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Numerical analysis of nanofluid flow conveying nanoparticles through expanding and contracting gaps between permeable walls

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ABSTRACT

In this study, the problem of nanofluid flow in a rectangular domain bounded by two moving porous walls, which enable the fluid to enter or exit during successive expansions or contractions is solved using Least Square Method. The concept of this method is briefly introduced, and it's application for this problem is studied. Then, the results are compared with numerical results and the validity of these methods is shown. Graphical results are presented to investigate the influence of the volume fraction of nanoparticle, non-dimensional wall dilation rate and permeation Reynolds number on the velocity, normal pressure distribution and wall shear stress. The present problem for slowly expanding or contracting walls with weak permeability is a simple model for the transport of biological fluids through contracting or expanding vessels. The results indicate that velocity boundary layer thickness near the walls decreases with increase of Reynolds number and nanoparticle volume friction and it increases as non-dimensional wall dilation rate increases.

1. Introduction

Recently, due to the rising demands of modern technology, including chemical production, power station, and microelectronics, there is a need to develop new types of fluids that will be more effective in terms of heat exchange performance. Nanofluids are produced by dispersing the nanometer-scale solid particles into base liquids with low thermal conductivity such as water, ethylene glycol (EG), oils, etc. [1]. The term "nanofluid" was first coined by Choi [2] to describe this new class of fluids. The materials with sizes of nanometers possess unique physical and chemical properties [3]. The presence of the nanoparticles in the fluids noticeably increases the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics. Therefore, numerous methods have been taken to improve the thermal conductivity of these fluids by suspending nano/micro-sized particle materials in liquids. Asymmetric laminar flow and heat transfer of nanofluid between contracting rotating disks was investigated by Hatami et al. [4]. Their results indicated that temperature profile becomes more flat near the middle of two disks with the increase of injection but opposite trend is observed with increase of expansion ratio. The problem of laminar nanofluid flow in a semi-porous channel in the presence of transverse magnetic field was investigated analytically by Sheikholeslami et al. [5].Their results showed that velocity boundary layer thickness decrease with increase of Reynolds number and it increases as Hartmann number increases. Several studies have been published recently on the modeling of natural convection heat transfer in nanofluids such as [6–8].

Studies of fluid transport in biological organisms often concern the flow of a particular fluid inside an expanding or contracting vessel with permeable walls. For a valve vessel exhibiting deformable boundaries, alternating wall contractions produce the effect of a physiological pump. The flow behavior inside the lymphatic exhibits a similar character. In such models, circulation is induced by successive contractions of two thin sheets that cause the downstream convection of the sandwiched fluid. Seepage across permeable walls is clearly important to the mass transfer between blood, air and tissue [9]. Therefore, a substantial amount of research work has been invested in the study of the flow in a rectangular domain bounded by two moving porous walls, which enable the fluid to enter or exit during successive expansions or contractions. Dauenhauer and Majdalani [10] studied the unsteady flow in semi-infinite expanding channels with wall injection. They are characterized by two non-dimensional parameters, the expansion ratio of the wall α and the cross-flow Reynolds number Re. Majdalani and Zhou [11] studied moderate to large injection and suction driven channel flows with expanding or contracting walls. Using perturbations in cross-flow Reynolds number Re, the resulting equation is solved both numerically and analytically. Boutros et al. [12] studied the solution of the Navier–Stokes equations which described the unsteady incompressible laminar flow in a semi-infinite porous circular pipe with

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Nomenclature

c	Injection/suction coefficient
NM	Numerical method
Δp_n	Pressure drop in the normal direction
Re	Permeation Reynolds number
u, v	Velocity components along x, y axes, respectively
V_w	Injection velocity
Greek symbols	
υ	Kinematic viscosity
α	Non-dimensional wall dilation rate
τ	Shear stress
ρ	Fluid density
Subscripts	
∞	Condition at infinity
nf	Nanofluid
f	Base fluid
s	Nano-solid-particles

injection or suction. Through the pipe wall whose radius varies with time. The resulting fourth-order nonlinear differential equation is then solved using small-parameter perturbations.

The objective of the present paper is to study the nanofluid flow in a rectangular domain bounded by two moving porous walls. The reduced ordinary differential equations are solved via Least squares method. The effects of the parameters governing the problem are studied and discussed.

2. Flow analysis and mathematical formulation

Consider the laminar, isothermal and incompressible flow in a rectangular domain bounded by two permeable surfaces that enable the fluid to enter or exit during successive expansions or contractions. A schematic diagram of the problem is shown in Fig. 1.

