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Vortex structure of turbulence over permeable walls

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ABSTRACT

In order to understand the effect of the wall permeability on the turbulent vortex structure near porous walls, based on PIV experimental data, a probability density analysis of fluctuating velocities, statistical quadrant and quadrant-hole analyses of the Reynolds shear stress are performed. The investigated flow fields are turbulent channel flows whose bottom walls are made of porous media. The porous media used are three kinds of foamed ceramics which have almost the same porosity ($\sim$0.8) but different permeability. From the discussions on those analyses, a conceptual scenario of the development of the vortex structure near a permeable wall is proposed for a moderate permeability Reynolds number case. It explains the reason why the near-wall long streaky structure tends to vanish near a porous wall with increasing wall permeability.

1. Introduction

It is now well known that turbulence has coherent structure near a solid impermeable wall because of shear production. Using dye injection at a wall, its trace was firstly observed in the 1950s (Corrsin, 1957). Since then understanding the structure of turbulent boundary layers has been an important issue because it helps us to develop a turbulent flow control technique for reducing surface friction of a flow passage either passively or actively. By the hydrogen-bubble flow-visualisation technique, Kline et al. (1967) discussed in detail the phenomena which was later named bursting (Kim et al., 1971) in a turbulent boundary layer. They observed streaky structure near the wall consisting of alternating high and low-speed regions which were considerably elongated in the streamwise direction. Based on hot-wire measurements, quantitative discussions of this coherent structure in turbulent boundary layers have been widely performed by various conditional sampling techniques such as the variable-interval time-averaging (VITA) (Gupta et al., 1971) and the conditional sampling quadrant analysis (Wallace et al., 1972; Willmarth and Lu, 1972). The conditional sampling has been extensively used to quantitatively recognise the flow field data related to organised coherent structure for supplementing qualitative information by flow-visualisation experiments. (See the review by Antonia, 1981.)

By the development of the particle image velocimetry (PIV), both quantitative and qualitative discussions became possible with the flow-visualisation data. Using PIV experimental data, Adrian et al. (2000) and Tomkins and Adrian (2003) thus discussed detailed vortex organisation in the outer region of turbulent boundary layers and proposed a conceptual scenario of vortices growing up from walls. Discussions by the direct numerical simulation (DNS) also provided large amount of information regarding the coherent structure in sheared turbulence. The coherent structure of turbulence over a smooth wall has been therefore well revealed by a large number of experimental and numerical studies (e.g. Cantwell, 1981; Robinson, 1991; Moin and Mahesh, 1998; Adrian et al., 2000; Tomkins and Adrian, 2003; Wu and Moin, 2009). Indeed, the generation of the hairpin vortex packets near a wall, which was detected by the PIV study of Adrian et al. (2000), was well visualised by the DNS of Wu and Moin (2009).

However, when the wall is made of a porous material, the flow characteristics become very different from those of the flows over solid walls. Compared with the solid wall flows, flow characteristics are not very well understood in the porous wall flows. Understanding the flow characteristics over porous walls is also important since flows over porous walls can be seen in many industrially important devices such as catalytic converters, metal foam heat exchangers and separators of fuel cells. (Unless pores inside porous media are interconnected, the porous media do not have permeability. Thus, porous media concerned here are permeable porous media.) Beavers and Joseph (1967) thus firstly performed measurements of the friction over porous walls. They measured mass flow rates over porous media in laminar flow conditions and found that the mass flow rates increased compared with those in impermeable cases. This means that the friction over porous permeable walls tends to be smaller than those over impermeable walls. Many other following studies also focused on the laminar flow regime (e.g. Gupte and Advani, 1997; Rudraiah,

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Nomenclature

d^h	deviation from the minor axis of a distribution oval
d^v	deviation from the major axis of a distribution oval
D_p	mean pore diameter
D^f_{m,H_ϕ}	duration fraction
H	channel height
H_ϕ	hole size based on ϕ
K	permeability
N, N_m	sampling number, conditional sampling number of the mth quadrant
$p(u', v')$	joint probability density function of (u', v')
Re_b	bulk Reynolds number: U_bH/ν
Re_K	permeability Reynolds number: $u^p_\tau\sqrt{K}/\nu$
Re_τ	shear Reynolds number: $u^p_\tau\delta/\nu$
S^f_{m,H_ϕ}	stress fraction
U_b	bulk mean velocity
u, v	instantaneous streamwise and wall normal velocity components
u', v'	streamwise and wall normal turbulent intensities
u^p_τ, u^t_τ	friction velocities at porous bottom and solid top walls
x	streamwise direction
y	wall normal direction or wall normal distance
y^{p+}	$u^p_\tau y/\nu$
δ	$(u^p_\tau)^2H/\{(u^p_\tau)^2 + (u^t_\tau)^2\}$
ν	kinematic viscosity
θ	angle between u'-axis and the major axis of a distribution oval
φ	porosity
$(\ )^p$, $(\ )^t$	variable at the porous wall, value at the top wall
$(\ )^{p+}$, $(\ )^{t+}$	normalized values by u^p_τ and u^t_τ

