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Simultaneous measurement of velocity and pressure near the turbulent/non-turbulent interface of a planar turbulent jet

Osamu Terashima *, Yasuhiko Sakai, Kouji Nagata, Yasumasa Ito, Kazuhiro Onishi, Yuichi Shouji

Nagoya University, Furo-cho, Chikusa-ku, Nagoya-shi, Aichi 464-8603, Japan

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A B S T R A C T

Simultaneous measurement of velocity and pressure near the interface of turbulent/non-turbulent region of a planar turbulent jet is performed. Simultaneous measurement is achieved by means of a combined probe comprising an X-type hot-wire and a static pressure probe. The measurement data are analyzed by the conditional sampling technique and the ensemble-averaging technique on the basis of the intermittency function for the turbulent/non-turbulent decision. Obtained results show that there is a thin interfacial layer between the turbulent/non-turbulent region accompanied with the rapidly changing of velocity, Reynolds stress, and pressure. The thickness of the interfacial layer is 0.08 times the half-width of the cross-streamwise profile of the mean streamwise velocity and almost the same as Taylor transverse micro scale at the measurement position. Further, the velocity and pressure field near the interfacial layer indicates the existence of vortices whose core is at the middle of the interfacial layer and its diameter is the same as the thickness of the interfacial layer. The turbulent energy production and diffusion near the interface are also investigated by estimating the production term and the diffusion term in the transport equation for the turbulent energy. Estimated results show that the turbulent energy is transported from the turbulent region to the outer non-turbulent region by the pressure diffusion. Therefore, the existence of the vortices near the interface has an important role to transport the turbulent energy to the outer non-turbulent region.

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1. Introduction

Nearly parallel shear flows are divided into two classes: wall-free shear flows and wall-bounded shear flows [1]. For the former flows, such as jet, wake and separated flows, the flow phenomena, characteristics, entrainment process and vortex structures near the interface of turbulent/non-turbulent region have been investigated experimentally and numerically (e.g., [2–4]). For the latter flows, such as turbulent boundary layer, the flow phenomena, characteristics, growth/decay mechanism of the turbulent region and vortex structures near the interface of turbulent/non-turbulent region have been also investigated in various ways (e.g., [5–7]).

At the interface between the turbulent/non-turbulent region in the wall-free shear flow observed in jets and wakes, the entrainment of the non-turbulent fluid into the turbulent region and the sticking out of the turbulent region into the ambient non-turbulent region occur. These phenomena are very interesting from academic and industrial viewpoints because they are related to the mixing and diffusion processes of the momentum and scalar.

The first study involving the interface of the turbulent/non-turbulent region in the wall-free shear flow was conducted by Corssin and Kistler [8]. From the experimental results of the turbulent round jet, it was found that there was a thin layer referred to as "laminar super layer," between the turbulent/non-turbulent region, and the thickness of this layer was almost the same as the Kolmogorov microscale of the turbulent region. It was also found that the laminar super layer was involved in the propagation of the vorticity into the fluctuating potential flow (i.e., non-turbulent region).

The vortex structure in the intermittent region of a self-preserving round free jet was investigated by Komori and Ueda [9]. From the measurement results of the Laser Doppler Velocimetry (LDV), they showed the existence of large-scale coherent vortex structures in the intermittent region that were similar to the coherent vortex structures observed by Yule [10] near the jet exit.

In recent researches, the interface between the turbulent/non-turbulent regions were investigated from another point of view. Westerweel et al. [11] indicated that the turbulent/non-turbulent interface was very sharp and that the physical quantities such as the mean streamwise velocity, Reynolds stress and the temperature, sharply changed at the interface; these findings were based

* Corresponding author.

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on combined Laser Induced Fluorescence (LIF)/Particle Image Velocimetry (PIV) measurements in the far field of a submerged self-similar turbulent jet. They also found that the Reynolds stress was not zero at the interface therefore there were the region which had irrotational velocity fluctuations outside of the turbulent/non-turbulent interface.

In association with the study by Westerweel et al. [11], Bisset et al. [12] investigated the turbulent/non-turbulent interface in the velocity fields of a turbulent wake behind a flat plate obtained from direct numerical simulations (DNS). They indicated that the thickness of the continuous interface which exhibited rapidly changing physical quantities, shown by the experiment of Westerweel et al. [11] was less than 0.1 times the half-width of the wake and was almost the same as the Taylor's microscale in the turbulent region.

In addition, Silva and Pereira [13] performed DNS to investigate the "invariants", which was defined as scalar quantities and could analyze the vortex stretching, rotation, and the topology and geometry of deformation of the infinitesimal fluid elements with small number of variables, near the turbulent/non-turbulent interface. They investigated the invariants of the velocity gradient, rate-of-strain and rate-of-rotation tensors across the turbulent/non-turbulent interface of the jet. Watanabe et al. [14] also investigated the vortex structures near the turbulent/non-turbulent of the planar turbulent jet. It was shown that the enstrophy was generated by vortex stretching almost without the vortex compression when the turbulent fluid moves toward the turbulent/non-turbulent interface, while large enstrophy reduction occurs by vortex compression when the turbulent fluid moves toward the interface.

