Quadrant analyses of separating and reattaching turbulence over rib-mounted porous walls

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Abstract. In order to understand the effect of the wall permeability on the turbulent vortex structure in a recirculating flow near a porous wall, based on the PIV experimental data of rib-mounted porous wall flows, quadrant and quadrant-hole analyses of the Reynolds shear stress are performed. The investigated flow fields are turbulent flows in rib-mounted channels whose bottom walls are made of porous media. Three kinds of porous media are used. They have almost the same porosity but different permeability. From the discussions through the analyses, as the wall permeability increases each quadrant event of the Reynolds shear stress tends to be damped in the region behind the rib and the vortex motions having stronger vertical fluctuating energy appear. It is considered that this vertical fluctuation comes from a perturbation mode which is similar to that induces the Kármán vortex.

1. Introduction

It is well known that highly permeable porous media have advantages in heat and mass transfer due to their large contact area. Thus, they are used in various engineering devices such as heat sinks and catalytic converters. As fluids flow around those highly porous media, understanding flow phenomena near the surface is important for engineers. However, flow physics near permeable walls, especially in turbulent flow regimes, is not fully understood though a number of studies have been performed. To provide engineering guidelines, it is important to investigate the effects of engineering parameters such as permeability and porosity of the materials on flow fields. Therefore, PIV measurements of porous channel flows have been performed by our group for understanding the effects of the wall permeability on turbulence. The results indicated that the net effect of the wall permeability is to increase the surface friction compared with that in an impermeable wall boundary layer (Suga et al., 2010). Furthermore, based on the PIV experimental data, a probability density analysis of fluctuating velocities, statistical quadrant and quadrant-hole analyses of the Reynolds shear stress were performed in order to investigate the relation between the wall permeability and the turbulent vortex structure near porous walls. From the discussions on those analyses, a conceptual scenario of the development of the vortex structure near a permeable wall was proposed for moderate permeability Reynolds number cases. It indicated that due to the increase of the wall permeability, the near-wall long streaky structure tended to vanish (Suga et al., 2011).

When an obstacle is mounted in the flow field, the flow behind it is drastically disturbed and the heat transfer coefficient becomes maximum near the reattachment point of a separation bubble behind the obstacle. A large number of related studies have thus been performed both...
experimentally and numerically. However, such a flow on a highly permeable wall has not been well studied. As those flow fields have large-scale turbulence, it is important to know the effects of the wall permeability on such large-scale eddy motions. Thus, by the PIV experimental facility used in our previous report (Suga et al., 2010), turbulent flows over rib-mounted permeable walls have been measured (Tominaga et al., 2011). The obtained mean velocity profiles of the rib-mounted flows have suggested that the reverse flow in the recirculation behind the rib becomes weak as the increase of the wall permeability. It has been considered that this resulted from the increase of the by-passing flow rate through the bottom porous wall underneath the rib.

To understand the vortex flow motions further, the present study attempts to discuss the mechanism of the turbulent vortex structure over rib-mounted permeable walls. By using conditional sampling methods to the PIV experimental data, the effects of the wall permeability are discussed in detail.

2. Experimental methods and Measurement conditions

The experiment setup used in the present study contains a channel flow facility and a PIV system. The channel flow facility consists of a rectifier device, a drive section and a test section. Fig.1 illustrates the present experimental flow geometry in the test section. One of the channel walls is a solid smooth acrylic wall (top wall) while another is a permeable wall (bottom wall) which is made of a porous medium. Three kinds of porous media are used. They have almost the same porosity $\phi$ but different permeability $K$ as listed in Table 1. The thickness of the porous layer is 0.03 m which is the same as the height $H$ of the clear channel fluid region. The channel width $W$ is 0.3 m, thus the aspect ratio of the cross section is $W/H = 10$. Hence, the flow is nominally two-dimensional near the symmetry plane of the channel. (This is also confirmed by the preliminary measurements.) In the test section, a square sectioned solid rib whose height is $h = H/2$ is mounted on the bottom wall. Upstream the test-section, there are the rectifier device and the drive section whose length is 3 m. Therefore, the flow is fully developed in the measurement zone of the test-section. The working fluid is tap water and the flow rate is adjusted to set the bulk Reynolds number as $Re_b(=\rho U_b H/\mu)= 1000 \sim 10000$ by controlling the output of the water pump through a power converter. Here, The viscosity $\mu$ and the density $\rho$ are estimated using the measured water temperature. The bulk mean velocity $U_b$ is obtained by integrating the measured sectional mean velocity profile at $x/h = -5$(see Fig.1, back side of the rib is the origin: $x = 0$) where the flow is almost unaffected by the rib.