1985; Sahraoui and Kaviany, 1992; James and Davis, 2001). It should be noticed that the flow physics, even in laminar flows, is rather complicated. One of the characteristic features is the slip velocity at the surface of the porous layer. From a macroscopic viewpoint, there can be seen a slip velocity at the porous wall because a fluid slips at pores of the interface though it does not slip at solid surfaces. Depending on the porosity and the permeability of the surface, this slip velocity makes the wall friction different from that of an impermeable wall. (See the discussions by Beavers and Joseph (1967), Ochoa-Tapia and Whitaker (1995), Alazmi and Vafai (2001) and Suga and Nishio (2009).)

Although the laminar friction over porous walls is smaller than that over solid walls, turbulence turns over this tendency. Since some geophysical fluid flows, i.e. water flows over river beds and air flows over vegetation, are concerned as flows over permeable surfaces, civil engineers firstly performed turbulent flow measurements over permeable beds. The measurements by Lovera and Kennedy (1969), Ruff and Gelhar (1972) and Zagni and Smith (1976) concluded that the friction factors over porous walls were higher than those over impermeable rough-walls. Indeed, the conclusion of Zagni and Smith (1976) was that energy losses resulting from the shear flow inside the porous bed caused the overall friction loss to be greater than that for a flow over an equivalent impermeable bed. The increase of the skin friction was attributed to the combined effects of roughness and porosity (Kong and Schetz, 1982; Zippe and Graf, 1983). The momentum exchange process across the interface was discussed by Shimizu et al. (1990), Vollmer et al. (2002) and Pokrajac and Manes (2009). From these studies it was recognised that due to the permeability, the momentum flux like the Reynolds stress was enhanced near the interface.

The summary of the understandings by the above studies on the turbulent porous wall flows is that flow energy is dissipated within the near-surface transitional zone in the porous medium and the momentum exchange across the interface is transported back to the main flow. These result in an additional energy loss and thus the net effect of the wall permeability is to increase the boundary friction compared with that in an impermeable wall boundary layer. The permeability enhances the additional flow phenomena causing friction losses which are superimposed on those by surface roughness. (A more detailed survey of the former studies is in our previous paper: Suga et al., 2010.)

Recently, this turbulence effect has been systematically investigated by numerical simulation (Breugem et al., 2006) and PIV measurements by the present authors' group (Suga et al., 2010). The main conclusion of these studies is that due to the weakened wall blocking effects by the wall permeability, the wall normal fluctuating velocity is not completely damped and this leads to the high wall shear stress over the permeable walls. Breugem et al. (2006) also showed that the streaky structure in vorticity was weakened by the increase of the wall permeability. They discussed on the origination of the structure and concluded that a Kelvin–Helmholtz type of instability was the main factor in a higher permeability case. From the statistical view point, based on the PIV measurement, Zhu et al. (2007) discussed the turbulence within and above a corn canopy using the conditional quadrant analysis of Willmarth and Lu (1972). They concluded that the dominant contribution of the sweeps and ejections to the shear stress was consistent with the results of impermeable wall turbulence of Raupach (1981) and that the sweeps are the largest contributors to both the vorticity and the Reynolds stress. Although the canopy flow is a sort of a permeable wall flow, as far as the authors' knowledge, the effects of parameters such as the porosity and the permeability on the flow structure have not been studied. From the view point of mechanical engineering, such parameters are important engineering parameters.

Since understanding the turbulent vortex structure is essential for controlling the turbulence over permeable walls, studying its origination and the effects of the engineering parameters of the porous media is important. Therefore, the present study attempts to investigate the mechanism of the development of the turbulent vortex structure over permeable walls using conditional statistics of the PIV experimental data focusing on the effects of the wall permeability.

2. Experimental methods

Although the detailed description of the present experimental methods, procedures and their uncertainty was addressed in our previous paper (Suga et al., 2010), its essence is repeated briefly.

Fig. 1 illustrates the present experimental setup. Tap water is pumped up from a water tank, and its total flow rate is measured by a digital flow meter. The water flow is rectified by a honeycomb-bundled nozzle, where its temperature is recorded by a digital thermometer. Then the flow is fully developed in a driver channel whose length is $L_D = 3.0$ m and enters the test section whose length is $L_T = 1.0$ m. The channel consists of solid smooth acrylic top and side walls and a porous bottom wall. The thickness of the porous wall is about 0.03 m which was the same as the channel height H for the clear fluid region whose width W is 0.3 m. Thus the aspect ratio of the cross section is $W/H = 10$.

By controlling the output of the pump with the power converter, flow rates are adjusted to set the range of the bulk Reynolds