PIV Measurements of the Flow and Turbulent Characteristics of a Round Jet in Crossflow

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Abstract: The instantaneous and ensemble averaged flow characteristics of a round jet issuing normally into a crossflow was studied using a flow visualization technique and Particle Image Velocimetry measurements. Experiments were performed at a jet-to-crossflow velocity ratio, 3.3 and two Reynolds numbers, 1,050 and 2,100, based on crossflow velocity and jet diameter. Instantaneous laser tomographic images of the vertical center plane of the crossflow jet show that there exists very different natures in the flow structures of the near field jet due to Reynolds number effect even though the velocity ratio is same. It is found that the shear layer becomes much thicker when the Reynolds number is 2,100 because of the strong entrainment of the inviscid fluid by turbulent interaction between the jet and crossflow. The mean and second order statistics are calculated by ensemble averaging over 1,000 realizations of instantaneous velocity fields. The detail characteristics of mean flow field, streamwise and vertical rms velocity fluctuations, and Reynolds shear stress distributions are presented. The new PIV results are compared with those from previous experimental and LES studies.

Keywords: crossflow jet, particle image velocimetry, Reynolds number dependency, flow and turbulence characteristics.

1. Introduction

The jet in crossflow (JICF) is one of the most complex turbulent flow, but it seems to be a canonical form of many industrial and/or environmental engineering problems. The fundamental behavior of a nonbuoyant turbulent round jet issuing normally into a wall boundary layer is essential for understanding pollutant dispersion from stacks, designing V/STOL aircraft and providing injection cooling of gas turbine combustor walls. Many experimental and numerical investigations of the JICF have been carried out and a thorough review of JICF has been conducted by Margason(1993).

Early stages of experimental work centered around measuring the jet trajectory for different combinations of flow parameters as performed by Pratte and Baines(1967). Later research began to collect mean velocity and turbulence statistics data using hot wires and laser Doppler velocimetry done by Crabb, Durao and Whitelaw(1981). Andreopoulos and Rodi(1984) used a triple wire probe to measure all three components of velocity simultaneously. Fric and Roshko(1994) suggested that the key features of vortical structures associated in the JICF are the horseshoe vortices in front of the jet, the shear layer vortices at the edge of the jet, the vertically oriented vortices which connect the jet body with wall boundary layer in the wake region, and the counter-rotating vortex pair (CVP) which is often observed in the far-field aligned with the trajectory of the jet. Kelso, Lim and Perry(1996) investigated detail nature of the jet structure employing dye tracer in a water tunnel and flying hot wires in a wind tunnel. They argued that the initial vortical roll up of the jet shear layer initiates the downstream development of the CVP through a vortex breakdown mechanism. Kim and Shin(1998) froze the vertical
centerplane of the jet flow using laser tomographic method and found that the Kelvin-Helmholtz type roll up structures are appeared both upstream and downstream boundaries of the JICF. Recently, Yuan, Street and Ferziger(1999, here after YSF) carried out the LES of a round jet in crossflow. Their simulations reproduced large scale, coherent structures observed in experimental flow visualizations and the mean and turbulent statistics computed from the simulations were reasonably matched with experimental measurements.

In spite of numerous studies for the JICF have performed, many questions are remained still unanswered. Many investigators seem to agree that the original source of the CVP in the jet shear layer, but the means by which this vorticity realigns to produce CVP is still unclean. The effect of flow parameters on the evolution of vortical motions in the JICF should be scrutinized in detail. To verify the predicted results from LES method, more accurate and plentiful experimental data are needed.

The objective of present study is providing accurate instantaneous and averaged velocity fields in the vertical centerplane of a jet in crossflow using a PIV method. The effects of Reynolds number on the jet development are also examined. We compare PIV measurements with LES results and previous experimental data.

2. Experimental Apparatus and Method

Flow visualization and flow field measurements were made in a small open type low speed wind tunnel. The tunnel has a working section measuring 30 cm height, 80 cm width and 200 cm in length. The test section walls are made of plexiglass and glass plates. The air driven by a variable speed 3 hp centrifugal fan passes a settling chamber, a 2.67:1 area ratio contraction, then enters to the test section through a fine mesh screen. The freestream turbulence intensity at the entrance of the test section is about 1%.

The round jet is issued normally into the test section from a 16 mm inner diameter nozzle pipe which is mounted at the bottom plate of the wind tunnel 25 cm downstream from the exit of the contraction nozzle. The jet is generated by air compressor then passes through a mixing chamber, a pressure regulator and a flowmeter. Olive oil aerosol particles whose diameter are 2 μm in average produced by a Laskin nozzle were supplied into the mixing chamber. A straight pipe of 35 cm in length is connected from the mixing chamber to the jet exit at the test section bottom plate.

The most dominant parameter which governs flow characteristics of the JICF is the momentum ratio between the jet and the crossflow. If the two flows have the same density, the momentum ratio turns out to be the velocity ratio \( R \) as following:

\[
R = \frac{V_j}{U_{\infty}}
\]

where, \( V_j \) equals to the flow rate divided by the jet cross section area and \( U_{\infty} \) denotes the free stream velocity. We fixed the velocity ratio \( R \) as 3.3 in this experiment. At the same velocity ratio conditions, Reynolds number may play a key role in the flow behavior. We performed experiments with two Reynolds numbers, 1,050 and 2,100 based on crossflow velocity and jet diameter. These Reynolds numbers are the same as YSF(1999) carried out LES of the JICF. The corresponding freestream velocities are 1.0 m/s and 2.0 m/s, respectively. We did not use a tripping wire, so that the approaching boundary layers are considered to be laminar boundary layers with initial boundary layer heights of 12 mm and 10 mm at the position of the hole, respectively. The incoming pipe flow Reynolds numbers are 3,470 and 6,940 based on the average velocity \( V_j \) and the pipe inner diameter.

Flow visualization study was conducted before the main PIV experiment. To obtain instantaneous tomographic image of the JICF, a laser sheet beam having less than 1 mm thickness was illuminated during 4 ns using a 200 mJ/pulse Nd:Yag laser. The olive oil aerosols were supplied only into the jet flow, hence the frozen jet flow patterns are clearly recognized as the scattering image.

Two dimensional velocity vector fields at the vertical centerplane were measured using an Nd:Yag based PIV system. The schematic diagram of the PIV setup and the coordinate system is appeared in Fig. 1. The online PIV system being used in this study consists of a dual pulse Nd:Yag laser system, a synchronizer(TSL 610032), a 1K by 1K high resolution CCD camera and a Pentium computer to control the system. We put a standard Nikon 50 mm lens in front of the CCD camera to prevent the image distortion error. The olive oil particles were supplied into both wind tunnel and pipe. The uniformity of the particle distribution and the intensity of the scattered light have been checked before experiment.

The interrogation of the velocity vector was carried out using INSIGHT-NT software adopting two frame cross-correlation method. A total of 16,002 velocity vectors are interrogated, hence the spatial resolution of the