COMPARISON OF HOT WIRE/LASER VELOCIMETER TURBULENCE INTENSITY MEASUREMENTS

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OBJECTIVE

Since the development of the laser velocimeter as a flow diagnostic tool in the early 1960's, researchers have thought of the laser velocimeter as a novel technique which could be used to measure the basic flow field characteristics in situations where classic probe techniques could not be used, were difficult to implement, or the results were suspect because of probe effects. Over the years a basic confidence level has been established in the use of the laser velocimeter to measure mean velocity. This confidence level does not exist, however, with the application of the laser velocimeter to measure turbulence intensity. The lack of confidence seems to have evolved from the question of whether a random measure of particle velocities yields a good statistical estimate of the stationary condition of the turbulence flow field. This question was further enhanced by the early attempts to compare the results from the laser velocimeter with a hot wire in which there always seemed to be an approximate 10-percent bias of the turbulence intensity measurements from the laser velocimeter, references 1 and 2. In an attempt to satisfy this question, the present comparative study was performed.

Great care was taken in the present study to insure that the instrument precision of both the laser velocimeter and hot wire was maximized. In this attempt to reduce the measurement uncertainties in the hot wire, direct digitization of the analog output signal was performed with point-by-point conversion to velocity through a spline fit calibration curve and the turbulence intensity function was calculated statistically. Frequent calibrations of the hot wire were performed using the laser velocimeter as the velocity standard to account for the presence of the small seed particles in the air flow and signal drift in the hot wire. A low velocity flow was also chosen because of the high confidence level in the hot wire measurements at low speeds. Measurement uncertainties in the laser velocimeter were reduced by using 0.35 - 0.55 micrometer polystyrene particles to remove the particle lag problem, forward-scatter was used to maximize signal-to-noise in the output signal, an off-axis receiver location was used to minimize the sample volume length, and velocity bias corrections were applied to the data along with calculating the time average quantities.

DEVELOP A BASE LEVEL OF CONFIDENCE IN LASER VELOCIMETRY TO MEASURE TURBULENCE INTENSITY

MINIMIZE ERRORS IN HOT WIRE MEASUREMENT

- **Direct Digitization**
- **Point-by-Point Velocity Conversion**
- **Frequent Calibrations**
- **Low Velocity Flow**
- **Calibrate with Particles**

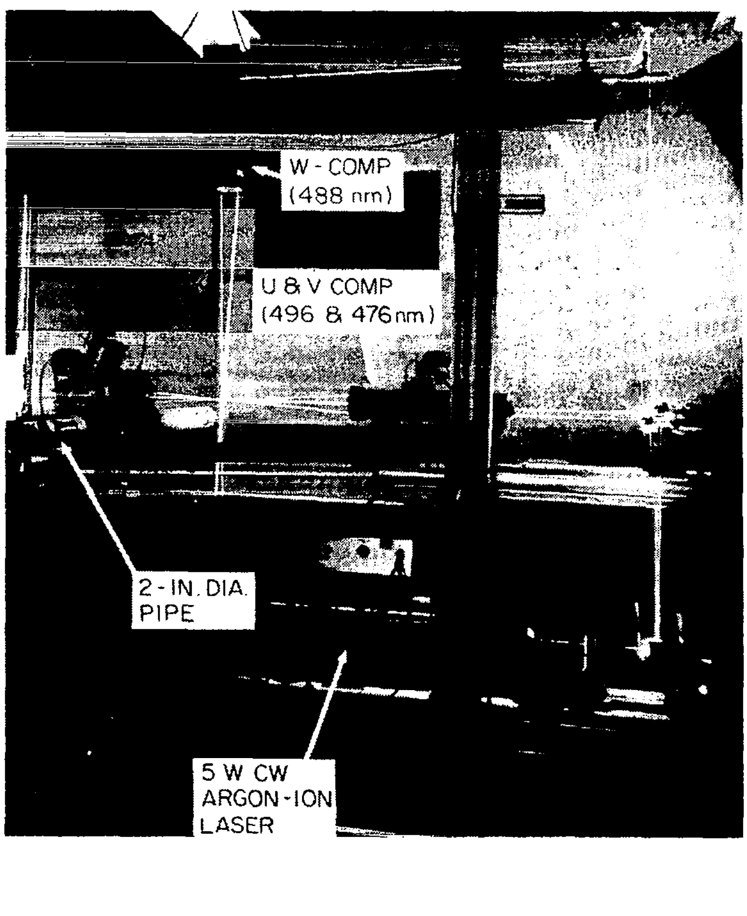
MINIMIZE ERRORS IN LV MEASUREMENT

- **Small Particles**
- **Forward Scatter**
- **Off-Axis Receiver**
- **Velocity Bias Correction**
- **Time Average**

