International Journal of Heat and Fluid Flow 000 (2016) 1–12

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijheatfluidflow

POD analysis of low Reynolds turbulent porous channel flow

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A R T I C L E I N F O

Article history:
Received 24 February 2016
Revised 20 May 2016
Accepted 18 July 2016
Available online xxx

Keywords:
Turbulent channel flow
Large eddy simulation (LES)
Porous media
Continuum approach
Coherent structures
Proper orthogonal decomposition (POD)

A B S T R A C T

Snapshot proper orthogonal decomposition (POD) is utilized to understand the turbulent channel flow physics over permeable porous surfaces. Our aim is to study how the flow structures vary in different wall permeabilities. The data needed for POD algorithm are provided by large eddy simulation (LES). Utilizing Volume-Averaged Navier-Stokes (VANS) equations inside the permeable wall, eliminates the need for detailed knowledge of the pore microstructure and porous medium can be easily specified with global properties like porosity and permeability. The bulk mean Reynolds number is 5500 and simulations are carried out in three different porosities, 0, 0.8 and 0.95. The reasons why the quasi-streamwise vortices become shorter and absent above a permeable wall are discussed. POD analysis has revealed that permeability of wall amends the size and even shape of the large scale, energetic dominant structures of the flow and these alterations are more vivid in highly permeable walls in which large spanwise vortical structures that stem from the Kelvin-Helmholtz instability are dominant structures of the flow.

1. Introduction

Understanding the dominant structure of turbulent boundary layer is a crucial issue to develop a turbulent flow control technique either passively or actively. In comparison with the solid wall flows, these structures are very different in the porous wall flows. There are many engineering and industrial fields in which porous materials play important role and thus better understanding and modeling the flows over or through porous structures will be beneficial. Examples are extraction of oil from oil wells, catalytic reactors, filtration processes, heat exchangers, flow through sedimentary rocks and riverbeds.

Prior studies have revealed increased turbulence activities at the permeable wall and compared to the impermeable wall diverse turbulence structures were seen at the permeable wall. Breugem and Boersma (2005) showed that the volume-averaged Navier-Stokes (VANS) equations can be applied for a precise simulation of turbulent flow over and through a permeable wall. Breugem et al. (2006) utilized the work by Breugem and Boersma (2005) to study the influence of a highly permeable porous wall, on turbulent channel flows. Their results indicated that the dynamics and structures of turbulence above a highly permeable wall are very different compared to an impermeable wall and there are no low and high speed streamwise velocity streaks and quasi-streamwise vortices above a highly permeable wall and turbulence is dominated by relatively large structures that favor the exchange of momentum between the porous medium and channel region, and induce a strong increase in the Reynolds-shear stresses and consequently, a strong increase in the skin friction compared to an impermeable wall. Chandesris et al. (2013) by using the geometry and the flow parameters of Breugem and Boersma (2005), performed a similar DNS and studied the turbulent thermal field with a Prandtl number $Pr = 0.1$. They observed that large vortical structures over the permeable wall are responsible for momentum exchange between the free region and the porous region and they also cause a strong peak in the r.m.s temperature profiles deep inside the porous region. They indicated that this peak is not related to turbulent mixing, but to the large scale pressure waves that penetrate deeply inside the porous region.

Based on PIV measurements Suga (2015) and Suga et al. (2010, 2011) systematically investigated the effect of the wall permeability on turbulence. Suga et al. (2010) experimentally studied the effects of wall permeability on a turbulent flow in a channel with a porous wall. They considered different cases with almost the same porosity and three different permeabilities. They observed that velocity fluctuations in the wall-normal direction increase as the wall permeability increases. They concluded that permeability weakens the blocking effects of a porous wall. Suga et al. (2011) discussed the mechanism of development of near-wall vortex structures, based on experimental data for turbulent porous channel flow. By performing statistical analyses they observed that, in spite of similarities between turbulence structures for lower wall permeability and impermeable wall, turbulence structures tend to be disordered

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.07.010

Please cite this article as: S.Y. Motlagh, S. Taghizadeh, POD analysis of low Reynolds turbulent porous channel flow, International Journal of Heat and Fluid Flow (2016), http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.07.010

at high wall permeabilities. Eventually, they concluded that at high wall permeabilities, sweep and ejection processes near the wall tend to become stronger and weaker respectively; hence, streamwise velocity streaks hardly develop above permeable walls. Leu et al. (2008) experimentally investigated flow passing through porous structures mounted on the bottom of a rectangular open channel with different porosities. They reported that porous structures display the elongating of the recirculation region in the downstream direction due to the bleed flow passing through the gaps of the structures and turbulence intensity and Reynolds shear stress over the structures decrease as the structure porosity increases. Over a porous bed composed of glass spheres, Pokrajac and Manes (2009) experimentally measured the detailed velocity field. They examined the momentum exchange near the porous/fluid interface and observed that, due to the effect of the wall permeability, the energetic turbulent sweeps penetrated into the pores. Many other experimental studies were also reported (e.g., Keramaris and Prinos, 2009; Suga et al., 2013; Suga and Kuwata, 2014a; Zenklusen et al., 2014; Patil and Liburdy, 2015).

