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Influence of particulate thermophoresis on convection heat and mass transfer in a slip flow of a viscoelasticity-based micropolar fluid

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ABSTRACT

We focus on the intriguing particulate thermophoresis characterized by multi-dependent Soret number in a shear flow of a viscoelasticity-based micropolar fluid (VMF) over a stretching sheet in the existence of the slip condition. The multi-dependent Soret number involving the temperature field and micro-particle size factors is introduced to analyze the critical role of the particulate thermophoresis on the temperature and concentration profiles of a VMF. Such procedure being significant for convection heat and mass transfer has never yet been considered in the transport system of such non-Newtonian fluids. Theoretically, we find the larger particles more susceptible to the actuation of temperature gradient. The local Sherwood number increases linearly with the bulk temperature difference, while the thickness of the concentration boundary layer are decreased. We also find that the flow relaxation and slip behavior can give rise to the obvious reduction of local Nusselt number and Sherwood number in different ways. Moreover, these two behaviors are found to be inherently divergent in varying the local skin friction. A power law expression can fit well the dependence of the local skin friction on the slip parameter. The practical routes of heat and mass transfer in the complex fluids will be implemented by tuning the various physical parameters presented in this paper.

1. Introduction

Non-Newtonian fluids with complex behavior have been found in numerous natural and engineered systems, for example, bio-fluids in biological tissue and polymers, and colloidal suspensions in engineering applications. Their experimental and theoretical investigations are central themes in rheology, shear flows and thermo-physics actively studied by scientists and engineers. Their complex characteristics, such as thixotropy, yield stress, shear thinning/thickening and viscoelasticity, manifest some extraordinary application prospects or potentials, even though unified views [1,2] have not yet emerged for the time being.

Micropolar fluids (MFs) described by micropolar theories are a kind of the typical non-Newtonian fluids due to the suspended micro-particles [3]. Theoretically, the collective micro-rotation effects of suspended particles of a MF in a shear flow can be modeled by an additional equation with respect to the conservation of the local micro-angular momentum with the spin gradient in the momentum equation, and the material parameter is therefore defined to clarify the non-Newtonian property. Scholars (Eringen, Dahler, Scriven and Condiff et al. [4–7]) have contributed to the pioneering work on the micropolar theories in which the stress tensor was anti-symmetric due to the oriented micro-rotation of particles in a shear flow. Besides, Stokes has discussed the microstructure in MFs by utilizing the gyration tensor restricted [8] in detail and motivated the critical role of couple stresses on MFs by combining variable conditions of a shear flow [9], for instance, hydromagnetic channel flows [10], flow past a sphere [11] and the plane Poiseuill flow [12]. A comprehensive understanding of the development in theories and applications of MFs could also be referred to some excellent review papers [13,14] and monographs [15,16]. As aforementioned, MFs can be treated as the colloidal suspensions with particles medium (discontinuous phase) dispersed in the solvent (continuous phase). These motile micro-particles would give rise to the typical non-Newtonian behaviors as expected in the earlier studies. Peters once reported experimentally that the collective micro-rotation of suspended micro-particles may result in the reduction of the bulk viscosity

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of MFs in a shear flow [17]. In our earlier work [18], this experimental result being akin to a shear-thinning behavior was modeled by employing the generalized power law diffusion theory [19–21] in which the nonlinear rheological and heat-conduction constitutive relationships were constructed, respectively.

To our knowledge, some researchers also considered the nanofluids (dispersing nano-scale particles whose size are smaller than 100 nm) to exhibit micropolar behaviors, and named them as so called "micropolar nanofluids". Apparently, there were little evidences to support the rationalization of such microstructures imposed in the ordinary macroscopic transport processes of nanofluids. Indeed, the further explorations would still be needed that if the collective micro-rotation behavior, i.e., the micro-angular momentum equation, is scientific to be considered for the nano-suspensions with some modified physical parameters including viscosity, density, thermal conductivity [22–25]. But the significant micropolar characteristics are convinced and probed in the homogeneous micro-particles suspensions [17].

Additionally, another important factor to be reckoned with is the physical properties of the based fluids. The majority of previous jobs were focused on the studies of the Newtonian based micropolar fluids, consequently the simple linear rheological model was frequently used in the flow equation. In spite of that, the diverse boundary conditions governing a shear flow are noteworthy. Herein, some typical investigations are reviewed.

