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Squeezing Cu–water nanofluid flow analysis between parallel plates by DTM-Padé Method

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ABSTRACT

In this paper, Cu–water nanofluid flow analysis between two parallel palates is investigated using a differential transformation method (DTM) and numerical method. The effective thermal conductivity and viscosity of nanofluids are calculated by the Maxwell–Garnetts (MG) and Brinkman models, respectively. For increasing the accuracy of DTM, Padé approximation is applied. Comparison between the DTM-Padé and numerical method shows that Padé with order [6,6] can be an exact and high efficiency procedure for solving these kinds of problems. The influence of the nanofluid volume fraction (φ), Eckert number (Ec), squeeze number (S) and Prandtl number (Pr) on the Nusselt number (Nu), non-dimensional temperature and velocity profiles are investigated. The results indicated for the case of squeezing flow that the Nusselt number increases with the increase of the nanoparticle volume fraction, Eckert number and squeeze number.

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1. Introduction

The incompressible fluid flow and heat transfer over rotating bodies have many industrial and engineering applications such as gas turbine engines and electronic devices having rotary parts and have been studied in many industrial, geothermal, geophysical, technological and engineering fields. Governing equations for fluids between rotating disks should be solved numerically or analytically. The differential transformation method is one of the powerful analytical methods which does not need any small parameter like p in the homotopy perturbation method (HPM) for discretization, perturbation or linearization. This method constructs an analytical solution in the form of a polynomial. It is different from the traditional higher-order Taylor series method. The Taylor series method is computationally expensive for large orders. The differential transform method is an alternative procedure for obtaining an analytic Taylor series solution of differential equations. The main advantage of this method is that it can be applied directly to nonlinear differential equations without requiring linearization, discretization and therefore, it is not affected by errors associated with discretization. The concept of DTM was first introduced by Zhou [1], who solved linear and nonlinear problems in electrical circuits. Ganji et al. [2] developed DTM and HPM for stream–aquifer interaction modeling and Ayaz [3] applied it to the system of differential equations [4]. Jang et al. [5] applied the two-dimensional DTM to partial differential equations. This method was successfully applied to various application problems [6,7]. All of these successful applications verified the validity, effectiveness and flexibility of the DTM. Keimanesh et al. [8] used the multi-step differential transform method (Ms-DTM) to find the analytical solution of the resulting ordinary differential equation. Steady hydromagnetic convective heat and mass transfer with slip flow from a spinning disk with viscous dissipation and Ohmic heating was investigated by Rashidi et al. [9] using DTM-Padé. DTM constructs for differential equations an analytical solution in the form of a power series. Furthermore, power series are not useful for large values of η, say $\eta \to \infty$. It is now well-known that the Padé approximants [10,11] have the advantage of manipulating the polynomial approximation into rational functions of polynomials. It is therefore essential to combination of the series solution, obtained by the DTM with the Padé approximant to provide an effective tool to handle boundary value problems at infinite domains. One of the first successful applications of DTM to boundary-layer flows was presented by Rashidi and Domairry [12]. Rashidi [13] studied the new analytical method (DTM-Padé) for solving magnetohydrodynamic boundary-layer equations. He showed that differential transform method (DTM) solutions are only valid for small values of independent variables. It can be found that DTM is a reliable and powerful method because it was applied in many problems successfully such as [1–13] and its results had a good agreement with numerical outcome methods for solving nonlinear problems but for problems that have highly nonlinear behavior it diverges.

The term “nanofluid” refers to a liquid containing a suspension of submicronic solid particles (nanoparticles). The term was coined by Choi [14]. The characteristic feature of nanofluids is thermal conductivity enhancement, a phenomenon observed by Masuda et al. [15]. This phenomenon suggests the possibility of using nanofluids in advanced nuclear systems (Buongiorno and Hu [16]). Numerous models and methods have been proposed by different authors to study convective flows of nanofluids. Sheikholeslami et al. [17] studied magnetohydrodynamic flow in a nanofluid filled inclined enclosure with sinusoidal walls. They reported that for all values of the Hartmann number, at

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$Ra = 10^4$ and 10^5, the maximum values of E are obtained at $\gamma = 60°$ and $\gamma = 0°$, respectively. Hatami and Ganji [18] investigated the third grade non-Newtonian nanofluid between two coaxial cylinders by a novel analytical method called least square method (LSM [19–21]). Also, Hatami et al. [22] analyzed the effect of a magnetic field on thermal and flow boundary layers over a horizontal plate. They considered force convection and Al_2O_3–water nanofluid flow for their study. In another study, Hatami and Ganji [23] used Cu–water nanofluid for the cooling process of the microchannel heat sink (MCHS). They considered a temperature-dependent convection coefficient for their study and used porous media approaches and LSM for their modeling.

