DIRECT NUMERICAL SIMULATIONS OF TURBULENT FLOW THROUGH POROUS CHANNELS AND DUCTS

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Abstract Direct numerical simulations of the fully developed turbulent flow through a porous channel and duct are performed based on the spectral element code Nek5000. The volume-averaged Navier-Stokes (VANS) equations are implemented in order to describe the flow in the composite medium. The numerical simulations of the VANS equations are carried out at a constant value of the bulk Reynolds number when the porosity, or equivalently, the permeability of the medium varies successively. The mean and turbulent energy budgets are computed and the effect of porosity on the secondary flow in a duct is examined.

INTRODUCTION

The flow over porous media is often encountered in many technological and physical processes such as liquid coating, oil refinement, river beds, ground flow or heat exchangers of open-cell metal foam. Besides, atmospheric flows over densely built-up urban areas and plant canopies are examples of turbulent flow over porous media [2]. This range of applications has motivated us to investigate in detail this configuration. In a microscopic sense, the flow in the porous medium is possible only through the pores and can be described by the Navier-Stokes equations. In order to study the macroscale system behavior, it is necessary to use an up scaling procedure to develop a modified form of the Navier-Stokes equations (here the VANS) that are valid in the entire porous medium, i.e., not only in the liquid phase but also in the solid phase. The derivation of the volume-averaged Navier-Stokes (VANS) equations is performed by the method of volume averaging [5]. In general, two approaches are followed to deal with this problem. Here we propose the continuum approach where fluid and porous media are considered as a single composite medium and flow in this medium is governed by the VANS equations

$$\nabla \cdot [\varepsilon \mathbf{u}] = 0, \tag{1}$$

$$\begin{aligned} \partial_t \mathbf{u} \quad = \quad & -\frac{1}{\varepsilon}\nabla \cdot [\varepsilon \mathbf{u} \otimes \mathbf{u}] - \nabla p + \frac{1}{Re_b}\nabla^2 \mathbf{u} + \frac{1}{\varepsilon Re_b}\nabla \varepsilon \cdot \nabla \mathbf{u} - \frac{1}{Re_b}\frac{Fo}{Da}\varepsilon |\mathbf{u}| \mathbf{u} \\ & + \frac{1}{Re_b}\left[\frac{\nabla^2 \varepsilon}{\varepsilon} - \frac{\varepsilon}{Da}\right]\mathbf{u}, \end{aligned} \tag{2}$$

where ε is the porosity, Re_b is the bulk Reynolds number, Da is the Darcy number and Fo is the Forchheimer number. In this formulation, boundary conditions at the liquid-porous interface are not required; however, the porosity and permeability of the medium are functions of space (the vertical coordinate in our configuration) and vary rapidly in the small region close to the liquid-porous interface. The porosity and permeability evolve from constant values below the interface to 1 and ∞ respectively in the liquid medium. The present study considers a three-dimensional viscous incompressible Newtonian flow through a porous channel and duct under the action of a streamwise pressure gradient. The sketch of the flow configuration used for the numerical experiment can be found in figure 1.

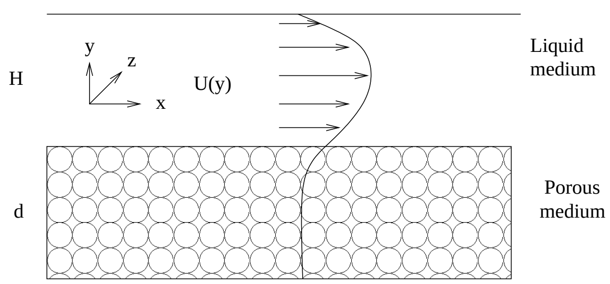

Figure 1. Sketch of the turbulent flow through a porous channel and a duct.

