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Numerical treatment for investigation of squeezing unsteady nanofluid flow between two parallel plates

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ABSTRACT

In this paper, a new method based on the Chebyshev wavelet expansion is proposed for solving a coupled system of nonlinear ordinary differential equations to model the unsteady flow of a nanofluid squeezing between two parallel plates. Chebyshev wavelet method is applied to compute the numerical solution of coupled system of nonlinear ordinary differential equations in order to model squeezing unsteady nanofluid flow. The approximate solutions of nonlinear ordinary differential equations thus obtained by Chebyshev wavelet method are compared with those of obtained by Adomian decomposition method (ADM), fourth order Runge–Kutta method and homotopy analysis method (HAM). The results obtained by the above methods are illustrated graphically and are discussed in details. The present scheme is very simple, effective and appropriate for obtaining numerical solution of squeezing unsteady nanofluid flow between parallel plates.

1. Introduction

Squeezing flow between parallel plates is a fascinating area of research as it occurs in numerous applications in science and engineering which include hydro dynamical machines, polymer processing, chemical processing equipment, formation and dispersion of fog, damage of crops due to freezing, compression, transient loading of mechanical components, injection modeling and the squeezed films in power transmission.

The seminal work on the squeezing flow under the impulsive deviation of lubrication was reported by Stefan [1] in 1874. Domairry and Aziz [2] analyzed the magneto hydrodynamic squeezing flow of a viscous fluid between parallel disks. The hydrodynamic squeezing flow of a viscous fluid by using homotopy analysis method (HAM) was studied by Rashidi et al. [3]. Mahmood et al. [4] investigated the heat transfer characteristics in the squeezed flow over a porous surface. Muhaimina et al. [5] examined the effect of suction on the flow past a shrinking surface along with heat and mass transfer phenomena. Abd-El Aziz [6] considered the outcome of time-dependent chemical reaction on the flow of a viscous fluid past an unsteady stretching sheet. Influence of thermal radiation and time-dependent chemical reaction on the flow past an unsteady shrinking sheet was studied by Hayat et al. [7]. Mustafa et al. [8] studied heat and mass transfer characteristics in a viscous fluid which is squeezed between parallel plates. They found that the magnitude of local Nusselt number is an increasing function of *Pr* and *Ec*.

In contemporary years, nanofluid technology is proposed and studied by some researchers experimentally or numerically to regulate heat transfer in a process [9–12]. Nanofluids are fluids with suspensions of metals, oxides, carbides or carbon nanotubes in a base fluid. Choi [13] was the first to introduce the term nanofluid that represents the fluid in which nano-scale particles are suspended in the base fluid with low thermal conductivity such as water, ethylene glycol, and oil. Pantzali et al. [14] studied the effect of the use of a nanofluid in a miniature plate heat exchanger (PHE) with modulated surface both experimentally and numerically. They found that the considered nanofluids (CuO–water) can be a promising solution towards designing efficient heat exchanging systems, particularly when the entire volume of the equipment is the main issue. Nanofluids are also significant for the production of nanostructured materials (sizes below 100 nm) for the engineering of complex fluids, and also for cleaning oil from surfaces owing to their excellent wetting and spreading behavior.

Many of the publications on nanofluids are about to understand their behavior so that they can be utilized where straight heat transfer enhancement is paramount as in many industrial applications, transportation, electronics, nuclear reactors as well as biomedicine and food. These fluids enhance thermal conductivity of the base fluid enormously. Due to the tiny size of nanoelements these fluids are very stable and have no additional problems, such as erosion, additional pressure drop, sedimentation and non-Newtonian behavior. The low volume fraction of nanoelements is required for conductivity enhancement.

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Enhancement of heat transfer performance in many industrial fields such as power, manufacturing and transportation, is an essential topic from an energy saving perspective. The low thermal conductivity of conventional heat transfer fluids such as water and oils is a primary limitation in enhancing the performance and the compactness of such systems.

Khanafer et al. [15] were first to conduct a numerical investigation on the heat transfer enhancement by adding nano-particles in a differentially heated enclosure. They established that the suspended nanoparticles substantially increase the heat transfer rate at any given Grashof number. Sheikholeslami et al. [16] investigated the heat transfer characteristics in squeezed flow by using the Adomian decomposition method (ADM). They used a Maxwell–Garnett (MG) model and a Brinkman model respectively. They found that for the case in which two plates are moving together, the Nusselt number increases with the increase of nanoparticle volume fraction (ϕ) and Eckert number (Ec), while it decreases with the growth of the squeeze number (S). It is assumed that the plate moves in the same or opposite direction to the free stream. Here Cu nanofluids are taken to investigate the effect of the volume fraction parameter ϕ of the nanofluid with the Prandtl number $Pr = 6.2$ on the flow and heat transfer characteristics (θ). Physical interpretation to several embedding parameters is assigned through graphs for temperature (θ) and tables for skin friction coefficient ($f''(1)$) and local Nusselt number ($\theta'(1)$).

