Experimental Thermal and Fluid Science 33 (2009) 527–537

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

PIV measurements of turbulent flow in planar mixing layer

Chiuan-Ting Li, Keh-Chin Chang *, Muh-Rong Wang

Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan, ROC

ARTICLE INFO

Article history:
Received 27 June 2008
Received in revised form 24 October 2008
Accepted 19 November 2008

Keywords:
Mixing layer
PIV
Taguchi method

ABSTRACT

A turbulent mixing layer consists of two different flow types, i.e. shear layer (shear-flow turbulence) and free stream regions (nearly homogeneous turbulence). The inherent non-uniform seeding tracer distributions observed around the interfaces between the shear layer and two free stream regions usually lead to a difficulty in particle image velocimetry (PIV) measurements. A parametric study on the application of PIV to the measurement of velocity field in a planar mixing layer is made by means of six factors, including interrogation window size, aspect ratio of interrogation window, interrogation window offset, threshold of data validation, sharpening spatial filters (Prewitt and Sobel masks), and smoothing spatial filter (median mask). The objective of this study is to obtain accurate turbulent measurements in both mean and fluctuating velocities using PIV under an appropriate parametric setting. The optimal levels, which are trade-off in between the accuracy and fine spatial resolution of velocity field measurements, are determined with the aid of the Taguchi method. It is shown that the PIV measurements made with this optimal set of parameters are in good agreement with the measurements made by a two-component hot-wire anemometer. Case independency of the proposed optimal set of parameters on the flow condition of the mixing layer is validated through the applications to two additional tests under the different experimental conditions in changing solely either velocity ratio of high-speed to low-speed free stream velocities or Reynolds number.

1. Introduction

Single-point velocity measurements such as laser doppler velocimetry (LDV) and hot-wire anemometry (HWA) can provide the temporal evolution of the characteristics of turbulence only, which are obtained from the time-sequential data of instantaneous velocities at a fixed point. In contrast, particle image velocimetry (PIV), which is a multi-point measuring technique, can provide the information of the spatial differential quantities of turbulence such as the dissipation rates of turbulent kinetic energy. Measurements of PIV are done with digitally recording particle (tracer) image motion. The fluid velocity in PIV is, thus, inferred from the motion of tracer particles. According to Westerweel [1], the tracer particles are considered as ideal when they (1) exactly follow the motion of fluid, (2) do not alter the flow properties and (3) do not interact to each other. When applying PIV to the measurements of turbulent flow field, Adrian [2] added one more condition that the mean spacing between the tracers should be much less than the Taylor micro scale in order to differentiate turbulent data with accuracy.

A number of studies has been conducted for the validation of PIV measurements in variety of turbulent flow fields by either using another measurement instruments such as pitot tube [3], LDV [4], and HWA [5–7] or using the theoretical simulation such as the direct numerical simulation (DNS) [8,9]. However, these studies were mostly addressed to the shear-flow turbulence. Relatively few experimental study such as the one made by Lavoie et al. [6] concerned the identification of PIV measurements in homogeneous turbulence. In this study, we are interested in the application of PIV to the velocity field measurements in a planar turbulent mixing layer in which there exist two different flow types, the shear layer and the free stream regions in both high- and low-speed sides. The turbulent features of the shear layer and free stream regions are of shear and nearly homogeneous turbulence, respectively. Presence of non-uniform distributions of seeding tracers around the interfaces between the shear layer and two free stream regions is observed. The non-uniform tracer distributions are attributed to the wake generated behind the trailing edge of the splitting plate in which the induced lift force drives tracers outward. The tracers are, thus, accumulated in band-like structure, which begins in the braid region and extends into the free stream region [10]. To enhance image resolution due to insufficient tracer illumination stemming from the non-uniform tracer distributions, an easy solution is by seeding with higher tracer concentrations in the flow field, but it deviates consequently farther from the ideal conditions as stated by Westerweel [1]. Another solution such as enhancing image resolution via the direct image post-processing is preferred.

The second problem is how to assure a condition in which the spatial averaging over an interrogation window is ergodic with

* Corresponding author. Tel.: +886 6 2757575x63679; fax: +886 6 2389940.
E-mail address: kcchang@mail.ncku.edu.tw (K.-C. Chang).

0894-1777/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.expthermflusci.2008.11.006

respect to the ensemble averaging [1]. As reported by Keane and Adrian [11], existence of high velocity gradient diminishes substantially the amplitude of the correlation peak and broadens the width in its cross-correlation analysis. When the amplitude becomes too small, the peak of cross-correlation function may not be detectable; and it, then, results in failed measurements for regions of high velocity gradients. To overcome this problem, Keane and Adrian [12] later suggested an approach to eliminate the signal bias resulting from velocity gradients in cross-correlation interrogation by making appropriate choices of the factors such as the interrogation window size and offset. An appropriate interrogation window size should be, in principle, large enough in order to attain statistically stationary result, while remain the capability to differentiate turbulent fluctuations.

Turbulent dispersion motion usually results in unequal tracer displacements causing a situation that some tracers in an interrogation region to correlate well at a significantly distant location than another tracers. It, then, generates significant errors due to an asymmetry in the peak correlation as applying PIV to the measurements of turbulent flow field. Westerweel et al. [13] showed that these bias errors were able to be effectively reduced by use of an interrogation window offset, which is equal to the integer part of the displacement (in pixel unit). Existence of wider range of velocity gradients in the flow field to be investigated, consisted of the shear layer (with steep velocity gradients) and free stream regions (with weaker velocity gradients), leads to an issue of how to determine an appropriate interrogation window offset for the PIV measurements of the turbulent mixing layer.

