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Near-Field Study of a Turbulent Freejet and Velocity Bias Effects

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A comparative study was conducted to measure turbulence parameters and to evaluate some of the velocity-bias correction techniques in the near field of a turbulent freejet. The overall objective of this investigation was to develop a reliable technique for obtaining nonintrusive measurements of the mean flow velocity components and turbulence and to construct a complete set of data in the developing region of a turbulent freejet.

Nomenclature

D = freejet nozzle diameter
r = radial measurement coordinate
T_{bd} = time between samples, $i, i \pm 1$
U = mean axial velocity
u = instantaneous axial velocity
$\overline{uv}$ = Reynolds shear stress
x = axial direction

Subscript
cl = centerline of jet

Superscripts
$'$ = rms value
$\bar{}$ = time-average value

I. Introduction

TURBLENT freejets have been studied by several researchers partly because of their vast practical applications and also their relative simplicity and universality. They provide very simple and good test cases for the developers of turbulence models. Their flowfields are usually considered to contain the following three zones: 1) the far field, 2) the transition (or intermediate) field, and 3) the near field. In the far field, self-similarity is a characteristic of the mean velocity field; therefore, it is not of prime interest in the present investigation. This study is only concerned with experimental investigation of the near and intermediate field of an isothermal freejet. The objective of this program is twofold: 1) to evaluate some of the laser Doppler velocimeter (LDV) velocity-bias correction techniques and 2) to provide additional detailed insight into the flowfield of a freejet. This confidence level in the LDV measurements of turbulent quantities is lacking and it seems to be evolving from the question of whether or not random measurements of particle velocities yield good statistical estimates of the turbulent quantities.

Many investigators have made comparative studies of this nature.[1,2] The present one is a continuation of the work of Nejad and Davis.[1] These investigators and others like them highlighted the widely recognized bias problems associated with LDV measurements. Adams and Eaton[2] reported that many corrections and sampling strategies have been proposed to eliminate this bias; however, its elusive nature has led some other investigators to abandon all velocity-bias corrections, such as Driver and Seegmiller.[3]

For the present investigation, a vertical freejet, 15.1 mm in diameter, was constructed. A two-component LDV was utilized for obtaining axial and radial velocity measurements together with the turbulence intensities and turbulent shear stresses at 12 different planes normal to the jet axis ($1 < X/D < 22$). Two velocity-bias correction schemes, based on the time between velocity samples, and constant time-interval sampling of velocity data were used for obtaining unbiased measurements, see Nejad and Davis[2] for more details about both methods.

The present study compares some of the LDV velocity-bias correction techniques used and documents the flowfield characteristics using these different methods of data analysis.

II. Experimental Setup

The nozzle assembly consists of an aluminum settling chamber with two sets of flow straighteners and a contoured discharge section. The nozzle exit diameter is approximately 15.1 mm. The jet exit velocity is kept constant at a nominal value of 30 m/s, which gives an approximate Reynolds number of 3×10^4, based on the nozzle exit diameter. The supply air pressure of the jet is regulated to control the volume flow rate through the nozzle. Air temperature is kept approximately the same as the room temperature to ensure an isothermal flow. Titanium dioxide seeds are injected in the settling chamber far upstream of the nozzle to ensure uniform distribution at the jet exit. They are generated by reacting titanium tetrachloride with the water vapor of saturated air in a separate chamber. The uniform distribution of the seeds at the nozzle exit is checked by monitoring the data rate across the jet to verify if it is approximately constant or not. The jet exit velocity profile of the air is nearly a "top hat" shape, with nozzle exit velocity varying by a maximum of 3% or less of the mean value. The jet tested is assumed to be fully turbulent with turbulence levels less than 3% at the exit.

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To provide a better controlled environment, a large enclosure from plastic sheets is built (1.5 × 1.5 m). This box is connected in turn with the exhaust system. This type of arrangement helped in prohibiting room drafts from altering the flow and is used to protect the operator from breathing the contaminated air. It is assumed that this enclosure is large enough not to affect the flow or the measurements.

The nozzle assembly is mounted on a three-dimensional traversing mechanism, which enables precise positioning of the freejet relative to the center of the sampling volume.

III. Instrumentation and Data Acquisition

A two-component LDV system with a four-beam configuration is used in the backscatter mode. The system is manufactured by TSI Inc., with several in-house modifications.[4] Two fringe patterns are aligned at a common point in space. These fringes are perpendicular to each other and approximately 45 deg to the jet axis. A 20-μm aperture is used in the alignment procedure to ensure that the four beams cross at the same point in air. Also, a beam stop having 20-μm aperture is used. This arrangement is utilized since the velocity measurements in both directions will be of the same order of magnitude. Both fringe patterns are frequency shifted 40 MHz using two Bragg cells. The entire optical system is mounted on a three-dimensional traversing table with a resolution of 0.025 mm.