Sheikholeslami et al. [17] examined the difficulty of free convection between a circular enclosure and a sinusoidal cylinder. They concluded that isotherms, streamlines, the quantity, size and formation of the cells inside the enclosure depend strongly upon the Rayleigh number and the values of amplitude. Free convection of ferrofluid in a cavity heated from below within the presence of magnetic field used to be studied by Sheikholeslami et al. [18,19]. They determined that particles with a smaller size have higher capacity to dissipate heat, and a larger volume fraction would deliver a driving force which results in increase in temperature profile. Lattice Boltzmann method was used to examine magnetohydrodynamic flow employing Cu–water nanofluid in a concentric annulus by Sheikholeslami et al. [20,21].

The literature survey reveals that no investigation regarding the combined effect of heat and mass transfer in the squeezing flow between parallel plates has been presented. Thus it seems a worthwhile attempt to compute a numerical solution for such a problem by using Chebyshev wavelet method. Graphical results representing the noticeable features of various physical parameters are sketched and are discussed in details. In this study, the Chebyshev wavelet method is applied to find the numerical solutions of nonlinear differential equations governing the problem of unsteady squeezing nanofluid flow and heat transfer. The effects of the squeeze number (S), the nanofluid volume fraction (ϕ), Prandtl number (Pr) and Eckert number (Ec) on Nusselt number ($\theta'(1)$) and skin fraction coefficient ($f''(1)$) are investigated.

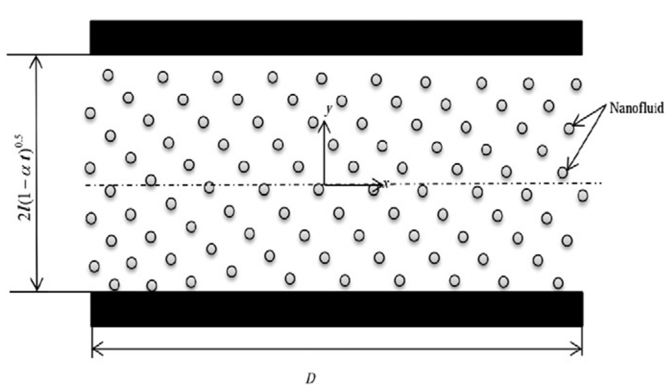

Fig. 1. Geometry of problem.

Macroscopic models for nanofluid flow and heat transfer can be classified as single-phase and two-phase models [22]. Single-phase models consider nanoparticles and base fluid as a single homogeneous fluid with respect to its effective properties. Two-phase models control momentum, continuity and energy equations for particles and base fluid utilizing three distinct approaches such as Eulerian-Mixture model (EMM), Eulerian–Eulerian model (EEM) and thermal dispersion effect. However, the two-phase modeling results exhibit higher heat transfer enhancement in comparison to the homogeneous single-phase model. Also, the heat transfer enhancement increases with increase in Reynolds number and nanoparticle volume concentration as well as with decrease in the nanoparticle diameter.

There are numerous numerical and experimental studies related to nanofluid heat and fluid flow on the macro- and microscale. From the numerical aspect, most of the studies have been completed making use of the homogeneous (single-phase) modeling for the nanofluid. In this process, the nanofluid is considered a homogeneous mixture of nanoparticles and the base liquid. Single-phase models with and without Eulerian–Eulerian, thermal dispersion effect and Eulerian-Mixture two-phase models are estimated by comparing expected convective heat transfer coefficients and friction factors with experimental results from literature. Dispersion model that uses velocity gradient to define dispersion conductivity is located to be more effective at entry region in comparison with other single-phase models. However, two-phase models forecast convective heat transfer coefficient and friction factor more accurately at the entry region.

Although two-phase models provide a better understanding of both phases, single-phase models are computationally more efficient, however produce less detail about each phase. Despite the single-phase modeling, in the two-phase modeling, the nanoparticle and the base fluid are considered as two different phases with different velocities and temperatures. In this method, the interfaces between the phases are taken into account in the governing equations. There are a few studies that used two-phase approach to study nanofluids [23]. The heat transfer enhancement results for two-phase modeling exhibit higher magnitudes in comparison to the single-phase modeling results.

This paper has been organized as follows: in Section 2, the problem is formulated and a coupled system of nonlinear ordinary differential equations for unsteady squeezing nanofluid flow and heat transfer is derived. The mathematical preliminaries of Chebyshev wavelet is presented in Section 3. The approximation of function using Chebyshev wavelet is presented in Section 4. In Section 5, the Chebyshev wavelet method is applied to solve the resulting governing system of nonlinear equations. The numerical results and discussions are discussed in Section 6 and Section 7 concludes the paper.

2. Mathematical formulation

The unsteady flow and heat transfer in two-dimensional squeezing nanofluid between two infinite parallel plates is considered in this paper (Fig. 1). The hypothesis of the problem can be found in more details in Ref. [16,24]. The governing equations are as follows:

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

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

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