mean streamwise velocity data is about 2%. Mean streamwise velocity off-center peaks are clearly evident at $X/t_p = 10$ and 20 in the X-Y plane (Fig. 2a). These mean streamwise velocity off-center peaks, which do not occur in the potential core region ($X/t_p \leq 3$, not shown) or in the X-Z plane, appear to move toward the jet centerline with downstream distance and seem to disappear after the shear layers growing in the X-Y plane merge on the jet centerline at about $X/t_p = 30$. The profiles in the X-Z plane seem to be geometrically similar after about $X/t_p = 10$ and those in the X-Y plane appear to be geometrically similar beyond $X/t_p = 30$. These observations are in accord with those made by other investigators.[2-8]

Static Pressure Distribution

The static pressure distribution on the jet centerline is presented in Fig. 3. Steep streamwise static pressure gradients are clearly evident.

Static pressure profiles in the central X-Y and X-Z planes are presented in Fig. 4 for the flow region ($X/t_p = 10$ to 30) where mean streamwise velocity off-center peaks are found. The static pressure profiles at $X/t_p = 10$ and 20 in the central X-Y plane (Fig. 4a) indicate that the static pressure drops significantly before it starts to recover to the atmospheric value at the edge of the jet. It is, indeed, interesting to note that the locations of the static pressure "valleys" at $X/t_p = 10$ and 20 in Fig. 4a correspond to those of the mean streamwise velocity off-center peaks at the same stations in Fig. 2a. The static pressure profile at $X/t_p = 30$ (Fig. 4a) exhibits a behavior similar to those at $X/t_p = 10$ and 20, but the drop in static pressure is not as significant as that at $X/t_p = 10$ and 20. It should be recalled that there is no mean streamwise velocity off-center peak at $X/t_p = 30$ (Fig. 2a). However, in view of the static pressure profile at $X/t_p = 30$ (Fig. 4a), it is possible that a mean streamwise velocity off-center peak indeed exists at $X/t_p = 30$ in the central X-Y plane, but that it is of such small magnitude, that the instrumentation used was incapable of resolving it. The central X-Z plane static pressure profiles (Fig. 4b) are characterized by monotonic recovery to the atmospheric value at the edge of the jet from low values on the jet centerline.

The systematic error in the static pressure data is about 3% but it should be noted that static pressure data in turbulent flows are, because of the unknown effects of turbulence, of uncertain quantitative value.[14] However, the qualitative trends shown by the static pressure data presented above are real.

Acknowledgment

The work reported herein was supported by Grant A4310 from the Natural Sciences and Engineering Research Council of Canada.

References

[1]Van der Hegge Zijnen, B. G., "Measurements of the Velocity Distribution in a Plane Turbulent Jet of Air," *Applied Scientific Research*, Section A, Vol. 7, 1958, pp. 256-276.

[2]Sforza, P. M., Steiger, M. H., and Trentacoste, N., "Studies on Three-Dimensional Viscous Jets," *AIAA Journal*, Vol. 4, May 1966, pp. 800-806.

[3]Trentacoste, N. and Sforza, P. M., "Further Experimental Results for Three-Dimensional Free Jets," *AIAA Journal*, Vol. 5, May 1967, pp. 885-891.

[4]Sfeir, A. A., "The Velocity and Temperature Fields of Rectangular Jets," *International Journal on Heat and Mass Transfer*, Vol. 19, 1976, pp. 1289-1297.

[5]Sfeir, A. A., "Investigation of Three-Dimensional Turbulent Rectangular Jets," *AIAA Journal*, Vol. 17, Oct. 1979, pp. 1055-1060.

[6]Marsters, F. G., "The Effects of Upstream Nozzle Shaping on Incompressible Turbulent Flows from Rectangular Nozzles," *Transactions of CSME*, Vol. 4, 1978/79, pp. 197-203.

[7]Marsters, G. F., "An Experimental Investigation of Spanwise Velocity Distributions in Jets from Rectangular Slots," AIAA Paper 80-0202, Jan. 1980.

[8]Krothapalli, A., Baganoff, D., and Karamcheti, K., "On the Mixing of a Rectangular Jet," *Journal of Fluid Mechanics*, Vol. 107, 1981, pp. 201-220.