Another problem pointed out by Keane and Adrian [11] is that interrogation performance has to be gauged in terms of the data yield (or detection probability), which is the probability indicating that a single interrogation window produces a velocity measurement being acceptable according to certain data validation criteria. The data validation criteria are to compare D to a threshold level D_0. Here the detectability D is defined as the ratio of the self-correlation peak to the displacement correlation peak. The velocity estimation is acceptable if $D \leqslant D_0$, otherwise the estimation is rejected.

To optimize the performance of PIV in the measurements of turbulent velocity field in the mixing layer, four interrogation and two image post-processing factors, including the interrogation size (D_0), aspect ratio of interrogation window, threshold of data validation, interrogation window offset, sharpening spatial filters (Prewitt and Sobel masks), and smoothing spatial filter (median mask) are investigated in this study. Detailed discussion on image post-processing factors (i.e. sharpening and smoothing spatial filters) will be elaborated later. The optimization process is performed with the aid of the Taguchi method which is an efficient approach to resolve the redundant efforts arose with the concurrent consideration in multi-factors.

2. Experimental set-up

2.1. Experimental facilities

The experimental facility is a vertically downward, rectangular, suction-type wind tunnel, schematically shown in Fig. 1, which is composed of the settling chamber, contraction section, test section, and noise reduction chamber. The test section of this tunnel with a cross-sectional area of 150 mm × 150 mm is divided into two independent flow paths by a central splitting plate. A perforated plate is placed in the upstream of the honeycomb to generate the required pressure drop for the low-speed flow path. The trailing edge of the central splitting plate extends 150 mm into the test section. Thickness of the central splitting plate at the trailing edge is 0.2 mm. A cartesian coordinate is selected such that the transverse coordinate y is positive toward the high-speed stream and the streamwise coordinate x is positive downward with the origin at the trailing edge of the splitting plate. Nearly invariant spanwise distributions of velocity components are observed in the interest of measured sections. It assures that the two-dimensional characteristics of the tested mixing layer flow are presented. All the results presented hereafter are made in the downstream streamwise stations where the flows are of stationary turbulence.

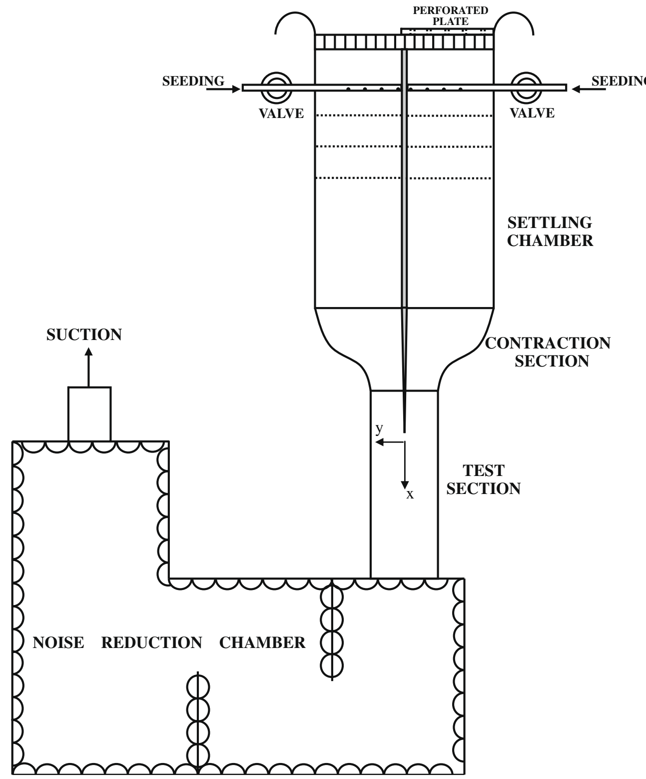

Fig. 1. Experimental set-up.

2.2. Instrumentation

A two-dimensional double-pulse PIV system with cross-correlation estimation, which was manufactured by Integrated Design Tools (IDT) Inc., is used for the instantaneous measurements of velocity field. The PIV system consists of a pulsed diode laser, a high-speed camera with a 50 mm Nikon standard lens, a synchronizing timing hub, and a personal computer for data acquisition. The f-number and magnification factor are set equal to 1.2 and 8, respectively. The wavelength of the diode solid state laser (Model XS-IR-10) is 795 nm, and the maximum pulse power is 10 W. The thickness of laser sheet is around 1 mm. According to Nyquist theorem [14], the frame rate must be at least twice as fast as the frequencies of small turbulent eddies such as that of Taylor-scale eddy to avoid the problem of aliasing statistics. The frame rate of CMOS camera (Model X-stream XS-4) for capturing digital images is 2565 frames/s with full spatial resolution of 512 × 512 pixel^2. The minimum spatial resolution of camera is, thus, estimated to be 0.125 mm/pixel. The minimum length of Taylor micro scale (λ), estimated using the following formulas, is around 2 mm.

$$\lambda^2 = \langle u'^2 \rangle \Big/ \left\langle \left(\frac{\partial u'}{\partial x}\right)^2 \right\rangle \tag{1}$$

where the symbol < > denotes the ensemble averaging and u' is the fluctuating velocity in contrast to the instantaneous (u) and mean