COUNTER-GRADIENT DIFFUSION OF REYNOLDS STRESS IN TURBULENT COUETTE FLOW WITH FORWARD-FACING STEP

Yohei Morinishi[1], Daiki Yoshikawa[1] & Shinji Tamano[1]
[1]*Nagoya Institute of Technology, Nagoya, Japan*

Abstract The turbulent Couette flow with a forward-facing step (sudden contraction) is investigated experimentally and numerically. The particle image velocimetry (PIV) measurement and direct numerical simulation (DNS) prove peculiar turbulence behavior, the counter-gradient diffusion of the Reynolds stress, near the front part of the corner separation on the forward step. The negative turbulence production which follows the counter-gradient diffusion is then evaluated through quadrant analysis. The negative contribution of Q1 and Q3 events inside the shear layer increases with decreasing the Reynolds number. The effect makes the counter-gradient diffusion rather pronounced in lower Reynolds number flows.

INTRODUCTION

The counter-gradient diffusion of the Reynolds stress and heat transfer has recently been observed in the direct numerical simulation (DNS) of flows around bluff body and forward-facing step in boundary layers [1, 2]. In the present study, the counter-gradient diffusion of the Reynolds stress is experimentally investigated in a Couette flow with a forward-facing step (sudden contraction) as a canonical turbulence field. The particle image velocimetry (PIV) measurement proves the counter-gradient diffusion around the corner separation on the forward step. The negative turbulence production which follows the counter-gradient diffusion is then evaluated through quadrant analysis. The direct numerical simulation (DNS) of the flow is also submitted to support the analysis.

EXPERIMENTAL AND NUMERICAL OUTLINES

Figure 1 shows the overview of the present experimental apparatus. The upstream flow is a fully developed turbulent Couette flow between moving and stationary walls with the duct aspect ratio of 21.6. The channel flow apparatus was also used in our previous experimental study of backward-facing step flow between moving and stationary walls [3]. In this study, the forward-facing step (step height H = 20 mm) on the stationary wall with contraction ratio of 0.5 is located at 3500 mm downstream of the channel inlet. The stationary and side walls around the step are made of transparent acrylic walls, and PIV measurement is conducted with double-pulse YAG laser (70 mJ/pusle) and CCD camera (1600×1200 pixels).

Figure 2 shows an instantaneous velocity field by PIV measurement. Tracer particles for the PIV are olive oil mist supplied upstream of the channel. The Reynolds number $Re_{c0} = U_{c0}H_1/\nu$ based on the upstream channel height H_1 and upstream mean centerline velocity U_{c0} is set at 3000, 5000, and 10000, where the flow is driven by the moving wall with velocity $U_w = 2U_{c0}$.

The DNS of the forward-facing step flow is also submitted at Re_{c0} = 3000 for comparison. In the DNS, the incompressible Navier-Stokes equations are solved using the fully conservative convection scheme in a staggered grid [4] and the implicit mid-point time-marching method [5], which results in an absolutely stable method in principal. Consequent set of fully implicit equations is solved using Jacobian-free Newton-Krylov method.

