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Effects of thermophoresis and Brownian motion on nanofluid heat transfer and entropy generation

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ABSTRACT

In this paper, entropy generation of kerosene–alumina nanofluid in a channel with thermal radiation is studied. The significant influences of Brownian motion and thermophoresis have been included in the model of nanofluid. Nonlinear ordinary differential equations have been obtained by means of similarity solution. These equations subjected to the associated boundary conditions are solved analytically using Differential Transformation Method. The effects of radiation parameter, viscosity parameter, thermophoretic parameter, Brownian parameter and Eckert number on flow, heat and mass characteristics are studied. Results indicate that Bejan number is an increasing function of viscosity parameter while it is a decreasing function of other active parameters. Nusselt number decreases with an increase of radiation parameter, thermophoretic parameter, Brownian parameter and Eckert number.

1. Introduction

All thermofluidic processes involve irreversibilities and therefore incur an efficiency loss. In practice, the extent of these irreversibilities can be measured by the entropy generation rate. In designing practical systems, it is desirable to minimize the rate of entropy generation so as to maximize the available energy. When it comes to seeking optimum design features for a system, Entropy Generation Minimization (EGM), as introduced by Bejan [1], serves as a common approach. Oliveski et al. [2] presented a numerical analysis on entropy generation of natural convection in rectangular cavities. Their results indicated that the total entropy generation in a steady state increases linearly with the aspect ratio and the irreversibility coefficient, and exponentially with the Rayleigh number. Sheikholeslami et al. [3] investigated the boundary layer flow of nanofluid over a permeable stretching wall. Their results showed that an increase in the nanoparticle volume fraction decreases the momentum boundary layer thickness and entropy generation rate. Mahmoudi et al. [4] studied the entropy generation in a nanofluid-filled cavity in the presence of magnetic field. They observed that adding nanoparticle reduces the entropy generation. Parvin and Chamkha [5] investigated natural convective flow, heat transfer and entropy generation in an odd-shaped geometry. They revealed that increasing Rayleigh number causes increase of the average Nusselt number as well as the heat transfer term of entropy generation and decrease of the viscous term.

Thermal radiation has an important role in the overall surface heat transfer when the convection heat transfer coefficient is small. The problem of steady two-dimensional magnetohydrodynamic (MHD) stagnation-point flow and heat transfer, with thermal radiation, of a nanofluid past a shrinking sheet was investigated by Nandy and Pop [6]. They showed that the velocity, temperature, the wall shear stress, the Nusselt number and the Sherwood number are strongly influenced by the magnetic parameter. Sheikholeslami et al. [7] investigated ferrofluid hydrothermal behavior in the presence of thermal radiation. Rashidi et al. [8] studied the heat transfer of a steady, incompressible water based nanofluid flow over a stretching sheet with thermal radiation and buoyancy effects. Later, Pal and Mondal [9] have investigated radiation effects on combined convection over a vertical flat plate embedded in a porous medium of variable porosity.

A recent way of improving the performance of these systems is to suspend metallic nanoparticles in the base fluid. Rashidi et al. [10] considered the analysis of the second law of thermodynamics applied to an electrically conducting incompressible nanofluid flowing over a porous rotating disk. They concluded that using magnetic rotating disk drives has important applications in heat transfer enhancement in renewable energy systems. Ellahi [11] studied the magnetohydrodynamic flow of non-Newtonian nanofluid in a pipe. He observed that the MHD parameter decreases the fluid motion and the velocity profile is larger than that of temperature profile even in the presence of variable

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Nomenclature

C	Nanofluid concentration
$C_f, \tilde{C}_f$	skin friction coefficients
C_p	specific heat at constant pressure
h	distance between the plates
k	thermal conductivity
Nu	Nusselt number
Nb	Brownian parameter $(=(\rho c)_p D_B(C_h)/((\rho c)_f \alpha))$
Nt	Thermophoretic parameter $(=(\rho c)_p D_T(T_H)/[(\rho c)_f \alpha T_2])$
p^*	modified fluid pressure
q_r	Radiation heat flux
Pr	Prandtl number $(=\mu/(\rho_f \alpha))$
Rd	Radiation parameter $(=4\sigma_e T_2^3/(\beta_R k))$
R	Viscosity parameter $(=ah^2/\upsilon_f)$
Sc	Viscosity parameter $(=\mu/(\rho_f D))$
$u_w(x)$	velocity of the stretching surface
u, v, w	velocity components along x, y, and z axes, respectively

