International Journal of Heat and Fluid Flow 73 (2018) 16–29

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Experimental study of turbulent flow over *and* within cubically packed walls of spheres: Effects of topography, permeability and wall thickness

Taehoon Kim[a,b], Gianluca Blois[b], James L. Best[a,d], Kenneth T. Christensen[b,c,e,*]

[a] Department of Mechanical Science and Engineering, University of Illinois, Champaign, IL, USA.
[b] Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN, USA.
[c] Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, IN, USA.
[d] Departments of Geology, Geography and Geographic Information Science and Ven Te Chow Hydrosystems Laboratory, University of Illinois, Champaign, IL, USA
[e] International Institute for Carbon Neutral Energy Research (WPI-I2CNER), Kyushu University, Fukuoka, Japan

ARTICLE INFO

Keywords:
Turbulent flow
Permeable wall
Flow interaction
PIV measurement
Refractive-index matching

ABSTRACT

Results of high-resolution particle-image velocimetry (PIV) measurements are presented to explore how turbulent flow overlying a permeable wall is linked to the underlying pore flow and how their interplay is controlled by the topography of the wall interface and wall thickness. Two permeable walls were constructed from uniform spherical elements (25.4 mm diameter) in a cubically packed arrangement (porosity ~ 48%): one with two layers of spheres and the other with five layers. In addition, an impermeable rough wall with identical topography was considered as a baseline of comparison in order to explore the structural modifications imposed by permeability in the near-wall region. First- and second-order velocity statistics provide a quantitative assessment of such modifications of the local flow. A double-averaging approach allowed investigation of the global representation of the flow and assessment of conventional scaling parameters. A momentum deficit in the first pore layer and subsequent recovery beneath is observed, consistent with previous studies, as is a decay of the turbulent fluctuations. The transitional layer resides at the wall interface where free flow and pore flow interact, exchanging mass and momentum through intermittent turbulent events. Statistical investigation based on conditional averaging reveals that upwelling and down-welling flow events are associated with the passage of large-scale, low and high streamwise momentum free flow near the wall, respectively.

1. Introduction

Turbulent flow overlying permeable walls is encountered in a range of environmentally- and industrially-relevant systems across seemingly disparate fields of science and engineering. In natural systems, permeable interfaces occur over a broad range of scales (Ghisalberti, 2009), spanning from small-scale biological interfaces (Khakpour and Vafai, 2008) to large-scale geophysical systems, such as alluvial river beds (Best, 2005; Blois et al., 2012) and aquatic and atmospheric canopies (Raupach et al., 1996; Nepf, 2012). In the case of geophysical systems, turbulence is actively involved in morphodynamic as well as environmental processes [i.e. contaminant transport and exchange; (Packman et al., 2004)]. Due to their larger specific surface area, porous media (e.g. foams, cylinder bundles, packed beds) are also prevalent in many industrial systems owing to their ability to enhance the kinetics of processes such as heat and mass transfer. Modern nuclear plants (El Hassan et al., 2015) and fuel cells (Wang et al., 2001) are relevant examples of industrial applications utilizing porous structures. However, despite the critical technological and social implications of these flows and decades of research focused on developing representative theoretical and numerical models, the physics of permeable-wall turbulence remains poorly understood.

A wall-bounded turbulent flow system that includes a permeable wall can be subdivided into two distinct flow regions, separated by a porous interface. The first is the surface (or free) flow, which overlies the interface. The second is the subsurface (or pore) flow, which occurs within the permeable wall. While the near-wall surface flow can be turbulent, deep within the subsurface the flow is often laminar and can be described by Darcy's law (a balance of viscous and pressure forces). Thus, a region must exist between these two extremes where the flow undergoes a transition from inertia-dominated turbulence to viscous-dominated, laminar flow across the permeable interface. This region, termed the "transitional layer," is marked by significant momentum and energy exchange and is the focus of increasing scientific interest.

* Corresponding author.
E-mail address: christensen.33@nd.edu (K.T. Christensen).

https://doi.org/10.1016/j.ijheatfluidflow.2018.06.004
Received 1 December 2017; Received in revised form 9 May 2018; Accepted 11 June 2018

While the near-wall surface flow is similar to that of a boundary layer overlying an impermeable surface, wall permeability introduces new characteristic scales and complex flow mechanisms promoted by the slip and penetration conditions at the permeable interface.

Alluvial river beds, which are the inspiring system of the current work, can be modeled as permeable walls with a rough interface. Due to the presence of significant subsurface flow through the uncohesive grains (hyporheic zone), the near-bed flow is conceptually different from the canonical notion of flow over an impermeable rough wall. The near-bed hyporheic flow is driven by the interplay between the topography, or roughness (i.e. grains at the bed interface protruding into the surface flow), and the permeability (interstitial fluid-filled spaces in the porous structure). The current effort explores the differences in turbulent flow overlying an idealized highly permeable rough wall which mimics a coarse-grained river bed and an impermeable wall of identical topography.