[9]McGuirk, J. J. and Rodi, W., "The Calculation of Three-Dimensional Turbulent Free Jets," *First Symposium on Turbulent Shear Flows*, University of Pennsylvania, University Park, Pa., Vol. 1, April 1977, pp. 1.29-1.36.

[10]Foss, J F., and Jones, J. B., "Secondary Flow Effects in a Bounded Rectangular Jet," *Journal of Basic Engineering, Transactions of ASME,* Vol. 90, June 1968, pp. 241-248.

[11]Holdeman, J. D. and Foss, J. F., "The Initiation, Development and Decay of the Secondary Flow in a Bounded Jet," *Journal of Fluids Engineering, Transactions of ASME*, Vol. 97, Sept. 1975, pp. 342-352.

[12]Rockwell, D. O., "Vortex Stretching Due to Shear Layer Instability," *Journal of Fluids Engineering, Transactions of ASME*, Vol. 99, March 1977, pp. 240-244.

[13]Quinn, W. R., "Turbulent Free Jet Flow from a Sharp-Edged Rectangular Slot," Ph.D. Thesis, Queen's University at Kingston, Canada, 1984.

[14]Hinze, J. O., *Turbulence*, 2nd ed., McGraw-Hill Book Co., Toronto, 1975, pp. 164-165.

Velocity Biasing of Two-Component LDV Data in Low-Turbulence Flows

R. R. Craig* and A. S. Nejad*
U.S. Air Force Wright Aeronautical Laboratories
Wright-Patterson Air Force Base, Ohio

THE velocity biasing of data obtained by laser Doppler velocimetry (LDV) in highly turbulent flows has been investigated for 11 years since it was originally identified by McLaughlin and Tiederman.[1] The constant time interval sampling approach developed and verified by Stevenson et al.[2-4] is the most reliable approach for eliminating this biasing. Improvements in technique and seeding detailed in Ref. 5 make this a viable approach in all flows of interest.

The purpose of this Note is to alert researchers using two-component LDV systems to a velocity biasing problem we have encountered in low-turbulence flows where it is generally assumed that velocity biasing is not a problem.

In general, it has been assumed that, when using LDV systems in flows with turbulence intensities below 10-15%, a correction for velocity biasing is not required. When measuring only the mean and fluctuating component of the directed flow, that assumption is true. However, when measuring a second or third component of velocity where the mean value of the other components is near zero and the turbulence is nearly isotropic, problems arise. Even though the turbulence level relative to the mean directed flow may be low (1-2%) the turbulence intensity relative to the near-zero mean secondary velocity component is extremely high.

Received May 7, 1984; revision recieved June 4, 1984. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Aerospace Engineer, Ramjet Technology Branch, Aero Propulsion Laboratory.

Table 1 Biased and unbiased two-component LDV data

	Biased data (2000 samples)	Unbiased data (2000 samples)
$\bar{U}$ m/s	28.0	27.99
$\bar{V}$ m/s	1.19	0.017
u' m/s	0.404	0.399
v' m/s	0.397	0.434
$\overline{u'v'}$ m²/s²	−0.0055	0.012

This problem became clearly evident in setting up our two-color TSI, back-scatter LDV. Measurements were to be made on the axis of a simple sudden expansion pipe flow where the entering mean axial velocity was about 30 m/s and turbulence intensity was 1.3%. After careful alignment of the LDV with the model and measurment of the beam convergence angles and angle of the beam planes relative to the directed flow, the measured mean radial velocity was nearly 4% of the mean axial velocity when it should have been zero.

The alignment procedure and angle measurements could not account for this magnitude of error. All angles were measured to ±0.1 deg. The alignment of the four beams was accomplished by placing a 20-μm pinhole at one of the beam waists and then making the other three beams pass through this same pinhole. With this procedure it was possible to require that the data-ready signals from the two counter processors be within 10 μs of each other and still obtain good data rates (a frequency shift of 40 MHz was used with each set of beams).

After much fruitless searching for errors, a set of data was taken using the constant time interval sampling approach of Ref. 5. A comparison of the biased and unbiased data is shown in Table 1. The radial mean velocity ($\bar{V}$) component was immediately reduced from 4% to 0.05% of the mean axial component ($\bar{U}$) with no perceptible changes to any of the other turbulence (u', v') or cross-correlation quantities ($\overline{u'v'}$), thus verifying that the problem was velocity biasing of the radial velocity component.