LASER VELOCIMETER SYSTEM

The laser velocimeter (LV) was an orthogonal three component fringe type system used in an off-axis, forward scatter mode. For the purposes of the present study, only one component was used to compare with the results from the hot wire. A Bragg cell was not used in the LV in order to maintain compatibility with the hot wire, since the hot wire is not sensitive to flow reversal. A 5.0 W Argon-ion laser was used as the light source with the 496.5 nm output line being selected. The output power at 496.5 nm was set to 0.2 W. The focal length was 0.38 m and the cross beam angle was 7.52 degrees, which yielded a fringe spacing of 3.78 micrometers with a sample volume diameter of 160 micrometers. The collecting optics were rotated 37 degrees off of the optical centerline in the plane of the laser beams, which reduced the sample volume length (measured to the points where the collected scattered light intensity value was $1/e^2$ of the peak) to 0.62 mm. The receiving optical system had a focal length of 0.38 m with a 7.5 cm clear aperture. The collected light was converted to electrical energy using a photomultiplier with a quantum efficiency of 0.21. This configuration yielded signal levels of approximately 0.2 V, peak-to-peak, from 0.35 - 0.55 micrometer polystyrene particles.

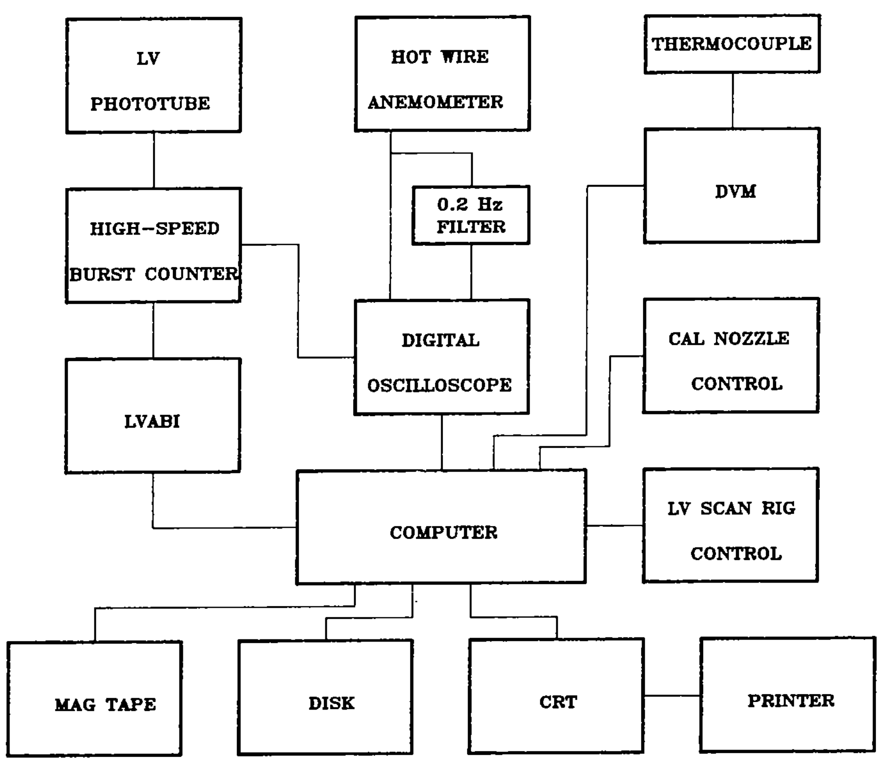
The output signals from the photomultiplier were processed by a high-speed burst counter which contained a double threshold triggering circuit and a 5/8 count comparison error detection circuit set to 2 percent. The digital output from the counter was input to a high-speed buffer memory, references 3 and 4, which will accept up to 4096 velocity measurements, and the associated measured interarrival times. The data contained within this buffer system was then transferred to a 16-bit minicomputer for data processing and analysis.



LV/HOT WIRE ELECTRONICS

A single component constant temperature hot wire was placed 2 mm downstream of the LV sample volume with its longitudinal axis oriented parallel with the LV sample volume. The wire was Pt-10Rh with a length of 0.8 mm and a length to diameter ratio of 229. It was soldered onto copper plated, tapered steel prongs extending 13 mm from the 2.4 mm diameter probe body. The anemometer was operated at a resistance ratio, (R_h/R_l), of 1.5. The frequency response was optimized with a square wave input. In order to obtain maximum measurement resolution, the hot wire signal was split into two signals, one unfiltered and the other passing through a 0.2 Hz high pass filter. These signals were then recorded on a digital oscilloscope at a sampling rate of 1.0 kHz. Further, to insure that the hot wire data was obtained during the same time period as the LV data, the oscilloscope was triggered by the first data validation pulse from the LV high-speed burst counter and the seeding rate was adjusted such that both the hot wire and the LV completed the measurement in approximately 2 seconds. The data obtained by the oscilloscope was transferred to the minicomputer for data processing and analysis.