The fluid is a water based nanofluid containing Cu. It is assumed that the base fluid and the nanoparticles are in thermal equilibrium and no slip occurs between them. The thermo physical properties of the nanofluid are given in Table 1. The effective density ρ_{nf}, the effective dynamic viscosity μ_{nf}, the heat capacitance $(\rho C_p)_{nf}$ and the thermal conductivity k_{nf} of the nanofluid are given as:

$$\rho_{nf} = \rho_f(1-\phi) + \rho_s\phi \tag{1}$$

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}. \tag{2}$$

Here, ϕ is the solid volume fraction. The walls expand or contract uniformly at a time-dependent rate$\dot{a}$. At the wall, it is assumed that

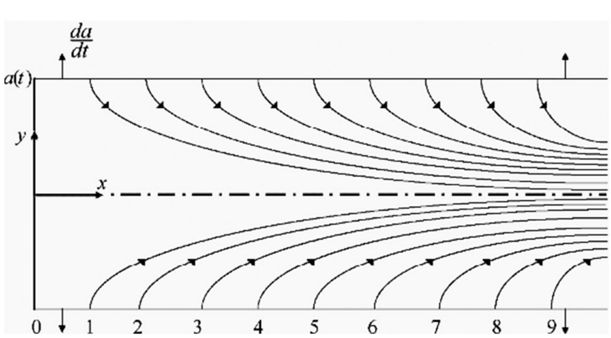

Fig. 1. Two-dimensional domain with expanding or contracting porous walls.

Table 1
Thermo physical properties of water and nanoparticles.

	$\rho(\mathrm{kg/m^3})$	$\mu(\mathrm{Pa\cdot s})$
Pure water	997.1	0.001
Copper (Cu)	8933	–
Silver (Ag)	10,500	–
Alumina (Al_2O_3)	3970	–

the fluid inflow velocity V_w is independent of position. The equations of continuity and motion for the unsteady flow are given as follows:

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

$$\frac{\partial u^*}{\partial t} + u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho_{nf}}\frac{\partial p^*}{\partial x^*} + \frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}}\right], \tag{4}$$

$$\frac{\partial v^*}{\partial t} + u^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*} = -\frac{1}{\rho_{nf}}\frac{\partial p^*}{\partial y^*} + \frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}}\right]. \tag{5}$$

In the above equations, u^* and v^* indicate the velocity components in x and y directions, p^* denotes the dimensional pressure, ρ_{nf},μ_{nf} and t are the density, dynamic viscosity of nanofluid and time, respectively. The boundary conditions will be:

$$\begin{aligned} y^* = a(t): &\quad u^* = 0, v^* = -V_w = -\frac{\dot{a}}{c},\\ y^* = 0: &\quad \frac{\partial u^*}{\partial y^*} = 0, v^* = 0,\\ x^* = 0: &\quad u^* = 0. \end{aligned} \tag{6}$$

Where $c = \frac{\dot{a}}{V_w}$ is the wall presence or injection/suction coefficient, that is a measure of wall permeability. The stream function and mean flow vorticity can be introduced by putting:

$$\begin{aligned} &u^* = \frac{\partial \psi^*}{\partial y^*}, v^* = \frac{\partial \psi^*}{\partial x^*}, \xi^* = \frac{\partial v^*}{\partial x^*} - \frac{\partial u^*}{\partial y^*}\\ &\frac{\partial \xi^*}{\partial t} + u^*\frac{\partial \xi^*}{\partial x^*} + v^*\frac{\partial \xi^*}{\partial y^*} = \frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 \xi^*}{\partial x^{*2}} + \frac{\partial^2 \xi^*}{\partial y^{*2}}\right]. \end{aligned} \tag{7}$$

Due to mass conservation, a similar solution can be developed with respect to x^* [13]. Starting with:

$$\begin{aligned} &\psi^* = \frac{\nu x^* f^*(y,t)}{a}, \quad u^* = \frac{\nu x^* f^*{}_y}{a^2}, \quad v^* = \frac{-\nu f^*(y,t)}{a},\\ &y = \frac{y^*}{a}, f^*_y \equiv \frac{\partial f^*}{\partial y}. \end{aligned} \tag{8}$$

Substitution Eq. (8) into Eq. (7) yields:

$$u^*_{y^*t} + u^*u^*_{y^*x^*} + v^*u^*_{y^*y^*} = \nu u^*_{y^*y^*y^*}. \tag{9}$$

In order to solve Eq. (9), one uses the chain rule to obtain:

$$f^*_{yyyy} + \alpha\left(yf^*_{yyy} + 3f^*_{yy}\right) + f^*f^*_{yyy} - f^*_yf^*_{yy} - a^2\left(\frac{\mu_{nf}}{\rho_{nf}}\right)^{-1} f^*_{yyt} = 0, \tag{10}$$

With the following boundary conditions:

$$\begin{aligned} at\, y = 0: &\quad f^* = 0, f^*_{yy} = 0,\\ at\, y = 1: &\quad f^* = \mathrm{Re}A^*(1-\phi)^{2.5}, f^*_y = 0, \end{aligned} \tag{11}$$

Where $\alpha(t) \equiv \frac{a\dot{a}}{\upsilon}$ is the non-dimensional wall dilation rate which is defined positive for expansion and negative for contraction and