ON THE EFFECTS OF POROUS WALLS ON TRANSITIONAL AND TURBULENT CHANNEL FLOWS

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Abstract We consider the pressure-driven, incompressible flow in a channel bounded by two layers of porous material. The flow is analysed first in terms of its non-modal stability characteristics; then results for the DNS of the Poiseuille flow in the turbulent regime are shown.

BACKGROUND AND OBJECTIVES

This research is motivated by the widespread use of permeable and transpirating walls in the most diverse applicative fields. Wall transpiration is also often used in flow control and transition delay studies, where the effects of the porous walls on the tangential velocity at the interfaces are often assumed to be negligible.

The flow of an incompressible viscous fluid within the pore-like structure of a porous medium is governed by the Navier-Stokes equations. Most such media, however, have a complicated geometric structure which involves a wide range of scales, so that solving the Navier-Stokes equations within the porous medium is prohibitively difficult and expensive. As a consequence, one is usually led to consider the flow at a macroscopic level. The present work models the porous material following Tilton & Cortelezzi [4, 5], who revealed how the asymptotic linear stability characteristics of the Poiseulle flow change significantly when the solid wall is replaced by a finite-thickness strip of porous material. In their linear stability analysis they employed the so-called method of volume averaging formally derived by Whitaker [6] which solves within the porous medium the governing equations averaged over a lengthscale smaller than a macrosopic legthscale but at the same time larger than the geometric scale(s) of the pores. Moreover, interfacial momentum transfer conditions analytically derived by Ochoa-Tapia & Whitaker [2] were used to couple the homogeneous fluid flow with the adjacent porous flow.

Here, as in [5], we study a plane Poiseuille flow bounded by two strips of porous material, which in turn are bounded by two solid walls. The porous material is described through its *porosity* ε and its *permeability* σ. Strip thickness is h_p, and τ is the interface coefficient governing the momentum transfer process at the interface between the channel and porous regions. Aim of the work is twofold. We intend to further extend the above stability studies and explore the non-modal characteristics of the flow, in the hope of shedding further light on the transition process. At the same time, we develop and present a Direct Numerical Simulation (DNS) solver to describe the flow over the porous walls when the Reynolds number Re increases and the turbulent regime takes place. We notice that turbulence over the porous material develops at lower Re compared to the standard Poiseuille flow over solid walls.

NON-MODAL STABILITY

The Orr-Sommerfeld equations associated with the porous channel are considered in the linear stability problem, and the non-modal stability characteristics [3] of a plane Poiseuille flow over the porous layers are addressed. The eigenvalues problem is discretized by Chebyshev expansion on Gauss-Lobatto nodes. We have carried out a large parametric study in which permeability, porosity, height of the porous layers as well as the interface coefficient τ are varied simultaneously. As a preliminary result, Fig.1 shows the maximum values of the transient-growth function obtained for a bulk Reynolds number of $Re = 650$, and highlights how the stability characteristics of the Poiseuille flow are affected. At the conference, we will report on the full parametric survey, and the role of the most influential parameters will be addressed.

TURBULENT FLOW

We have developed a new DNS solver that solves the full incompressible Navier–Stokes equations in the bulk of the channel, and the volume-averaged Navier–Stokes equations within the porous strips. The two sets of equations are coupled by the interfacial boundary condition described above. The code is a substantial extension of an existing DNS solver [1], and uses a Fourier discretization for the streamwise and spanwise directions, while the discretization of the wall-normal differential operators is carried out through compact, explicit high-order finite-difference schemes.

Fig.2 shows preliminary results that emphasize how the changes in the mean velocity profile are almost undetectable outside of the interfacial region for this choice of porosity parameters, but the effect of the porous layer on friction drag and Reynolds stress is significant and reaches well into the bulk of the flow, with the intensity of streamwise velocity fluctuations being reduced compared to the solid-wall case, although very near the wall an increase can be observed. The

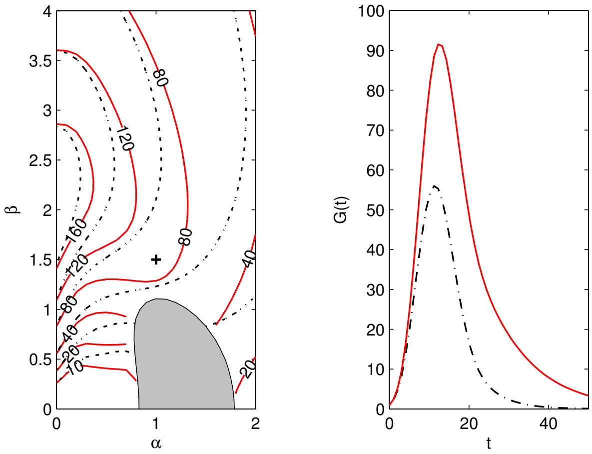

Figure 1. Left: contours of the maximum value of the energy-growth function $\max G(t)$ as a function of the perturbation wavenumbers α and β. Bulk Reynolds number is 650. The black dash-dotted line is Poiseuille flow over solid wall, while the red continuous line is the porous case with $\sigma = 0.02$, $\varepsilon = 0.6$, $h_p = 1$ and $\tau = -0.5$. The grey area marks the linearly unstable region. Right: $G(t)$ for $\alpha = 1$ and $\beta = 1.5$ (indicated by the cross in the left plot).

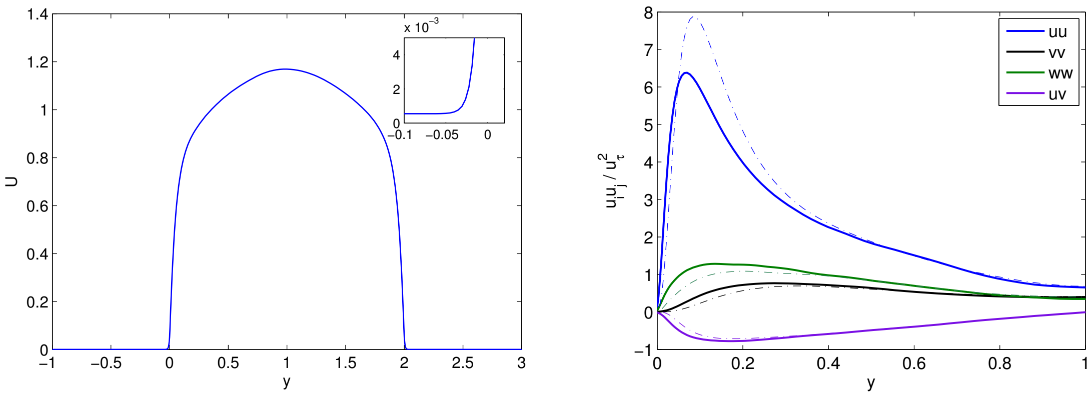

Figure 2. Left: mean velocity profile, with the inset showing a zoomed view of the interfacial region. Bulk Reynolds number is $Re = 2800$, corresponding to $Re_\tau \simeq 180$. Parameters are: $\sigma = 0.005$, $\varepsilon = 0.6$, $h_p = 0.5$ and $\tau = 0$. Right: components of the Reynolds stress tensor as a function of the distance from the porous strip. Dash-dotted lines identify the solid-wall case, whereas continuous lines are used for the porous case.

other diagonal components, and in particular the spanwise one, appear to increase, and the off-diagonal component shows a near-wall increase that can be linked to the larger friction.

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