NUMERICAL EXPERIMENT

The present model is investigated numerically by using the spectral element code Nek5000 which is extensively used to study turbulent flows in different applications [3]. We have modified the available numerical code by including the extra forcing terms that appear in the VANS equations owing to the effect of the porous medium at the bottom wall. In

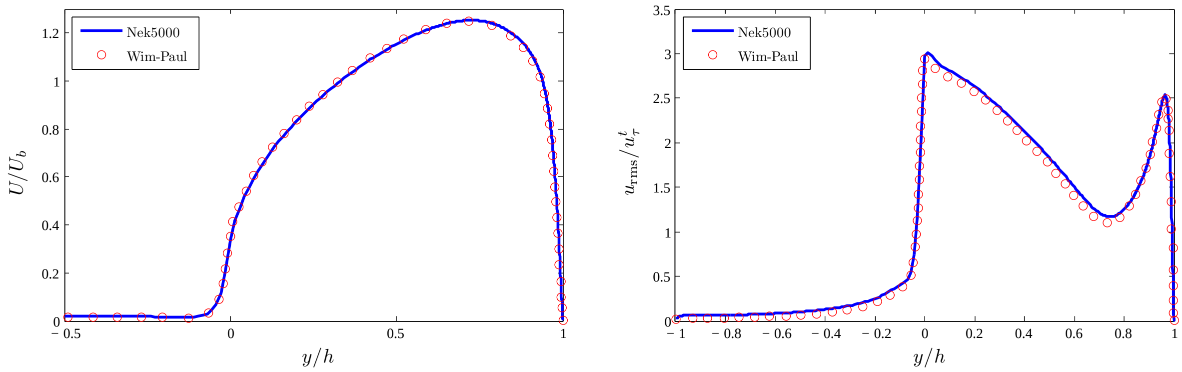

Figure 2. (a) Comparison of mean streamwise velocity U and (b) rms of streamwise velocity u_{rms} when $Re_b = 5500$ and $\epsilon_c = 0.95$. Line represents the present results and circular points represent the results from [1].

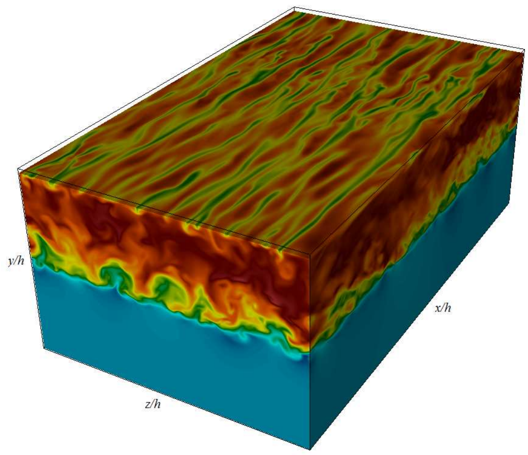

Figure 3. Instantaneous streamwise velocity field of the channel flow simulation. Upper wall removed to allow proper visualization of the near-wall structures.

addition, we cluster more spectral elements in the vicinity of the liquid-porous interface in order to accurately capture the interactions between turbulence and the interface. The goal is to decipher the effect of permeability on the turbulent flow structure and analyze the different terms in the mean and turbulent energy budgets. To initially exclude additional effects due to the impermeability of the lower wall, it is assumed that the porous layer thickness is at least equal to the liquid layer thickness. The present numerical results are verified against results available in the literature [1] and excellent agreement is achieved as displayed in figure 2. An instantaneous flow field of the channel flow simulation is illustrated in figure 3 for a fixed value of porosity $\epsilon_c = 0.95$, and a bulk Reynolds number $Re_b = 5500$ based on channel half-height h and bulk velocity U_b over the liquid region. In a turbulent duct flow, the presence of the side walls induce cross-stream motions, the so-called Prandtl's secondary flow of second kind, produced due to the imbalance of the Reynolds stress tensor at the corner. The impact of the porous substrate on the strength and extent of the secondary flow will be assessed in the final contribution, by comparing with available numerical data of Newtonian duct flow [4]. Mean and turbulent energy budgets will be also computed to further evaluate the impact of the porous layer on the most relevant flow features.

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