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ORIGINAL ARTICLE

The squeezing flow of Cu-water and Cu-kerosene nanofluids between two parallel plates

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Abstract The present article investigates the squeezing flow of two types of nanofluids such as Cu-water and Cu-kerosene between two parallel plates in the presence of magnetic field. The governing non-linear partial differential equations are transformed into ordinary differential equations by applying suitable similarity transformation and then solved numerically using RK-4 method with shooting technique and analytically using differential transformation method (DTM). The influence of arising relevant parameters on flow characteristics has been discussed through graphs and tables. A comparative study has been taken into account between existing results and present work and it is found to be in excellent harmony.

1. Introduction

The squeezing flow of Newtonian and non-Newtonian fluids continues to stimulate significant interest by the researchers owing to increasing application in different fields of engineering, technology such as polymer processing, transient loading of mechanical components, compression, the squeezed film in power transmission, moving pistons, and chocolate filler. Such flows are performed between two moving parallel plates. Classical work in this sector was first reported by Stefan [1] considering the squeezing flow using lubrication approach in 1874. After that Reynolds [2] considered the problems for elliptic plates in 1886. Archibald [3] analyzed the squeezing flow through rectangular plates in 1956. Gradually day by day considerable efforts have been devoted by the researchers to avail the squeezing flow easier and reliable. Rashidi et al. [4] discussed the two dimensional axisymmetric squeezing flow between parallel plates. Effects of magnetic field in the squeezing flow between infinite parallel plates were reported by Siddiqui et al. [5]. Hamdan and Baron [6] investigated the squeezing flow of dusty fluid between parallel disks and discussed the squeezing effects on the velocity profiles. Domairry and Aziz [7] delivered the approximate analytic solution for the squeezing flow of viscous fluid between parallel disks with suction or blowing. Hayat et al. [8] extended the work of Domairry and Aziz [7] to analyze the squeezing flow of non-Newtonian fluids by taking second grade fluids.

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Recently the study of heat transfer characteristics of squeezing flow of viscous fluid has gained considerable attention owing to its various applications in many branches of science and engineering. The squeezing flow through a porous surface has been addressed by Mahmood et al. [9]. Investigation reveals that magnitude of local Nusselt number increases with Prandtl number. The results are satisfied with Mustafa et al. [10]. Heat transfer characteristics in a squeezing flow between parallel disks has been studied by Duwairi et al. [11]. Khaled and Vafai [12] analyzed the hydromagnetic effects on flow and heat transfer over a horizontal surface placed in an externally squeezed free stream. They found that Nusselt number and wall shear stress are both increasing functions of the magnetic parameter. Analytical investigation of the unsteady squeezing flow of viscous Jeffery fluid between parallel disks was performed by Qayyum et al. [13] and discussed the porosity and squeezing effects on the velocity profiles.

The modern age is rightly called the age of science. Whenever we cast our eyes, we see that ongoing advanced technology requires further improvement of heat transfer from energy saving point of view. Since the conventional heat transfer fluids such as water, kerosene, and ethylene glycol have low thermal conductivity, modern science bestowed blessing in the form of nanofluid in which nano-sized particles are added to the base fluid to increase the heat transfer capabilities of the base fluid. It should be noticed that there have been published several recent papers [14–18] on the mathematical and numerical modeling of convective heat transfer mechanism in nanofluids. Mandy [19] investigated mixed convection flow and heat transfer of nanofluids due to an unsteady stretching sheet. These models have some advantage over experimental studies due to many factors that influence nanofluid properties. Recently, nanofluid flow and heat transfer characteristics under different flow configuration were discussed by Hatami et al. [20,21]. Analytical investigation of unsteady squeezing nanofluid flow has been discussed by Pourmehran et al. [22]. They showed that highest value of Nusselt number can be obtained by selecting silver as nanoparticle. All the abovementioned models are single phase model. Recently a new dimension has been added by [23,24] in terms of complex geometry or two phase model for simulating nanofluid.

Nowadays modern science and engineering fields are blessed with so many numerical and analytical methods to obtain accurate approximate solutions from non-linear equations. The methods are variation of parameter method (VPM) [25,26], differential transformation method (DTM) [27–31], adomian decomposition method (ADM) [32,33], homotopy analysis method (HAM) [34,35], homotopy perturbation method (HPM) [36], etc. In this article we have applied relatively a novel analytic technique, say differential transformation method (DTM) which can be said as a modified version of Taylor series method. Zhou [37] was the first to initiate the differential transformation method (DTM). It is the method in which we determine the coefficient of Taylor series of the function by solving the recursive equation from the given differential equation. While the Taylor series method requires very time consuming symbolic computation and derivatives of the data function for higher order equations, DTM plays a powerful authority to obtain the solution in a purely numerical way providing a smooth, functional form within a very few steps. Another essential advantage of this DTM method is that it reduces the size of computational work providing the desired accuracy together with fast convergence rate. More or less every semi analytical technique is helpful to obtain solutions but DTM is free from any linearization, perturbation, discretization or restrictive assumption like HAM, HPM, etc. That's why it is not affected due to any round off errors. Hence it can be applied directly to linear and non-linear ordinary differential equations as a promising tool.

Motivated by the above investigations the present paper deals with the squeezing flow of Cu-water and Cu-kerosene nanofluid considering the presence of external applied magnetic field. Similarity transformation has been used to obtain ordinary differential equations from the governing equations. The reduced ordinary differential equations have been solved by DTM as well as by RK-4 method with shooting technique.

2. Mathematical formulation

2.1. Flow analysis

Consider the viscous incompressible nanofluid flow and heat transfer in a two dimensional co-ordinate system. The co-ordinate system is chosen in such a way that x-axis is measured along the plate and y axis is normal to the plate as shown in Fig. 1. The squeezing flow has been performed through a system having two parallel plates situated at $h(t) = H(1-\alpha t)^{1/2}$ distance apart where $\alpha > 0$ refers to the squeezing movement of both plates with velocity $v(t) = \frac{dh}{dt}$ until they touch each other at $t = \frac{1}{\alpha}$. Also $\alpha < 0$ refers to movement of the plate away to each other and α is called the characteristic parameter having dimension of time inverse. H is the initial position of the plate at time $t = 0$. A uniform magnetic field of strength $B(t) = B_0(1-\alpha t)^{-1/2}$ is applied normal to the plate where B_0 is the initial intensity of the magnetic field. In the mathematical formulation scheme we proceed with the 0 following assumption that there is no chemical reaction, radiative heat transfer, nanoparticles and base fluid are in thermal equilibrium and no slip occurs between them. All body forces are assumed to be neglected. Here we have considered two types of nanofluids cu-water and cu-kerosene. The thermophysical properties of the nanofluid are given in Table 1.

Under the above stated situation the governing equations are as follows:

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

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

$$\rho_{nf}\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), \tag{3}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{(\rho C_p)_{nf}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{\mu_{nf}}{(\rho C_p)_{nf}}\left[4\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right], \tag{4}$$

where u, v are the velocity components in x and y directions respectively. Here $T, p, \rho_{nf}, \mu_{nf}, (\rho C_p)_{nf}, k_{nf}$ represents the temperature, pressure, effective density, effective dynamic viscosity, effective heat capacity and effective thermal conductivity of the nanofluids respectively. Now the relations between base fluid and nanoparticles are given by