Greek symbols

α	thermal diffusivity
ϕ	Dimensionless concentration
η	Dimensionless variable
μ	dynamic viscosity
υ	kinematic viscosity
θ	dimensionless temperature
ρ	fluid density
σ	electrical conductivity
τ_w	skin friction or shear stress along the stretching surface
σ_e	Stefan–Boltzmann constant
β_R	Mean absorption coefficient

viscosities. Sheikholeslami and Rashidi [12] studied the effect space dependent magnetic field on free convection of Fe_3O_4–water nanofluid. They showed that Nusselt number decreases with an increase of Lorentz forces. Sheikholeslami et al. [13] applied LBM to simulate three dimensional nanofluid hydrothermal behavior in the presence of magnetic field. They indicated that adding magnetic field leads to decrease in rate of heat transfer. Sheikholeslami et al. [14] studied the magnetic field effect on CuO–water nanofluid flow and heat transfer in an enclosure which was heated from below. They found that the effect of Hartmann number and heat source length is more pronounced at high Rayleigh number. Hatami et al. [15] investigated magnetohydrodynamic Jeffery–Hamel nanofluid flow in non-parallel walls. They found that skin friction coefficient is an increasing function of Reynolds number, opening angle and nanoparticle volume friction. Hatami et al. [16] simulated the flow and heat transfer of nanofluid flow between two parallel plates. They showed that in order to reach maximum Nusselt number, copper should be used as nanoparticle. Free convection of ferrofluid in a cavity heated from below in the presence of an external magnetic field was studied by Sheikholeslami and Gorji [17]. They found that particles with a smaller size have better ability to dissipate heat, and a larger volume fraction would provide a stronger driving force which leads to increase in temperature profile. Effect of static radial magnetic field on natural convection heat transfer in a horizontal cylindrical annulus enclosure filled with nanofluid is investigated numerically using the Lattice Boltzmann method by Ashorynejad et al. [18]. They found that the average Nusselt number increases as nanoparticle volume fraction and Rayleigh number increase, while it decreases as Hartmann number increases. Recently, different passive methods have been used for improving the rate of heat transfer [19–59].

All the above studies assumed that there aren't any slip velocities between nanoparticles and fluid molecules and assumed that the nanoparticle concentration is uniform. It is believed that in natural convection of nanofluids, the nanoparticles could not accompany fluid molecules due to some slip mechanisms such as Brownian motion and thermophoresis, so the volume fraction of nanofluids may not be uniform anymore and there would be a variable concentration of nanoparticles in a mixture. Nield and Kuznetsov [60] studied the natural convection in a horizontal layer of a porous medium saturated by a nanofluid. Their analysis revealed that for a typical nanofluid (with large Lewis number) the prime effect of the nanofluids is via a buoyancy effect coupled with the conservation of nanoparticles, the contribution of nanoparticles to the thermal energy equation being a second-order effect. Khan and Pop [61] published a paper on boundary-layer flow of a nanofluid past a stretching sheet. They indicated that the reduced Nusselt number is a decreasing function of each dimensionless number. Sheikholeslami and Abelman [62] used two phase simulation of nanofluid flow and heat transfer in an annulus in the presence of an axial magnetic field. Two phase model was applied by several authors in order to simulate nanofluid flow and heat transfer [63–69].

A significant exciting subject area of research in launch vehicle technology development is cooling of liquid rocket engine. Various types of cooling techniques are being used to protect the chamber and nozzle walls. The major factors controlling the cooling performance are thermo-physical properties of the fluid and flow velocity. An innovative cooling system for semi-cryogenic engine needs to be explored by improving thermo-physical properties of kerosene, which can enhance the heat transfer capacity of kerosene. Agarwal et al. [70] studied the stability, thermal conductivity and viscosity of kerosene–alumina nanofluid at low volume concentration of nanoparticles. Pizzarelli et al. [71] investigated the flow behavior inside cooling channels to improve design and performance of regenerative cooled rocket engines.

The concept of DTM was first introduced by Zhou [72], who solved linear and nonlinear problems in electrical circuits. Hatami et al. [73] used Multi-step Differential Transformation Method in order investigate motion of a spherical particle in plane couette fluid flow. Sheikholeslami and Ganji [74] applied DTM to solve the problem of nanofluid flow and heat transfer between parallel plates considering Brownian motion. They concluded that Nusselt number increases with augment of nanoparticle volume fraction, Hartmann number while it decreases with an increase of the squeeze number. Recently several authors used numerical and analytical methods in order to study the nanofluid flow and heat transfer [75–95].

The main purpose of this work is to study the effect of thermal radiation on entropy generation and nanofluid flow in a channel. The reduced ordinary differential equations are solved analytically using DTM. The effects of radiation parameter, viscosity parameter, thermophoretic parameter, Brownian parameter and Eckert number on flow, heat transfer and entropy generation are examined.

2. Governing equations

Consider the steady nanofluid flow between two horizontal parallel plates when the fluid and the plates rotate together around the y-axis which is normal to the plates with an angular velocity. A Cartesian coordinate system is considered as follows: the x-axis is along the plate, the y-axis is perpendicular to it and the z-axis is normal to the xy plane (see Fig. 1). The plates are located at $y = 0$ and $y = h$. The lower plate is being stretched by two equal and opposite forces so that the position of the point $(0, 0, 0)$ remains unchanged. The governing equations in a rotating frame of reference are [67]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$