point flow of Powell-Eyring fluid. Yacob et al. [21] discussed boundary layer stagnation point flow of micropolar fluid with melting heat towards a plate. Swati [22] demonstrated heat transfer in Casson fluid flow by nonlinearly stretching surface. Bachock et al. [23] studied characteristics of melting heat transfer in stagnation-point boundary layer flow towards a stretching/shrinking sheet. An experimental observation on melting heat characteristics of paraffin in the presence of Al_2O_3 nanoparticles in a vertical enclosure is investigated by Ho et al. [24]. Hayat et al. [25] analyzed melting heat transfer and double diffusive convection in the stagnation point flow of Maxwell fluid. Melting heat transfer and homogenous-heterogeneous reaction effects in viscoelastic fluid flow are reported by Hayat et al. [26]. Impacts of melting heat transfer and Newtonian heating in the stagnation point flow of carbon nanotubes are addressed by Hayat et al. [27]. Melting heat transfer in MHD stagnation point flow of tangent-hyperbolic fluid is explored by Hayat et al. [28]. Hemalatha et al. [29] explained non-Darcy fluid flow by a vertical surface with melting heat transfer and solute dispersion. Merkin et al. [30] described mixed convection flow with porous medium and melting heat. Mahmoud and Waheed [31] discussed flow of micropolar liquid in presence of melting heat transfer. Boundary layer flow of couple stress fluid over a stretching surface with melting heat transfer is examined by Hayat et al. [32]. Melting heat in stagnation point flow of third grade fluid is studied by Hayat et al. [33].

Chemical reactions connect mutually with heterogeneous-homogeneous reactions. There are many reactions with the ability to progress slowly or not at on spot except in involvement of a catalyst. There are very composite relations between the homogeneous and heterogeneous reactions. The establishment and applications have different rates together within the fluid and on the catalyst surface by the reactant species. These reactions occur in burning, catalysis and biochemical mechanism. Hayat et al. [34] explored unsteady flow of couple stress fluid in presence of chemical reaction. Rashidi et al. [35] investigated mixed convection in boundary layer flow with chemical reaction effects. Batacharyya [36] examined stagnation point boundary layer flow with chemical reaction. Here flow is due to stretching/shrinking surface.

The object of present study is to investigate the stretched flow of nanofluid by a cylinder in three dimensions. Firstly to examine melting heat transfer. Secondly to predict the influence of homogeneous and heterogeneous reactions. Thirdly to analyze the porous medium features. Incoming non-dimensionalized nonlinear analysis is computed using homotopy procedure [37–44]. Results of velocity $f'(\eta)$, temperature $\theta(\eta)$, concentration $\varphi(\eta)$, skin friction coefficient $f''(0)$ and local Nusselt number $\theta'(0)$ are obtained and interpreted. The solutions obtained by HAM are preferred than the numerical solutions in view of the following points. (a) HAM gives the solutions within the domain of interest at each point while the numerical solutions hold only for a set of discrete points in the domain. (b) Algebraically produced approximate solutions require less effort and having a reasonable amount of accuracy when compared to numerical solution which is always handy for the scientist, an engineer or an applied mathematician. (c) Although most of the scientific packages required some initial guesses for the solution are not generally convergent. In such conditions approximate solutions can offer better initial guess that can be readily advanced to the exact numerical solution in a limited iterations. Finally an approximate solution, if it is analytical, is most pleasing than the numerical solutions.

2. Formulation

The boundary layer flow of nanofluid by a stretching cylinder is addressed. Effects of melting heat and heterogeneous-homogeneous reactions are considered. We assume that $T_m < T_\infty$, where T_∞ stands for the ambient temperature and T_m the temperature of the melting surface. Heat transfer process does not include the dissipation effects. An incompressible fluid fills the porous medium. Here SWNTs (single wall nanotubes) and MWCNTs (multi-wall carbon nanotubes) are used as the nanoparticles and water as a base fluid. The heat produced is neglected throughout the irreversible chemical reaction. In cubic auto catalysis the homogeneous reaction can be expressed by:

$$\mathbf{A}^* + 2\mathbf{B}^* \rightarrow 3\mathbf{B}^*, \text{rate} = k_r a b^2, \tag{1}$$

isothermal reaction of first order on the catalyst surface is defined by

$$\mathbf{A}^* \rightarrow \mathbf{B}^*, \text{rate} = k_s a \ . \tag{2}$$

Here a and b are the chemical species of concentrations $\mathbf{A}^*$ and $\mathbf{B}^*$ and k_r and k_s indicate the constant rates. The reaction rate is minimum at the outer edge of boundary layer and in the external flow due to this irreversible reaction. Coordinates (cylindrical) are assigned when the z-axis and r-axis are along the normal and the axial direction respectively (Fig. 1). Stretching character of the cylinder is produced by applying two different forces of equal magnitude in opposite direction. The

Table 1
Thermophysical characteristics are elaborated for base fluid and nanoparticles [46].

Physical properties	Base fluid	Nanoparticles	
	Water	SWCNT	MWCNT
$\rho(\text{kg/m}^3)$	997	2600	1600
$c_p(\text{J/kgK})$	4179	425	796
$k(\text{W/mK})$	0.613	6600	3000