With this arrangement and TiO_2 as the seeding particles (1-μm size approximately), data rates of 5000–10,000/s are achieved. The corresponding coincidence rates vary between 2000–6000/s when a 20-μs coincidence window is chosen. Sixty-three blocks of data (each block has 1365 realizations/channel) at the center (corresponding to the highest coincidence rate of 6000/s) are collected at any axial location in the flowfield. The number of blocks is decreased gradually as r increases, to reach a minimum of three blocks (corresponding to the lowest coincidence rate of 2000/s).

The uncertainty of the measured mean velocities was determined using the techniques described by Snyder et al.[5] The uncertainty ΔU is determined by the relation

$$\Delta U = \pm 1.96\ \sigma_u/\sqrt{(N)} \tag{1}$$

For 95% confidence level the constant 1.96 is used; σ_u is an estimator for the true standard deviation and N is the sample size (e.g., $N = 4095$). From the previous relation the maximum uncertainty of U due to random errors was found to be 0.3% of the jet exit velocity.

For each measurement location, the upstream flow parameters together with the calculated moments and velocity probability density functions are displayed on a graphic terminal. A hard copy of all of these variables is documented and obtained for each radial location.

Three different methods of velocity-bias correction have been examined. First, the velocity of each particle is measured and the average is calculated directly without any corrections (particle average). The second method involves correcting the previous measurements by utilizing the time between measured data points T_{bd} as the weighting function. Third, the random digital data from LDV processors are sampled with a constant sampling rate of approximately ≤ 0.1 of the original data rate. A detailed comparison of the previous different techniques was reported earlier by Nejad and Davis[1] and will not be discussed here again for brevity.

IV. Results and Discussion

Figures 1–3 show the radial distributions of the mean velocities, rms turbulent fluctuations, and shear stress profiles at X/D = 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20. For each of the previous axial locations, three profiles are plotted utilizing three techniques of data analysis: the first with no correction (particle average); the second utilizes the time between two consecutive realizations, T_{bd} average; and the third uses the near-periodic sampling method. These techniques of LDV data processing are utilized to examine their agreement, or differences, if any.

Figure 1 shows the evolution of the mean axial velocity profiles from X/D = 2 to 20. These results are typical of developing freejet data. The three schemes give approximately the same results. As expected, the biased data have slightly higher values.

Figure 2 shows the evolution of the axial rms velocity fluctuations in the initial region of the freejet. The off-center peaks are illustrated indicating the planes of maximum mixing. As expected, the biased data have slightly lower values than their respective corrected ones. The differences between the corrected and the uncorrected data increase when the local turbulence increases.

Figure 3 shows the evolution of turbulent shear stress $\overline{uv}/U_{cl}^2$ vs r/x. The results here show better trend and near antisymmetry. Discrepancies between the different techniques are minimal in this set of the shear stress data.

In the present investigation it seems that velocity bias effects are not important and the results do not change significantly, with or without correction. This is in agreement with what was reported earlier by Adams and Eaton,[2] that several investigators have not found any bias effects in boundary-layer-type flows. In fact, they claimed that the uncorrected LDV is closer to the hot wire measurements than the cor-

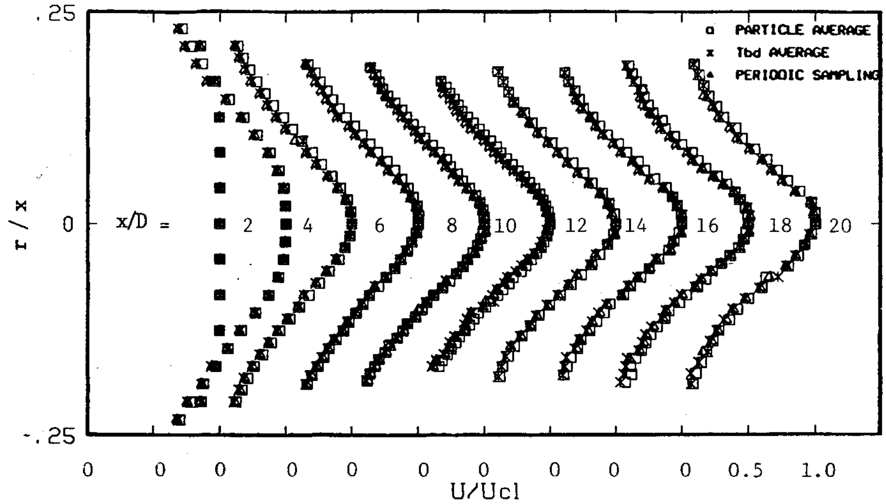

Fig. 1 Evolution of axial mean velocity.