Das studied the heat and mass transfer of a hydromagnetic micropolar fluid over an inclined permeable plate by taking the effect of thermophoresis and chemical reaction into account, also the conditions of the non-uniform hear source/sink and thermal radiation were considered [26]. Swapna et al. showed the double-diffusive mixed convection flow of a chemically reacting magneto-micropolar fluid over a wedge [27]. The analogous magnetohydrodynamics (MHD) flow of a MF towards nonlinear stretching surface was addressed by Waqas et al. [28]. Besides, the local slip velocity condition on a permeable stretching sheet was considered by Ramzan [29], and the entropy generation in a MF with slip and convective boundary conditions have also been analyzed by Srinivasacharya [30]. Saqib et al. have shown the effects of the first-order chemical reaction and slip conditions on the heat and mass transfer of a Casson fluid [31]. Recently, the periodic MHD boundary condition was seen to be employed in natural convection boundary layer flow of a radiating MF [32], and an interesting cured stretching surface condition was also examined with applied magnetic field by polar coordinate [33], even a macroscopic 3-D rotating flow of a MF between the two parallel plates with angular velocity could be cited [34].

In fact, a MF composed of the non-Newtonian based fluids exhibits the more fascinating macroscopic transport properties, however such appealing explorations have been studied little. There are diverse non-Newtonian fluids under the consideration for the based fluids. In early days, Yeremeyev had proposed a theoretical model of a viscoelastic liquid medium with couple stress, which constructed the constitutive relations of an elastic micropolar liquid on the basis of the Cosserat continuum with a memory [35]. Mehmood et al. (2013) reported the theoretical study of steady heat transfer of a second grade elastic base micropolar fluid in the stagnation point flow [36]. In the present paper, we consider the base fluid of a MF with the Maxwell viscoelastic behavior [37–39], as a result the Maxwell viscoelasticity-based micropolar fluid (MVMF) can exhibit the noticeable flow relaxation as the same degree of non-Newtonian behavior arising from the micro-rotation effect.

For a MVMF, in addition to the micro-motion of the particles, the oriented phoresis of the suspended particles induced by temperature gradient (Soret efftects) and concentration gradient (Dufour effects) also play the critical roles. The Soret effect, also named thermophoresis, has been studied both theoretically and experimentally in the binary suspensions [40], whereas the Dufour effect (diffusion-thermo) is seen to be more significant in the binary gases mixtures [41]. These two reciprocal phenomena have been considered in both Newtonian [42] and non-Newtonian fluids, such as the power law fluids [43], the Jeffrey fluids [44], the Maxwell viscoelastic fluids [37,45] and the second grade fluids [46]. Nevertheless, the Soret coefficient S_T in those previous studies was often treated as an ordinary parameter so that its multi-dependency features were overlooked. According to the earlier study of Iacopini et al. [47], the Soret coefficient was indeed dependent on the temperature field and the particle size simultaneously, and the nonlinear empirical expression of temperature-dependent $S_T(T)$ was proposed. Such an empirical formula has been corroborated to be accurate by fitting the experimental data well [48,49]. Meanwhile, it was also mentioned an approximately linear dependence of Soret coefficient on particle radius [49], which could be concluded from the fitting results appreciably [48]. Such multi-dependent thermophoresis procedure is therefore introduced by us in the heat and mass transfer of a MVMF, which is helpful in understanding how the factors of temperature field and particle size play the critical roles on the concentration profiles. Such configuration incorporating the variable Soret procedure in a heat-mass transport of the complex fluids, i.e., the MVMF, will make the present work strikingly divergent from any other previous studies. In particular, the present work makes a further investigation on the basis of our earlier series work on the viscoelastic [37] and micropolar behaviors [18] of the non-Newtonian fluids.

Inspired by forementioned motivations, this paper aims to achieve the study of heat and mass transfer induced by multi-dependent featured particulate thermophoresis in the Maxwell viscoelastic base micropolar fluid (MVMF) toward a stretching sheet with the slip property. Maxwell relaxation flow and the collective micro-rotation effects of micro-particles are characterized by viscoelastic parameter δ_m and material parameter K, respectively. Both of them are found to be significant to affect the convection heat and mass transfer of the MVMF. In particular, the dependency of the thermophoresis on the temperature boundary condition can be described by the multi-dependent Soret number explicitly. Additionally, it is indicated that viscoelastic parameter and slip parameter are intrinsically divergent in terms of the storage of local shear stress, though both of them can lead to the alike results of reduction in the fluid velocity. The approximate analytical solutions of the present problems are obtained by means of the homotopy analysis method (HAM) proposed by Liao [50–52], which has been used in solving many nonlinear transport problems of the non-Newtonian fluids [18,53,54].

2. Mathematical model

We consider a steady two-dimensional steady convection heat and mass transfer in an incompressible Maxwell viscoelasticity-based micropolar fluid (MVMF) over a horizontal stretching sheet in attendance of the slip velocity condition. The slipping behavior is generally observed for the complex viscoelastic fluids undergoing a forced shear flow towards a stretching surface condition [37,39]. Herein, The stretching sheet has a linear velocity assumed as $u_w = \omega x$ and the slip velocity of the fluid on the stretching sheet surface is u_{slip}. Fig. 1 illuminates the physical schematic drawing that the MVMF outside the boundary layer is at rest with nonrotating suspended micro-particles, while there would be large gradient phenomenon in boundary layer, e.g., viscosity, thermal and mass diffusion layers.