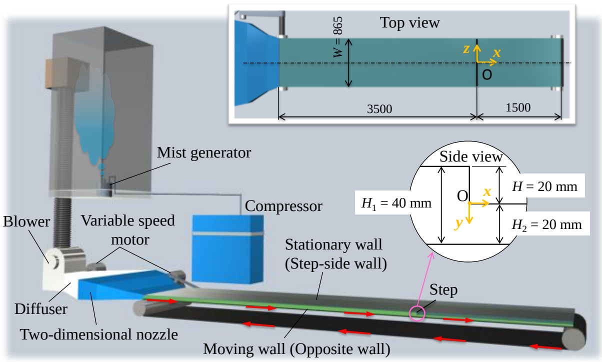


Figure 1. Experimental apparatus

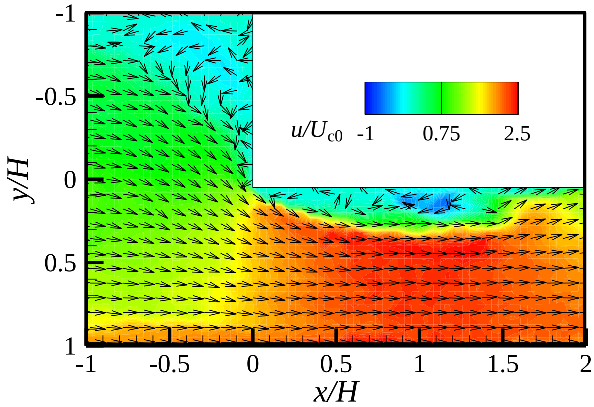


Figure 2. An instantaneous velocity field by PIV

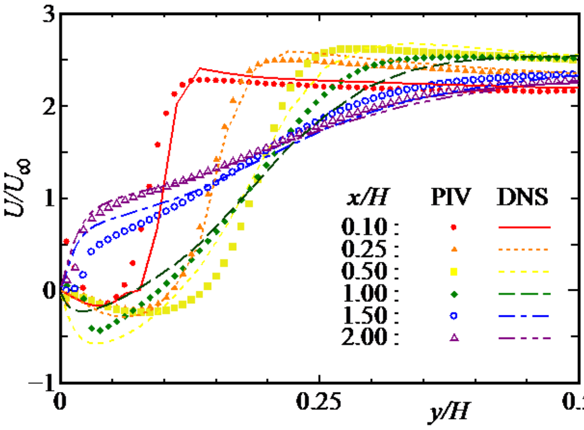


Figure 3. Comparison of PIV and DNS results at Re_{c0} = 3000

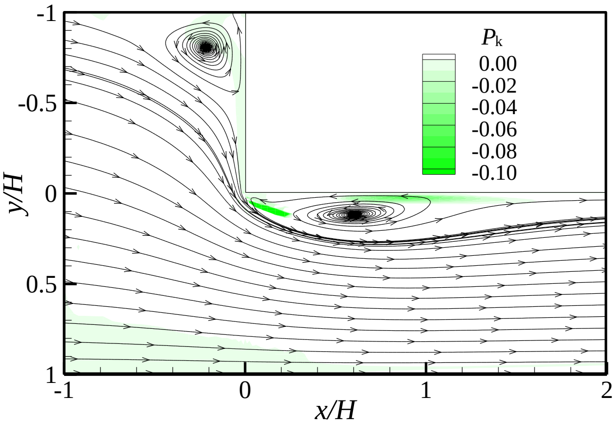


Figure 4. Negative production region and streamlines by DNS at Re_{c0} = 3000

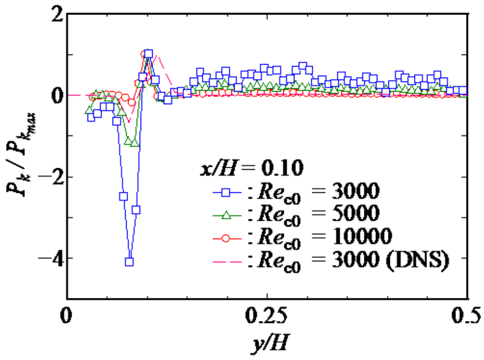
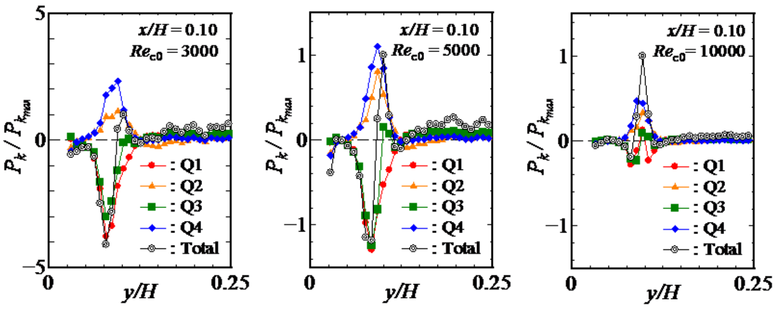


Figure 5. Turbulence production at $x/H = 0.10$



(a) Re_{c0} = 3000 (b) Re_{c0} = 5000 (c) Re_{c0} = 10000

Figure 6. Quadrant analysis of the production term by PIV data

RESULTS AND DISCUSSIONS

Figure 3 shows comparison of mean streamwise velocity profiles by PIV and DNS at several downstream sections at Re_{c0} = 3000. The results by PIV and DNS compare well with each other even for the separated region.

The eddy viscosity assumption is a gradient-diffusion model for the Reynolds stress; $\tau_{ij} - \tau_{kk}\delta_{ij}/3 = 2\nu_t S_{ij}$, where ν_t is the eddy viscosity and S_{ij} is the strain rate tensor. The production of turbulence energy, $P_k = \tau_{ij}S_{ij} = 2\nu_t S_{ij}S_{ij}$, is a suitable measure of the scalar for the counter-gradient diffusivity, since the negative production automatically means the negative eddy viscosity ($\nu_t < 0$). The production term computed by the DNS data in figure 4 shows the region for pronounced counter-gradient diffusion appears near the front part of the corner separation on the forward-facing step. Figure 5 shows the production profiles at $x/H = 0.1$ section at different Reynolds numbers. The amplitude of the negative production is grater in lower Reynolds number flows.

The Reynolds stress is the correlation of turbulence fluctuation which reflects the event of turbulence motion. The $u'_1 - u'_2$ sample space of the fluctuating velocities is divided into four quadrants, i.e., Q1 for $u'_1, u'_2 > 0$, Q2 for $u'_1 < 0$ and $u'_2 > 0$, Q3 for $u'_1, u'_2 < 0$, and Q4 for $u'_1 > 0$ and $u'_2 < 0$, where Q2 and Q4 correspond to ejection and sweep, respectively. Figure 6 shows the results of the quadrant analysis for the production term by PIV data at $x/H = 0.1$ section. The negative contribution of Q1 and Q3 events inside the shear layer increases with decreasing the Reynolds number. The effect makes the counter-gradient diffusion rather pronounced in lower Reynolds number flows.

References

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