The study of heat and mass transfer unsteady squeezing viscous flow between two parallel plates in motion normal to their own surfaces independent of each other and arbitrary with respect to time has been regarded as one of the most important research topics due to its wide spectrum of scientific and engineering applications such as hydrodynamical machines, polymer processing, lubrication system, chemical processing equipment, formation and dispersion of fog, damage of crops due to freezing, food processing and cooling towers. The first work on the squeezing flow under lubrication approximation was reported by Stefan [24]. Mahmood et al. [25] investigated the heat transfer characteristics in the squeezed flow over a porous surface. Abd-El Aziz [26] considered the outcome of time-dependent chemical reaction on the flow of a viscous fluid past an unsteady stretching sheet. Magnetohydrodynamic squeezing flow of a viscous fluid between parallel disks was analyzed by Domairry and Aziz [27]. Haji-Sheikh et al. [28,29] studied heat transfer in a porous passage through weighted residual methods and series solution. Mustafa et al. [30] solved the problem of the fluid flow between parallel plates by a homotopy analysis method (HAM). According to their study, we want to solve Cu–water nanofluid flow between parallel plates, but we used another analytical method called DTM due to following advantages.

a) Unlike perturbation techniques, DTM is independent of any small or large quantities. So, DTM can be applied no matter if governing equations and boundary/initial conditions of a given nonlinear problem contain small or large quantities.
b) Unlike HAM [31–35], DTM does not need to calculate auxiliary parameter $\hbar_1$, through h-curves.
c) Unlike HAM [31–35], DTM does not need initial guesses nor an auxiliary linear operator and it solves equations directly.
d) DTM provides us with great freedom to express solutions of a given nonlinear problem by means of Pade approximant and Ms-DTM.

According to the above descriptions, the main objective of this study is to apply DTM-Pade to find the approximate solution of nonlinear differential equations governing the problem of flow and heat transfer of unsteady squeezing nanofluid flow between parallel plates. The effects of active parameters such as the Eckert, Prandtl and squeeze numbers are discussed.

2. Problem description

We considered the heat transfer analysis in the unsteady two-dimensional squeezing nanofluid flow between the infinite parallel plates (Fig. 1). The two plates are placed at $z = \pm \ell(1-\alpha t)^{1/2} = \pm h(t)$. For $\alpha > 0$, the two plates are squeezed until they touch $t = 1/\alpha$ and for $\alpha < 0$ the two plates are separated. The viscous dissipation effect, the generation of heat due to friction caused by shear in the flow, is retained. This effect is quite important in the case when the fluid is largely viscous or flowing at a high speed. This behavior occurs at a high Eckert number (>> 1). Further the symmetric nature of the flow is adopted. The fluid is a water based nanofluid containing Cu (copper) nanoparticles. The nanofluid is a two component mixture with the following assumptions: incompressible; no-chemical reaction; negligible viscous dissipation; negligible radiative heat transfer; nano-solid-particles and the base fluid are in thermal equilibrium and no slip occurs between them. The thermo physical properties of the nanofluid are given in Table 1 [20]. The governing equations for momentum and energy in unsteady two dimensional flow of a nanofluid are:

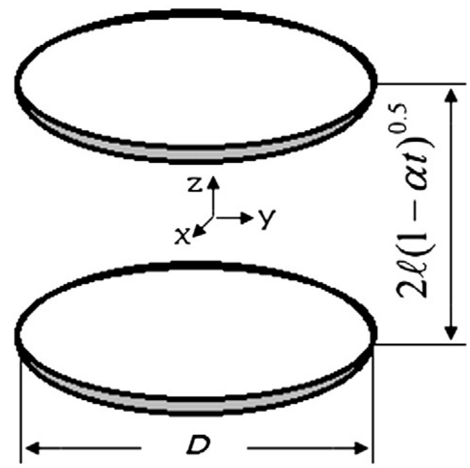

Fig. 1. Schematic of the problem, nanofluid between parallel plates.

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

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

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

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

Here u and v are the velocities in the x and y directions respectively, T is the temperature, P is the pressure, effective density (ρ_{nf}), the effective dynamic viscosity (μ_{nf}), the effective heat capacity $(\rho C_p)_{nf}$ and the effective thermal conductivity k_{nf} of the nanofluid are defined as [23]:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s, \quad \mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}, \quad \left(\rho C_p\right)_{nf} = (1-\phi)\left(\rho C_p\right)_f + \varphi\left(\rho C_p\right)_s$$
$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\phi\left(k_f - k_s\right)}{k_s + 2k_f + 2\phi\left(k_f - k_s\right)} \tag{5}$$

The relevant boundary conditions are:

$$\begin{aligned} &v = v_w = dh/dt, \quad T = T_H && at\, y = h(t), \\ &v = \partial u/\partial y = \partial T/\partial y = 0 && at\, y = 0. \end{aligned} \tag{6}$$

Table 1
Thermo-physical properties of water and nanoparticles [20].

	ρ (kg/m^3)	C_p (j/kg k)	k(W/m · k)
Pure water	997.1	4179	0.613
Copper(Cu)	8933	385	401

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