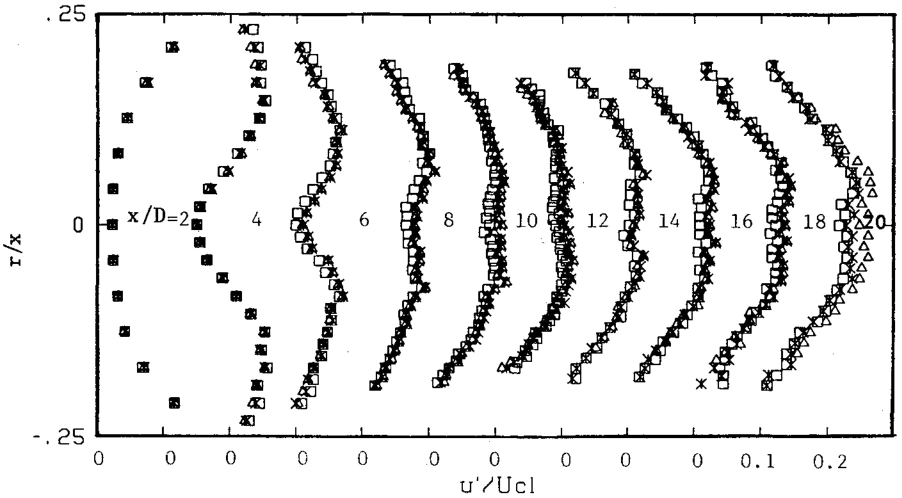

Fig. 2 Evolution of turbulent axial velocity; symbols are the same as in Fig. 1.

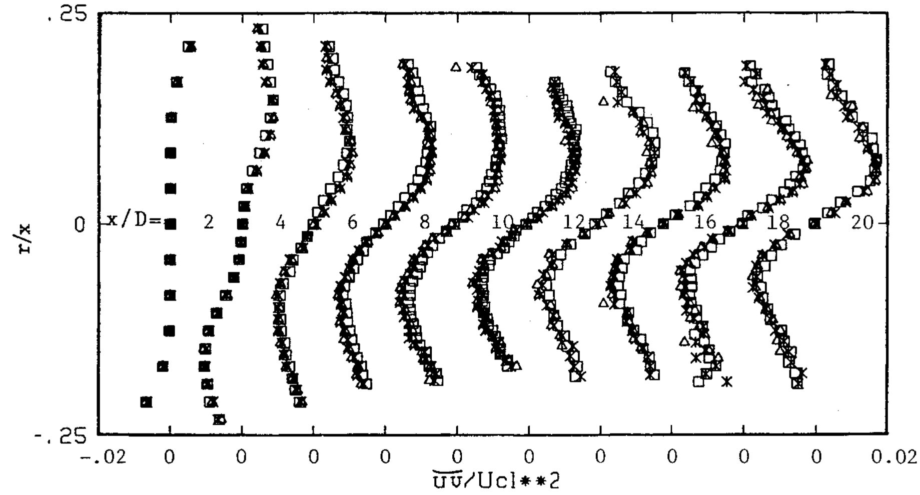

Fig. 3 Evolution of turbulent shear stress; symbols are the same as in Fig. 1.

rected ones. The previous argument is also supported by Buchhave[6] in a similar freejet study case. The implication of that is the magnitude of the LDV bias observed in their flow was not worse than the accuracy of the technique utilized in the same flow. Meyers and Wilkinson[7] have gone one step further by questioning the validity of using the velocity-bias correction techniques. This is in contrast with Nejad and Davis,[1] and also with Craig and Nejad,[8] who confirmed the need for a correction, even for flows with low turbulence levels.

V. Conclusions

A two-component LDV in the coincidence mode was utilized in a novel experimental arrangement to obtain and document detailed experimental data in the near and intermediate field of a freejet. Three different methods to analyze the data were used: 1) the arithmetic average, 2) the interarrival time weighting, and 3) the constant time sampling.

The discrepancies between the different methods of analyzing data were found to be insignificant. The correction procedures were found to raise the turbulence intensity results by up to 2% over the biased LDV data.

Acknowledgments

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