However, due to the complexity of porous structures and difficulty in measurements inside the porous media, understandings from experiments are mostly limited to bulk quantities and numerical simulation is a better choice to study turbulence inside the porous media. Hence, many numerical studies with a number of turbulence models such as, Reynolds average Navier–Stokes (RANS), LES and DNS have been attempted. Most of research studies on modeling turbulent flows in porous media are based on the k–e eddy viscosity model (EVM). Nakayama and Kuwahara (1999) applied the standard k- ε model to flows in a periodic array of square rods and referring to the simulation data they developed a macroscopic turbulence model. By utilizing a low Reynolds number (LRN) k- ε model, Teruel and Rizwan-uddin (2009) computed laminar to turbulent flows for square rod array flows and suggested a porosity dependent form for the drag coefficient. Pedras and de Lemos (2001) also simulated elliptic periodic rod array flows by a low Reynolds number $k-\varepsilon$ model to collect data for constructing turbulence models. Kundu et al. (2014) numerically studied the turbulent flow through porous media by considering the porous media as array square cylinders and they employed the low RE-k-ε-Lam-Bremhorst (LB) model for describing the turbulent flow in the porous region. Some other studies by similar methodologies were also carried out (e.g., Guo et al., 2006; Mathey, 2013). Kuwahara et al. (2006) performed a LES study for periodic array of square cylinders and observed that turbulence can appear in porous media at comparatively low Reynolds number and confirmed the validity of the Ergun's equation for the turbulent drag in porous media. Hutter et al. (2011) studied the influence of the geometric details of the porous material on turbulence by performing a LES study on the flow in open-cell structure porous media. There are also other high resolution pore-scale LES studies in the literature (e.g., Suga and Kuwata, 2014b; Kuwata and Suga, 2015).

Due to the simplicity of the wall treatment and high computer efficiency, the lattice Boltzmann method (LBM) also has got more attention to conduct pore-scale simulations (e.g., Suga et al., 2009; Suga and Nishio, 2009; Beugre et al., 2010; Parmigiani et al., 2011; Chukwudozie and Tyagi, 2013). Also, the strategies to perform LESs by the LBM have been utilized for turbulent porous medium flows (e.g., Suga et al., 2015; Kuwata and Suga, 2015). In order to systematically investigated the effects of wall roughness and wall permeability on turbulence, Kuwata and Suga (2016) performed direct numerical simulation (DNS) of porous- and rough- walled channel flows at the bulk Reynolds number of 3000 by utilizing the D3Q27 multiple-relaxation time lattice Boltzmann method. They used two-point autocorrelation, one-dimensional energy spectrum and proper orthogonal decomposition (POD) analyses to study the characteristics of the transverse pressure waves induced by the Kelvin–Helmholtz (K–H) instability over the porous and rough walls.

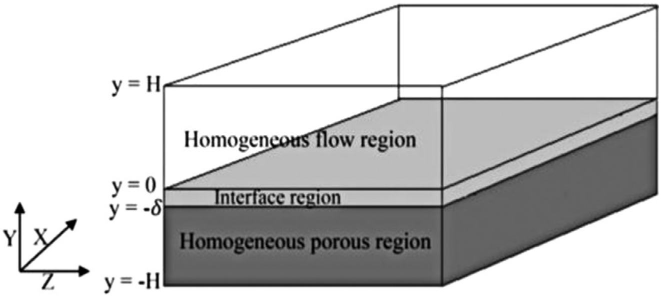

Fig. 1. Geometrical model of computation domain.

Although turbulent porous channel flow has been investigated extensively, yet there are some unknown regarding the precise flow dynamics and structures in the interface region over the porous wall and the nature and extent of impact of porous wall on dynamical traits of the turbulent flow. Two are the major motivations of this study: to study the accuracy and validation of the large eddy simulation (LES) method of turbulent channel flow over porous layers in different wall porosities and to investigate whether there is a fundamentally different self-sustaining process (SSP) at turbulent porous channel flow. As far as the authors know, there is no study to utilize the continuum approach in large eddy simulation of turbulent porous channel. Proper orthogonal Decomposition (POD) is one of the methods for mechanism study of turbulence which will be used as an effective tool to gain a vivid insight of the nature of dominant structures. POD (Berkooz et al., 1991; Sirovich, 1987) extracts a complete orthogonal set of spatial eigenfunctions (modes) from the measured second-order correlation function. The decomposition is optimal in the sense that energy convergence is more rapid than any other linear representation. The combination of the most energetic POD eigenfunctions is associated with the large scale, energy containing structure of the flow. Alfonsi and Primavera (2006) by utilizing the DNS method, simulated the flow of a viscous, incompressible fluid in a plane channel. They educed the dominant structures of turbulence by applying the POD technique. Podvin et al. (2010) by using POD method, investigated the flow structures in the near wall region based on measurements and information from upper buffer layer at two different Reynolds number. Wang et al. (2011) studied the mechanisms of drag and heat transfer reduction by utilizing POD algorithm and extracting multi-scale structures from DNS database. Yang et al. (2014) performed direct numerical simulations for turbulent nanofluid flows and they applied POD analysis to study coherent structures of temperature fields.

In this work we perform snapshot POD analysis (Sirovich et al., 1991; Sirovich and Rodriguez, 1987) because of its computational efficiency, this method uses the correlation of instantaneous snapshots of the flow and thus reduces the order of the eigenvalue problem to that of the number of snapshots and not the physical mesh. Firstly, large eddy simulation of turbulent flow over a permeable wall at three different porosities 0, 0.8 and 0.95 were performed to create snapshots. Finally, POD analyses of these snapshots were taken to study the influence of wall permeability on dynamical features of the flow.

2. Physical model and governing equations

In this study, we carried out LES simulations for fully developed turbulent channel flow by utilizing the geometry and the flow parameters of Breugem et al. (2006). The flow geometry and coordinates are shown in Fig. 1. The flow domain consists of three parts:

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