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Analysis of entropy generation effects in unsteady squeezing flow in a rotating channel with lower stretching permeable wall

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ABSTRACT

The present article aims to examine the entropy effects due to the flow of a viscous fluid in a rotating channel having a lower porous wall which is stretching in its own plane and upper wall squeezing downwards. The considered problem is modeled by using Navier–Stokes Equations. The governing partial differential equations are changed into non-linear ordinary differential equations with the aid of suitable similarity variables. The Optimal Homotopy Analysis Method (OHAM) is employed to obtain the analytical solution of the converted equations. The equations are again solved numerically via fourth-fifth order Runge–Kutta–Fehlberg method and the resulted are compared. The effects of various physical parameters on flow and heat transfer characteristics as well as on entropy production are displayed through tables and graphs and the results are discussed in detail.

1. Introduction

Squeezing flows between rigid surfaces are of considerable interest for researchers due to their wide existence and applications in industrial technology and biomechanics. Such form of flows is found in polymer processing, food industry, lubrication theory, compression and injection moulding, blood flow due to expansion and contraction of vessels, etc. Squeezing flows are caused by the application of normal stresses to the running surfaces. The beginning of the study of squeezing flows goes back to the 19th century and the rudimentary work on this subject was done by Stefan [1]. He considered the squeezed flow of Newtonian fluid between two parallel plates and found an asymptotic solution. However, the geometry of squeezing flow gained the attention of scientists in late 20th century and a lot of research was done on this topic. Langlois [2] and Salbu [3] studied the compressible squeezed films by neglecting the inertial effects. Thorpe [4] included the contribution of inertial terms in squeezing flow and presented an explicit solution of the problem. However, it was later on shown by Gupta and Gupta [5] that the solution given by Thorpe fails to satisfy the boundary conditions. They also gave their solution which was valid for small Reynolds number. The effects of fluid inertial forces on squeezing film flow between two circular plates were examined by Kuzma [6]. Elkouh [7] analysed the inertial effects of fluid in squeezed film flow between two plates. Verma [8] and Singh et al. [9] numerically investigated the problem of squeezing flow between parallel surfaces. Hamza and MacDonald [10] made use of finite difference scheme to discuss the 2D squeezing flow between two parallel surfaces. Later on, Hamza [11] also considered the presence of magnetic field and investigated the squeezed flow between two rotating disks using similarity variables. Singh et al. [9] discussed the squeezed flow of viscous fluid in a channel with perpendicularly moving walls. Bhattacharyya and Pal [12] examined the unsteady flow of viscous fluid between two rotating disks in the presence of magnetic field. Khaled and Vafai [13] considered the oscillatory squeezed flow of a thin viscous film in a channel with its upper plate inclined and found that the fluctuations have great impact on axial and normal velocities. Duwairi et al. [14] studied the heat transfer effects in a squeezed flow of Newtonian fluid between two parallel plates. Ghori et al. [15] utilized homotopy perturbation method to investigate the squeezing flow of Newtonian fluid. The same problem was considered by Ran et al. [16] and explicit series solution was obtained by means of famous homotopy analysis method. Domairy and Aziz [17] examined the magnetohydrodynamic flow of a viscous fluid squeezed between two parallel disks and the effects of suction and injection were analysed. The three dimensional unsteady MHD flow in a rotating channel with lower wall stretching and upper plate squeezing was studied by Munawar et al. [18]. Hussain et al. [19] used both analytical and numerical approaches to investigate the flow and heat transfer characteristics between two parallel disks with velocity slip and temperature jump conditions.

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Entropy effects on flow and heat transfer phenomenon inside a channel have been discussed a lot due to its wide applications in engineering systems such as heat exchangers, combustion engines, cooling systems, transport phenomena, etc. An abundant amount of literature is available relating to thermodynamic analysis of flow in a channel with different geometry and physical configurations [20–36]. Sahin and Yilbas [37] discussed the entropy generation effects in the flow between parallel plates channel where the fluid flow is due to bidirectional compression of the upper plate. Rajvanshi et al. [38] examined the entropy effects on squeezing flow through a porous medium between two parallel rotating disks and found that the total entropy generation becomes less as the plates move apart from each other.

In the present study, effects of entropy generation are investigated in three dimensional unsteady flow and heat transfer of viscous fluid in a parallel plate rotating channel with lower plate stretching and upper plate moving downwards and producing a squeezing effect on fluid. The governing equations are solved analytically and numerically and the results are interpreted in detail through graphs and tables.

