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Original Research Paper

Exact-solution of entropy generation for MHD nanofluid flow induced by a stretching/shrinking sheet with transpiration: Dual solution

Navid Freidoonimehr, Asghar B. Rahimi *

Faculty of Engineering, Ferdowsi University of Mashhad, P.O. Box No. 91775-1111, Mashhad, Iran

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ABSTRACT

In this article, attempts are made to present an exact solution for the fluid flow and heat transfer and also entropy generation analysis of the steady laminar magneto-hydrodynamics (MHD) nanofluid flow induced by a stretching/shrinking sheet with transpiration. This paper is the first contribution to the study of entropy generation for the nanofluid flow via exact solution approach. The governing partial differential equations are transformed into nonlinear coupled ordinary differential equations via appropriate similarity transformations. The current exact solution illustrates very good correlation with those of the previously published studies in the especial cases. The entropy generation equation is derived as a function of the velocity and the temperature gradients. The influences of the different flow physical parameters including the nanoparticle volume fraction parameter, the magnetic parameter, the mass suction/injection parameter, the stretching/shrinking parameter, and the nanoparticle types on the fluid velocity component, the temperature distribution, the skin friction coefficient, the Nusselt number and also the averaged entropy generation number are discussed in details. This study specifies that nanoparticles in the base fluid offer a potential in increasing the convective heat transfer performance of the various liquids. The results show that the copper and the aluminum oxide nanoparticles have the largest and the lowest averaged entropy generation number, respectively, among all the nanoparticles considered.

1. Introduction

Working fluids have great demands placed upon them in terms of increasing or decreasing energy release to systems, and their influences depend on thermal conductivity, heat capacity and other physical properties in modern thermal and manufacturing processes. A low thermal conductivity is one of the most remarkable parameters that can limit the heat transfer performance. Further, the classical heat transfer fluids such as ethylene glycol, water and engine oil have limited heat transfer capabilities due to their low thermal conductivity and thus they cannot congregate with modern cooling requirements. On the other hand, the thermal conductivity of metals is extremely higher in comparison to the conventional fluids. Suspending the ultrafine solid metallic particles in technological fluids causes a remarkable increase in the thermal conductivity. This idea is one of the most modern and appropriate methods for increasing the heat transfer coefficient. Choi and Eastman [1] were probably the first to employ a mixture of nanoparticles and base fluid which were designated as "Nanofluid". Experimental studies have displayed that with 1–5% volume of solid metallic or metallic oxide particles, the effective thermal conductivity of the resulting mixture can be increased by 20% compared to that of the base fluid [2–4]. One of the technological applications of nanoparticles that hold enormous promise is the use of heat transfer fluids containing suspensions of nanoparticles to confront cooling problems in the thermal systems. Xuan and Li [5] displayed the flow and heat transfer performances of nanofluids under the turbulent flow in tubes. Their experimental results showed that the convective heat transfer coefficient and the Nusselt number of nanofluids are enhanced by an increase in the Reynolds number and volume fraction of nanoparticles.

There are several investigations on nanofluids characteristics available in recent literatures. Rashidi et al. [6] studied numerically the comparison of two-phase and single phase of heat transfer and flow field of copper-water nanofluid in a wavy channel. Freidoonimehr et al. [7] investigated the transient MHD laminar free convection flow of a nanofluid past a vertical surface using four different types of water based nanofluid, numerically, via a fourth order Runge-Kutta method using a shooting technique. In another study, Freidoonimehr et al. [8] surveyed three-dimensional flow of a nanofluid in a rotating channel on a lower permeable stretching

* Corresponding author.
E-mail address: rahimiab@um.ac.ir (A.B. Rahimi).

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porous wall. Further, Freidoonimehr and Rashidi [9] presented dual solutions for the problem of magneto-hydrodynamic Jeffery–Hamel nanofluid flow inside non-parallel walls using Predictor Homotopy Analysis Method (PHAM). Moreover, Freidoonimehr et al. [10] employed PHAM to solve the problem of two-dimensional nanofluid flow through expanding or contracting gaps with permeable walls considering different type of nanoparticles including silver, copper, copper oxide, titanium oxide, and aluminum oxide.

In the recent past years, the efficiency calculations of the heat exchanger systems were restricted to the first law of thermodynamics in many studies. In many industrial systems, various mechanisms that account for irreversibility compete with each other. Hereupon, thermodynamic optimization became the concern of several researchers and also it turned into the determinative condition of the most desirable trade-off between two or more competing irreversibilities, [11]. Entropy generation minimization was comprehensively covered by Bejan [12] specifically in the fields of refrigeration, heat transfer and storage, solar thermal power conversion, and thermal science education. Entropy generation minimization (EGM) method was employed to optimize the performance of thermal engineering devices for higher energy efficiency. In order to access the best practical design of thermal systems, one can employ the second law of thermodynamics to minimize the irreversibilities [13,14]. The performance of an engineering device is reduced in the presence of the irreversibilities and the entropy generation function is a measure of the level of the availability of this factor in a process. Since the entropy generation is the criteria for the measurement of the available work destruction of the systems, reduction of the entropy generation is essential to obtain the optimal design characteristics of the energy systems [15]. Moreover, entropy generation causes a decrease in the useful power cycle outputs in a power production device and an increase in the power input to the cycle for power consumption devices. It is important to emphasize that the studies based on the second law of thermodynamics are more reliable than the first law of thermodynamics analysis, because of the limitation of the first law efficiency in the heat transfer engineering systems [16]. The entropy generation analysis is done to improve the system performance. In addition, heat transfer, mass transfer, viscous dissipation, finite temperature gradients, and so on can be used as the sources of entropy generation [17].