The two-component PIV (Dantec Dynamics) consists of a double-pulse Nd-YAG laser (15Hz , 120mJ/pulse , $\lambda=532nm$), a CCD camera (2048×2048 pixels), a camera lens (Nikon Micro-Nikkor 60mm f/2.8D), and a computer for data acquisition. The thickness of the light sheet is approximately 1.0 mm. The sheet illuminates the symmetry plane of the channel through the top wall, where the instantaneous images are recorded by the CCD camera. The size of a single measurement zone is $30\times30mm^2(2048\times2048$ pixels).To cover the measurement area of $x/h = -5 \sim 8$, the camera is moved 8 times in a parallel fashion. Each measurement zone is set to have 15% overlapping areas with both the neighbour zones. The tracer particles of the PIV
measurement are acrylic colloid particles whose specific gravity is 1.19 and mean diameter is 3.1 µm. In each interrogation window area whose size is set to 32×32 pixels, the seeding density is adjusted to have more than 10 particles. The uncertainty in the measured displacement can be expected to be less than 5% of the diameter of the particle image. The estimated uncertainty interval at 95% coverage is 0.04U_b for the statistical velocity. To obtain the statistical data, in each zone, 4800 image pairs are processed.

3. Results and discussions

3.1. General flow fields

To provide general ideas of the presently discussed flows, Fig.2 shows the mean flow patterns reported by Tominaga et al. (2011). Fig.2(a) shows the mean streamwise velocity U profiles. Figs.2(b) and (c) compare the effects of the wall permeability on the streamlines at Re_b = 4000. Since a part of entraining fluid is supplied through the permeable bottom wall from the region upstream the rib, the magnitude of the reverse flow of the recirculation behind the rib becomes lower as the increase of the wall permeability (as in Table 1, the permeability increases as #20 → #06). The separation bubble thus becomes smaller as the increase of the wall permeability and eventually turns into a blowing flow region as shown in Fig.2(c).

For understanding the vortex structure and the mechanism of the phenomena in the region behind the rib, the following section performs statistical analyses such as quadrant and quadrant-hole analyses of the Reynolds shear stress.

3.2. Quadrant analysis

Fig.3 compares the decomposed Reynolds shear stress profiles of three kinds of porous medium (#20,#13,#06) used for the bottom wall in the rib-mounted channel flow using the quadrant analysis method. The bulk Reynolds number is Re_b = 4000 and four locations are considered from x/h = 1.5 ~ 6.0. The profile of Q_m is defined as Q_m = (uv)_m = Σ(u'v')_m/N_m where the subscript m (=1-4) denotes each quadrant event. The magnitude of each profile is normalized by the reference friction velocity determined at x/h = -5.0 where the conditions
Figure 3. Quadrant analysis of the Reynolds shear stress at $Re_b \approx 4000$; (a) case #20; the broken line denotes positions of $U = 0$, (b) case #13, (c) case #06.

are confirmed to be the same as those in the corresponding fully developed porous-channel flow. In Fig.3, it is indicated that strong turbulence is generated by the rib and the magnitude of each quadrant event indicates the maximum value at $x/h = 1.5$. With the development of the flow downstream the rib, turbulence is spread into the whole channel region and the magnitude tends to be weakened.

It is obvious that the events in the second quadrant(Q2) and those in the fourth quadrant(Q4) become dominant compared with those in the first and third quadrants(Q1 and Q3). Additionally, the contribution of Q4 becomes more dominant near porous wall side than that of Q2. It is recognized that due to the increase of the wall permeability(#20 → #13 → #06) the area where the profiles diminish is enlarged near the porous walls. In the region behind the rib($1.5 \leq x/h \leq 3.0$), as the wall permeability increase the contribution of each event is more damped rapidly near the permeable wall($0 \leq y/H \leq 0.3$). As, Tominaga et al. (2011) confirmed the more permeable the porous wall became, the more by-passing flow came through the porous wall resulting in weakening the recirculation bubble. Thus, the turbulence in the reverse/stagnating flow region looses its strength. In the recirculation bubble, although each quadrant event tends to be damped as the increase of the permeability in the region behind the rib, it may not mean that turbulent vortex motions are totally damped there. Therefore, to investigate this further, the quadrant-hole analysis is performed based on the way of Willmarth & Lu (1972).