As more two-component LDV data become available for turbulence modeling, it becomes necessary to review carefully the method of data collection and data handling to assess its validity in even low-turbulence intensity flows. Often, sufficient details are not reported to validate the data collection and data handling procedures. Any such data should be discarded from consideration for turbulence modeling.

References

[1] McLaughlin, D. K. and Tiederman, W. G., "Bias Correction for Individual Realization Laser Anemometry Measurements in Turbulent Flows," *Physics of Fluids*, Vol. 16, No. 12, 1973, p. 2082.

[2] Roesler, T., Stevenson, W. H., and Thompson, H. D., "Investigation of Bias Errors in Laser Doppler Velocimeter Measurements," AFWAL-TR-80-2108, Dec. 1980.

[3] Stevenson, W. H., Thompson, H. D., and Luchik, T. S., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part I, Sept. 1982.

[4] Stevenson, W. H., Thompson, H. D., and Gould, R. D., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part II, July 1983.

[5] Craig, R. R., Nejad, A. S., Hahn, E. Y., "A General Approach for Obtaining Unbiased LDV Data in Highly Turbulent Non-Reacting and Reacting Flows," AIAA Paper 84-0366, Jan. 1984.

The Reduction of Pressure Drop Across a Vortex Chamber

G. H. Vatistas,* C. K. Kwok,† and S. Lin†
Concordia University, Montreal, Canada

Introduction

VORTEX chambers, in general, have a cylindrical configuration with a central axis outlet and tangential inlets. The swirling motion, imparted to the fluid by the inlet ports, generates a strong centrifugal force field and produces the complex flow pattern of Fig. 1. A common sight in vortex chambers are the two recirculatory flow areas[1,2] shown. The toroidal, eddy-type fluid motion within the chamber is of the same nature as that through a bend. The reverse flow, which takes place in the vortex core and in the vicinity of the outlet, is attributed to a local static pressure reduction to values that are below the ambient pressure P_a (where P_a is the pressure of the stagnant air ouside the chamber). The present study focuses on this reverse flow and shows, through experiments, that the pressure drop across the chamber (inlet to ambient) can be reduced by preventing the stagnant air from entering the chamber.

Experimental Apparatus

The present tests were conducted in Concordia's experimental cold cyclone furnace model. The cylindrical chamber has a constant cross-sectional area of radius R_0 of 15.24 cm (0.5 ft) and a height H of 45.72 cm (1.5 ft). Swirl is imparted to the fluid by four identical tangential inlet ports, located around the lower periphery of the chamber, 90 deg apart. The total inlet area of the ports is 68.75 cm² (0.074 ft²), each port having a diameter of 4.67 cm (1.84 in.). The modular construction of the top plate incorporates several rings to allow for a variation of the exit port.

The experimental layout is schematically illustrated in Fig. 2. The volumetric flow rate is read from two variable area rotameters (not shown) connected in parallel. The static pressure drop across the chamber (inlet pressure/ambient pressure) is recorded using a sensitive well-type inclined manometer (B). The position of the conical plug is controlled with a screw-type transversing arrangement. The axial travel of the plug is read from scale A, which is graduated in 0.127 cm (0.005 in.) increments.

Results and Discussions

The effect of contraction ratio R_E/R_0 on the dimensionless pressure drop across the chamber ($\overline{\Delta P} = 2(P_{in} - P_a)/\rho V_{rin}^2$) for unrestricted exit flow is presented in Fig. 3. The parameters P_{in}, ρ, and V_{rin} are the static pressure at the inlet, the fluid density, and the inlet radial velocity, respectively. It is evident from Fig. 3 that $\overline{\Delta P}$ increases dramatically for small contraction ratios. Using a conical plug, one can reduce $\overline{\Delta P}$ while maintaining the same inlet flow rate Q. This is demonstrated by the experimental results given in Fig. 4. As the cone is lowered, a partial reduction of the reverse flow is achieved, which is manifested by a corresponding reduction in the static pressure drop across the chamber. When an optimum position of the cone is reached, $\overline{\Delta P}$ is at its minimum. Any further decrease of (Z/h) from the optimum results in a drastic in-

Received Dec. 6, 1983; revision received June 1, 1984.

*Ph.D. Candidate, Department of Mechanical Engineering. Member AIAA.

†Professor of Engineering, Department of Mechanical Engineering.