2. Mathematical formulation

Assume a three dimensional rotating flow of an incompressible viscous fluid in a parallel plate channel. The lower wall is placed at $y = 0$ and is stretching along the x-direction with a velocity $U_w = \frac{ax}{1-ct}$. The upper wall of the channel is situated at a distance $h(t) = \sqrt{\frac{\nu(1-ct)}{a}}$ and is squeezing downwards with a time dependent velocity $V_h = \frac{dh}{dt}$. Further, it is considered that there is a suction of fluid from the lower wall of the channel with a velocity $\frac{-V_0}{1-ct}$. The walls of the channel and the fluid confined between them are rotating about the y-axis with an angular velocity $\omega^* = \frac{\omega_0}{1-ct}$. Here c is the parameter having dimensions of $(\text{time})^{-1}$ and $ct < 1$. The lower stretching wall of the channel has the temperature T_w and the squeezing wall has temperature T_h such that $T_w > T_h$. The schematic diagram of the considered problem is shown in Fig. 1. Then the governing equations for the flow and heat transfer phenomenon in a rotating frame of reference are [18]

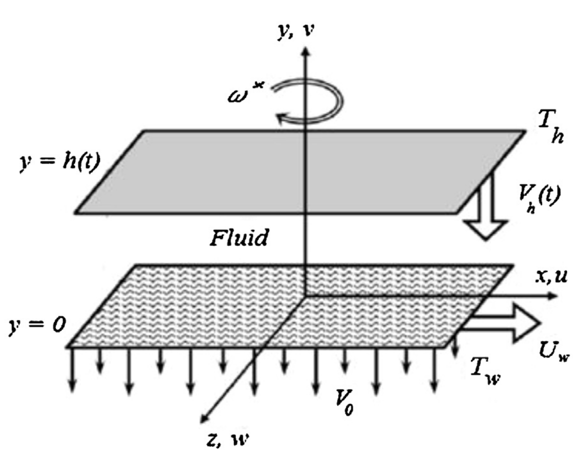

Fig. 1. Schematic diagram of the problem.

$$\nabla.\mathbf{V} = 0, \tag{1}$$

$$\rho\left[\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}.\nabla)\mathbf{V} + 2\omega^* \times \mathbf{V}\right] = \nabla.\mathbf{T}, \tag{2}$$

Where $\mathbf{V}$ is the fluid velocity and $\mathbf{T}$ represents the Cauchy stress tensor.

The above equations can be written in component form as follows [18]

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + 2\frac{\omega_0}{1-ct}w = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right), \tag{4}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), \tag{5}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} - 2\frac{\omega_0}{1-ct}u = \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right), \tag{6}$$

$$\begin{aligned}\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} &= \frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial y^2}\right) \\ &+ \frac{\mu}{\rho c_p}\left[4\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right],\end{aligned} \tag{7}$$

subject to the boundary conditions

$$\left.\begin{aligned} &u(x,y,t) = U_w = \frac{ax}{1-ct},\ v(x,y,t) = \frac{-V_0}{1-ct},\ w(x,y,t) = 0,\ T(x,y,t) = T_w\ at\ y = 0, \\ &u(x,y,t) = 0,\ v(x,y,t) = V_h = -\frac{c}{2}\sqrt{\frac{\nu}{a(1-ct)}},\ w(x,y,t) = 0,\ T(x,y,t) = T_h\ at\ y = h(t). \end{aligned}\right\} \tag{8}$$

Here ρ is the density of the fluid, ν is the kinematic viscosity, c_p is the specific heat at constant pressure, k is the thermal conductivity of the fluid, $a > 0$ is the constant representing the stretching rate of lower wall of the channel, (u, v, w) are the components of velocities in (x, y, z) directions and T denotes the temperature of the fluid.

In order to convert the Eqs. (3)–(7) with boundary conditions (8) in non-dimensional form, following similarity variables are taken

$$\eta = \frac{y}{h(t)},\ u = U_w f'(\eta),\ v = -\sqrt{\frac{a\nu}{1-ct}}f(\eta),\ w = U_w g(\eta),\ \theta = \frac{T-T_w}{T_w-T_h}. \tag{9}$$

By making use of (9) in Eqs. (3)–(7), the continuity equation is satisfied identically and the Eqs. (4)–(7) after elimination of pressure take the shape

$$f^{IV} - f'f'' + ff''' - \frac{S_q}{2}(3f'' + \eta f''') - 2\omega g' = 0, \tag{10}$$

$$g'' + fg' - f'g - S_q\left(g + \frac{\eta}{2}g'\right) + 2\omega f' = 0, \tag{11}$$