Wall permeability enhances the friction factor at the permeable interface compared to flow over impermeable surfaces. Zagni and Smith (1976) performed pitot-tube measurements in an open channel flow over a permeable wall constructed of spheres. They reported that the friction factor (*f*) over the permeable wall was higher than that produced by an impermeable wall of identical topography. A similar effect was also reported by Kong and Schetz (1982) and Zippe and Graf (1983). This increase in *f* is likely associated with the enhanced energy dissipation across the permeable interface owing to momentum exchange between the pore flow and the surface flow. More recently, several investigations demonstrated that this increase in *f* is accompanied by modifications to the near-interface flow structure. The degree of wall porosity and the wall thickness are key parameters in controlling such modifications as they alter the intensity of the interactions (Breugem et al., 2006; Suga et al., 2010; Manes et al., 2011). Breugem et al. (2006) performed direct numerical simulations (DNS) of turbulent channel flow and, using numerical artifacts, they maintained smooth-wall conditions while varying wall permeability. This approach allowed them to avoid unwanted roughness effects and thus decouple permeability and topography effects. Among other observations, their results showed the disappearance of quasi-streamwise near-wall streaks when the wall porosity was high ($\varphi = 95\%$), suggesting that permeability alone induces structural modifications of the overlying turbulence. Such modifications include the shape of the velocity profiles as well as the statistical distribution of turbulent events. Validating these results required a number of years of research due to the inherent technical challenges involved with replicating Breugem's permeable wall conditions in an experimental setting. Suga et al. (2010) and Manes et al. (2011) performed direct measurements of flow over a number of walls made of foam with different porosities and claimed that this permeable material is suitable for achieving smooth-wall conditions. Both studies corroborated the notion that wall permeability does impact the near-wall turbulence.

One of the most controversial aspects of the flow over permeable walls is whether Townsend's hypothesis of outer-layer similarity (Townsend, 1980) exists in the surface flow. This notion of similarity implies that, while the conditions at the wall set the bulk charateristics of the flow (outer length scale and wall friction), the turbulence adjusts iteself to be similar to smooth-wall flow when scaled with these characteristics. This similarity is often observed in flow over impermeable rough walls for which the characteristic roughness height is small compared to the outer length scale of the flow (Flack et al. 2005, Wu and Christensen 2007, for example). In the case of turbulence overlying a permeable wall, Breugem et al. (2006) reported that such a condition was not achieved in their simulations, owing to the weakened wall blocking effect of the permeable wall with the highest porosity. Unlike Breugem et al. (2006), Manes et al. (2011) showed similarity in the outer layer for both the mean and turbulence intensity profiles. Manes et al. (2011) attributed the occurrence of this outer-layer similarity to the relatively high Reynolds number (*Re*) of their experiments coupled with the much higher ratio between shear penetration depth and the boundary layer thickness as compared to that of Breugem et al. (2006).

The very nature of the flow *within* a permeable bed is also the subject of debate. For example, Ruff and Gelhar (1972) conducted hot-wire measurements of flow over a foam-type porous bed in a pipe flow and reported that mean velocities and turbulence intensities decayed exponentially within the porous bed. Unlike the accepted notion that the turbulent fluctuations decay in a monotonic manner, the behavior of the mean velocity profile within the bed is still under study. Manes et al. (2009) employed an ultrasonic profiler to examine the pore flow in a turbulent open channel flow with cubically-packed spheres. Measuring the velocity at various depths inside the bed, they found that the mean streamwise component of velocity just beneath the interface was lower that in the layers below. This observation challenges the classical notion of monotonic mean velocity decrease, which is well-established for laminar flows. The most compelling theory for this unexpected behavior is that turbulence, which controls surface–subsurface interactions throughout the transitional layer, may be responsible for the modifications of the mean flow across the interface.

Taken together, the impact of wall permeability on the surface and subsurface flows and the turbulence interactions between these two flow regimes is still not as well-understood as that of impermeable smooth- and rough-wall turbulence owing to challenges both in computations and experiments. In the case of Breugem et al. (2006), their simulation was limited to low Re, which means that a fully turbulent flow may not be formed over the permeable wall. Experiments, on the other hand, face practical challenges in achieving quantitative observations of the flow, particularly in the critical transitional layer near and within the porous bed. For example, modern optical methods like particle-image velocimetry (PIV) are severely limited in this flow region due to light reflections at the wall interface and the opaque nature of a standard porous wall (Pokrajac and Manes, 2009).

The goal of the current study is to experimentally explore the role of permeability in surface–subsurface turbulent interactions across the interface of a packed bed of spheres meant to represent a simplified gravel-river bed. In this scenario, the interface dynamics are predominantly controlled by porosity, bed thickness and bed topography. To this end, extreme cases of high and low permeability were considered to account for large gravel (> 5 cm) and armored beds, respectively, using a periodically-packed bed of uniform spheres formed from acrylic. By deploying these permeable beds in a flume whose working fluid has the same optical refractive index as the acrylic, the solid matrix effectively disappears allowing PIV measurements to be made both above and within the permeable beds. These data were analyzed using statistical and conditional averaging methods to explore the nature of turbulence interactions across the permeable interface for two different bed thicknesses.

2. Experiments

2.1. Flow facility and wall models

All experiments were conducted in a closed-loop refractive-index matching (RIM) flow facility at the University of Notre Dame (Blois et al., 2012). The test section is 2.5m long and its cross-section is 0.11 m × 0.11 m, constructed with acrylic. This flow facility provides a turbulent boundary layer flow and enables a bulk *Re* of $\sim 10^5$ (or up to $1.0\ \mathrm{m\ s^{-1}}$ free stream velocity). An aqueous solution of sodium iodide (NaI), ~63% by weight, was employed as the working fluid for the experiments herein. The specific gravity and kinematic viscosity (ν) of the NaI solution at ambient temperature are about 1.8 and $1.1 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$, respectively. The refractive-index (RI) of the solution is ~1.496 at 20 °C (Budwig, 1994). Since the RI of the fluid is very sensitive to temperature (Narrow et al., 2000), it was controlled using an in-line heat exchanger which allowed fine tuning with a