However, the pressure statistics near the turbulent/non-turbulent interface are not measured and investigated experimentally because of the difficulty of the measurement of the pressure in turbulent flows. In this paper, simultaneous measurement of the velocity and pressure field near the interface between the turbulent/non-turbulent region is performed in a planar turbulent jet in order to clarify the flow characteristics and vortex structure just near the turbulent/non-turbulent interface by means of a combined probe [15] for the simultaneous measurement. The measurement data are analyzed by using the conditional sampling technique and the ensemble-averaging technique on the basis of the intermittency function for the turbulent/non-turbulent decision, and the obtained results are discussed by comparing the results with those obtained by direct numerical simulation [16].

2. Experiment setup and procedure

2.1. Planar turbulent jet

Fig. 1 shows a schematic view of the experimental apparatus and coordinate system of a planar turbulent jet used in this study. A skimmer is installed approximately 1.0 mm downstream of the nozzle exit in order to eliminate the boundary layer that developed along the wall of the contraction nozzle. Height d and width l of the skimmer exit are 12 mm and 236 mm, respectively. Velocity U_0 at the skimmer exit is 27.5 m/s, and the Reynolds number Re ($= U_0 d/\nu$, where ν is kinematic viscosity) is 22,000. Further, the sidewall is set vertically in the test section to inhibit entrainment from the surroundings on each side. Using the skimmer and the sidewall, a uniform velocity profile at the skimmer exit and a good two-dimensional flow field in the test section are realized. The coordinate system is as follows: The axial (streamwise) coordinate is x_1, the vertical (cross-streamwise) coordinate is x_2, the spanwise coordinate is x_3, and the origin of the coordinate is set at the center of the nozzle exit.

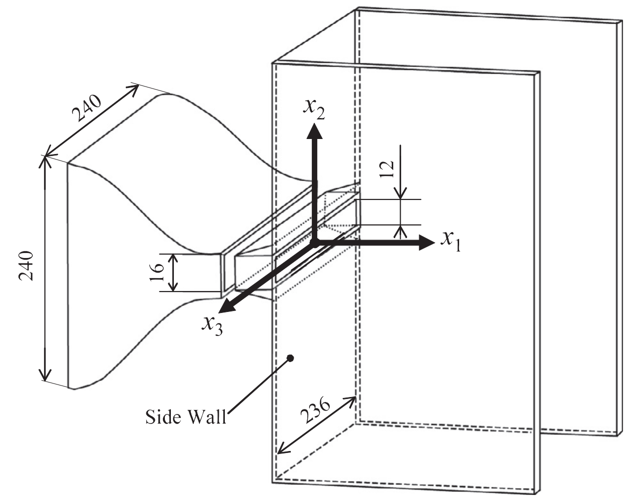

Fig. 1. Experimental apparatus and coordinate system of a planar turbulent jet (Unit: mm).

In this study, a single hot-wire probe (hereinafter called the I-type hot-wire probe) is installed in the intermittent region to detect the interface of the turbulent/non-turbulent region as shown in Fig. 2. Here, it should be noted that the meaning of "intermittent region" in this study is the places in the flow where the transition between turbulent and non-turbulent takes places. The combined probe (will be shown next section in detail) is set in the measurement point to make the simultaneous measurement of velocity and pressure that consists of an X-type hot-wire probe and a static pressure probe connected to the traverse system. By using the stepping motor to move the combined probe, spatial resolution of the combined probe is 0.1 mm.

2.2. Simultaneous measurement of velocity and pressure

Many useful techniques for the simultaneous measurement of the velocity and pressure in turbulent flows have been developed and used to date [17–19]. In this study, a combined probe which consists of two hot-wires and a pressure probe is used for the simultaneous measurement with reference to our previous research [15]. Fig. 3 shows a schematic view of the combined probe. The pressure probe is placed between two hot-wires (diameter: 5.0 μm, length: 1.0 mm) which construct the X-type hot-wire sensor for the measurement of two velocity components. The gap between the side wall of the pressure tube and the hot-wire is 0.5 mm, and the streamwise gap between the tip of the pressure tube and the cross point of the two hot-wires is 2.0 mm. These gaps

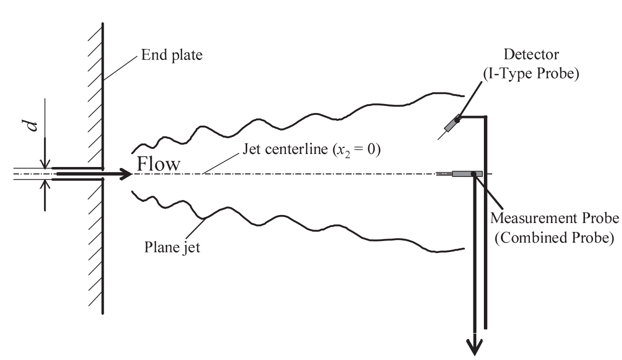

Fig. 2. Schematic view of the measurement apparatus (Unit: mm).

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