In recent decades, many researchers were motivated to study and employ the applications of the second law of thermodynamics in the design of thermal engineering systems. Rashidi et al. [18] studied the first and second law analyzes of an electrically conducting fluid past a rotating disk in the presence of a uniform vertical magnetic field analytically and then applied Artificial Neural Network (ANN) and Particle Swarm Optimization (PSO) algorithm to minimize the entropy generation. In another study, Rashidi et al. [19] employed the second law of thermodynamics to study an electrically conducting incompressible nanofluid flowing over a porous rotating disk. Abolbashari et al. [20] employed Homotopy Analysis Method (HAM) to study an entropy analysis in an unsteady magneto-hydrodynamic nanofluid regime adjacent to an accelerating stretching permeable surface. In another study, the same authors [21] displayed an analytical investigation of the fluid flow, heat and mass transfer and entropy generation for the steady laminar non-Newtonian nanofluid flow induced by a stretching sheet in the presence of velocity slip and convective surface boundary conditions using Optimal HAM. Jafari and Freidoonimehr [22] studied the second law of thermodynamics over a stretching permeable surface in the presence of the uniform vertical magnetic field in the slip nanofluid regime. Moreover, Rashidi et al. [23] performed the study of a magnetic field with temperature-dependent thermo-physical properties numerically by using fourth-order Runge-Kutta method. Rashidi et al. [24] studied and analyzed the convective flow of a third grade non-Newtonian fluid due to a linearly stretching sheet subject to a magnetic field by using OHAM.

The study of heat transfer in the stretched flow is of great importance because of its extensive applications in chemical engineering. Several processes in chemical engineering including the metallurgical and polymer extrusion, glass-fiber and paper production processes involve cooling of a molten liquid being stretched into a cooling system. In such processes, the rates of cooling and stretching influence the quality of the final product considerably.

The current study is mainly motivated by the need to understand the fluid flow, heat transfer and entropy generation analyses for the steady laminar MHD nanofluid flow induced by a stretching/shrinking sheet considering the transpiration effect through a surface. An exact solution is obtained for the velocity distribution and also for the temperature distribution by using the generalized Laguerre polynomial function. By achieving these exact solutions for both the velocity and temperature gradients, the entropy generation function can be obtained in exact form. Many graphs are plotted and the variations of the different involved parameters are discussed in details. The paper is divided up as follows: Section 2 describes the mathematical formula and geometric model of the problem. The exact solutions for both velocity and temperature profiles are presented in Section 3. Section 4 deals with the physical quantities of interest in this problem including the skin friction coefficient, Nusselt number and entropy generation function. Results are discussed in Section 5 and the conclusion section is presented finally.

2. Problem statement

Consider a steady MHD laminar nanofluid regime over a permeable stretching or shrinking surface in a water based incompressible nanofluid containing different type of nanoparticles, as shown in Fig. 1. It is assumed that the base fluid and the nanoparticles are in thermal equilibrium and no slip condition exists between them. It is also supposed that the magnetic Reynolds number is very small. Therefore, it is conceivable to neglect the induced magnetic field in comparison to the applied magnetic field. The flow occupies the $y > 0$ domain. The sheet is stretched in the x-direction by keeping the origin as fixed. The velocity of the sheet along the x-direction is equal to $u_w(x) = bx$. The velocity of the mass transfer perpendicular to the stretching surface is presented by v_w. The temperature of the surface, $T_w(x)$, varies linearly by x while the temperature of the ambient fluid is represented by T_∞. The basic steady 2-D conservation of mass, momentum and thermal energy equations for the nanofluid is written as the following by using the above assumptions and applying the Boussinesq and boundary-layer approximations for negligible viscous dissipation:

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

$$\rho_{nf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu_{nf}\frac{\partial^2 u}{\partial y^2} - \sigma B^2 u, \tag{2}$$

$$(\rho c_p)_{nf}\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k_{nf}\frac{\partial^2 T}{\partial y^2}, \tag{3}$$

where u and v are the velocity components in the x and y directions, respectively, ρ_{nf} and μ_{nf} are the density and the dynamic viscosity of the nanofluid, respectively, where μ_{nf} has been proposed by Brinkman [25], T is the nanofluid temperature, σ is the electrical conductivity, B_0 is the magnetic field imposed along the y-axis, $(\rho c_p)_{nf}$ is the heat capacitance of the nanofluid and k_{nf} is the