3.3. Quadrant-hole analysis

Fig.4 compares the duration fraction against the hole size $H_r$ based on the Reynolds shear stress at $1.5 \leq x/h \leq 6.0$. The hole size and the duration fraction are defined as $H_r = \left[\left( u'v' \right)_{\text{threshold}} / \left( u'v' \right)^{\text{ref}} \right]$ and $D_{m,H_r}^f = \sum I_{m,H_r} / \sum N_m$, respectively, where the indicator
Figure 4. Duration fraction of the Reynolds shear stress at \( \text{Re}_b \approx 4000 \): (a) case \#20 at \( y/H = 0.1 \), (b) case \#06 at \( y/H = 0.1 \), (c) case \#20 at \( y/H = 0.3 \) (d) case \#06 at \( y/H = 0.3 \).

function \( I_{m,H} \) is defined as \( 1 \) if \( (u', v') \) is in \( Q_m \) and \( |u'v'| \geq H_r\text{ref} \) otherwise it is zero. The value of \( |u'v'|\text{ref} \) is the Reynolds shear stress at the reference point \( x/H = -5 \) in each condition. By the definition, \( D_{m,H} \) means the probability density of the event.

In Fig.4, it is clearly recognized that generally, the events in Q2 and Q4 which contribute to the production of turbulence are dominant compared with those in Q1 and Q3. With increasing the distance from the permeable wall, it is obviously shown that the duration fractions in all events are enhanced. By comparing Figs.4(a) and (b) or Figs.4(c) and (d), it can be noted that due to the increase of the wall permeability \( \#20 \rightarrow \#06 \) the contribution of each event is decreased at \( x/H = 1.5 \) and 3.0. It is thus confirmed that the probability of turbulent eddy motions having large strength tends to decrease near the porous wall behind the rib as the increase of the permeability. In other words, since the increase of the wall permeability induces more by-passing flow rate through the bottom wall underneath the rib, it is hard for turbulent vortex motions to be convected from the shear layer. This corresponds to the fact that turbulence tends to be damped just behind the rib as the increase of the wall permeability.

To discuss the energy containing eddies, Fig.5 shows the duration fraction of the Reynolds shear stress near porous walls at \( y/H = 0.05 \) based on \( H_{u'} \) and \( H_{v'} \) which are defined as respectively, \( H_{u'} = |(u')_{\text{threshold}}|/|\sqrt{u'^{2}\text{ref}}| \) and \( H_{v'} = |(v')_{\text{threshold}}|/|\sqrt{v'^{2}\text{ref}}| \). This analysis indicates which turbulent intensity component \( u' \) or \( v' \) is contributed to the magnitude of \( uv' \). In Fig.5, it is obvious that in case \#06 at \( x/H = 1.5 \), the distribution based on \( H_{u'} \) is much larger than that of \( H_{v'} \) though in case \#20 and case \#06 at \( x/H = 6.0 \), the distributions based on
Figure 5. Duration fraction of the Reynolds shear stress based on $H_u', H_v'$ at $Re_b \approx 4000$; (a) case #20, (b) case #06.

$H_u'$ and $H_v'$ are in nearly the same level. As the increase of the permeability, the more vortex motions having vertical fluctuation energy only appear behind the rib ($x/h = 1.5$). This means the vortex structure there is different from the other areas. It is then considered that due to the increase of the permeability, a perturbation mode, which is similar to that induces the Kármán vortex, tends to appear behind the rib causing the vertical fluctuation.

4. Conclusions

By the quadrant analysis, it is confirmed that each quadrant event tends to be damped as the increase of the permeability in the region behind the rib. From the discussion on the quadrant-hole analysis, as the wall permeability increases the more vortex motions having strong vertical fluctuation appear behind the rib. This indicates that the by-passing flow through the permeable bottom wall affects the flow field and turbulent structure behind the rib. In the higher permeability case (#06), since the entrainment flow to the shear layer behind the rib is more supplied from the by-passing flow, a perturbation mode, which is similar to that induces the Kármán vortex, tends to be generated behind the rib.

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