Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Engineering Science 44 (2006) 650–661

International Journal of Engineering Science

www.elsevier.com/locate/ijengsci

Laminar flow of a non-Newtonian fluid in channels with wall suction or injection

Fethi Kamışlı

Department of Chemical Engineering, Faculty of Engineering, Firat University, Elazig 23119, Turkey

Received 5 August 2005; received in revised form 30 January 2006; accepted 1 April 2006
Available online 17 July 2006

(Communicated by HILMI DEMIRAY)

Abstract

The one-dimensional approximate equation in the rectangular Cartesian coordinates governing flow of a non-Newtonian fluid confined in two large plates separated by a small distance of h, with the upper plate stationary while the lower plate is uniformly porous and moving in the x-direction with constant velocity, is derived by accounting for the order of magnitude of terms as well as the accompanying approximations to the full-blown three-dimensional equations by using scaling arguments, asymptotic techniques and assuming the cross-flow velocity is much less than the axial velocity. The one-dimensional governing equation for a power-law fluid flow confined between parallel plates, with the upper plate is stationary and the bottom plate subjected to sudden acceleration with a constant velocity in the x-direction and uniformly porous, is solved analytically for a Newtonian fluid case ($n = 1$) and numerically for various values of power-law index to determine the transient velocity and thus the overall transient velocity distribution. The effects of mass suction/injection at the porous bottom plate on the flow of non-Newtonian fluids are examined for various values of time and power-law index. The results obtained from the present analysis are compared with the data available in the literature.

Keywords: Porous channel; Non-newtonian fluid; Wall suction/injection

1. Introduction

The motion of fluid through porous media at low Reynolds numbers has long been an important subject in the field of chemical, biomedical, and environmental engineering and science. This phenomenon is fundamental in nature and is of great practical importance in many diverse applications, including the production of oil and gas from geological structures, the gasification of coal, the retorting of shale oil, filtration, ground-water movement, regenerative heat exchange, surface catalysis of chemical reactions, adsorption, coalescence, drying, ion exchange and chromatography.

E-mail address: fkamisli@firat.edu.tr

0020-7225/$ - see front matter
doi:10.1016/j.ijengsci.2006.04.003

Some of the applications mentioned above involve two or even three fluids, and multidimensional and unsteady flows. In some applications the details of the local velocity field are of concern.

As expressed previously, the flow of fluid through porous media and in tubes of circular or rectangular cross-section with porous walls has long been investigated in many engineering applications. Wang et al. [1] theoretically investigated the flow distribution and pressure drop in a channel with a porous wall. An analytical solution of the non-linear ordinary differential equations, based on the varying flow coefficients, was obtained. They claimed that the predicted flow distribution agrees well with experimental data. Hayat et al. [2] studied the flow of a third-order fluid occupying the space over a porous wall. The suction or blowing velocity was applied at the surface of the wall. By introducing a velocity field, the governing equations were reduced to a non-linear partial differential equation and the resulting equation was analytically solved by using Lie group methods. Fang [3] undertook an analysis of an unsteady laminar flow of a Newtonian fluid confined in a tube of rectangular cross-section with a porous wall. The steady state temperature distribution was also presented. It was concluded that the characteristics of transient velocity and transverse mass transfer across the fluid has great influence on the velocity and temperature distributions that affect the heat transfer behavior at the two plates. In another paper, Fang [4] studied the unsteady velocity profile for a pressure-driven Poiseuille flow in a channel with porous walls where mass transfer is analyzed and solved analytically. He discussed the influences of mass transfer on transient velocity and steady state temperature profiles.

Oxarango et al. [5] analyzed the laminar flow of a Newtonian fluid confined in channels with wall suction or injection and proposed a one-dimensional model to determine the laminar flow behavior. The model was developed based on the integration of the Navier–Stokes equations using the analytical solutions for the two-dimensional velocity and pressure fields. It was claimed that the resulting one-dimensional model preserves the whole flow properties, in particular the inertial terms which can affect the wall suction conditions and the spatial distribution of the growing particle cake layer at the wall encountered in filtration processes. It was concluded that the effect of non-uniform boundary conditions and the influence of heterogeneous geometrical characteristics on the heterogeneity of the fluid flow structure can be studied using such a model.

Deng and Martinez [6] studied the viscous flow of a Newtonian fluid in a channel partially filled with porous medium and a porous wall. In the porous medium the Brinkman–Darcy law relationship was considered. In order to solve the model equations, a similarity variable was used to reduce the governing equations to two coupled, non-linear ordinary differential equations.

Fransson et al. [7] performed experiments to determine the surface pressure distribution, vortex shedding frequency, and the wake flow behind a porous cylinder when continuous suction of blowing is applied through the cylinder walls. It was found that even moderate levels of suction/blowing ($\leqslant 5\%$ of the oncoming streamwise velocity) have a large impact on the flow around the cylinder. Suction delayed separation contributing to a narrower wake width, and a corresponding reduction of drag, whereas blowing shows the opposite behavior. The drag force on the cylinder was indicated to increase linearly with blowing rate, whereas for suction there is a drastic decrease at a specific suction rate.

Ariel [8] obtained exact analytical solutions of two problems of laminar flow of a second-order fluid confined in a tube of rectangular cross-section and annulus with porous walls. For each problem the rate of injection at one wall is assumed equal to the rate of suction at the other wall. It was reported that the viscoelasticity of the fluid tends to destroy the formation of the boundary layer at the wall where the suction takes place for large values of the cross-flow Reynolds number.

Aydın and Kaya [9] performed an analysis of the laminar boundary layer flow over a porous flat plate with injection or suction. Similarity and numerical solution techniques were used to solve the boundary layer equations. The effect of uniform suction/injection on the heat transfer was discussed and it was reported that the suction enhances the heat transfer coefficient while injection causes a decrease in heat transfer.

Zaturska and Banks [10] analyzed a Newtonian fluid in a tube of rectangular cross-section. They reported that an exact solution of the Navier–Stokes equation is found to decay for increasing time if the Reynolds number is less than a critical value and grows without limit if the Reynolds number is larger than that critical value.

Ogulu and Amos [11] studied the problem of suction/injection on free convective flow of a non-Newtonian fluid past a vertical porous plate. The governing non-linear partial differential equations are decoupled. Expressions for temperature, velocity, skin-friction and rate of heat transfer were obtained at very slow