The potential core of a convergent nozzle exit flow was used to calibrate the hot wire over a velocity range from 0 m/s to 30 m/s using the LV as the velocity standard. The calibration was conducted using the digital oscilloscope so that any errors present within the instrumentation would be accounted for. Also, by using the LV as the calibration standard, the effects on the hot wire due to the presence of the seed particles would be removed by the calibration. The resulting calibration data were curve fit using spline functions. During the experiment, the mean voltage from the unfiltered signal was added to the high pass filtered signal to obtain the hot wire output signal with improved measurement resolution. In order to linearize the signal, the resulting voltage was converted, point-by-point, to velocity via the spline fit calibration curve.

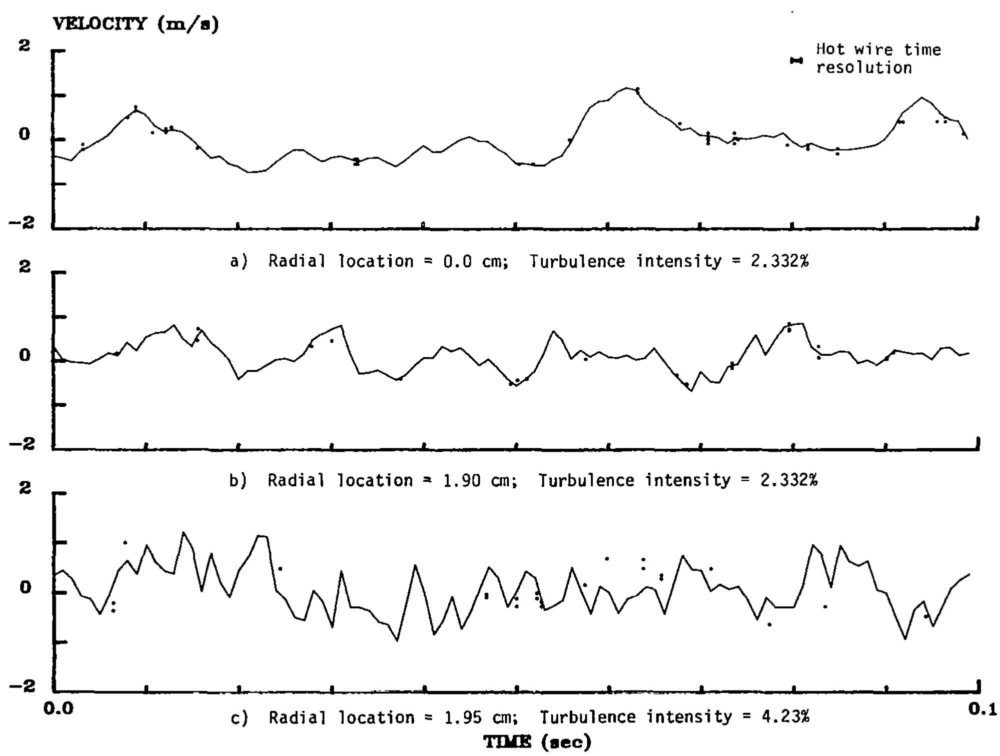


LV/HOT WIRE TIME HISTORY — CAL RIG

In the present study, two free turbulent flows were tested: the exit flow from the convergent nozzle (calibration facility), and the exit flow from a fully developed turbulent pipe. The convergent nozzle was fan driven with velocity controllable over a range of 0 m/s to 30 m/s by a gate valve located at the fan exit. The nozzle settling chamber contained a honeycomb and screens with an 8:1 convergent, 4.0-cm diameter output nozzle.

The seeding particles used by the laser velocimeter were 0.35 - 0.55 micrometer polystyrene particles suspended in a water-alcohol solution. This solution was atomized using an air jet atomizer whose output was directed into the fan inlet of the convergent nozzle and into the settling chamber of the pipe. The water and alcohol evaporated leaving the particles to follow the air flow. Since the resulting signals from the LV were nominally the same voltage level, it was concluded that agglomeration was not a problem.

The effect of the seeded flow on the hot wire response was first examined by comparing the instantaneous hot wire and LV output. This was done by comparing the hot wire output obtained with the digital oscilloscope with the measured particle velocities from the LV. The hot wire (continuous trace) and the laser velocimeter (each dot is a single particle velocity) velocity time histories in the convergent nozzle jet flow are shown in the figure. Since the LV sample volume and the hot wire were axially displaced by 2 mm and since the LV yields instantaneous point measurements within the sample volume whereas the hot wire yields instantaneous spatial averages over the length of the wire, it would not be expected that the two signal traces would be identical. Referring, however, to the figure, it is seen that the two signals follow each other well and there is no evident erratic hot wire response due to particle impingement.



a) Radial location = 0.0 cm; Turbulence intensity = 2.332%

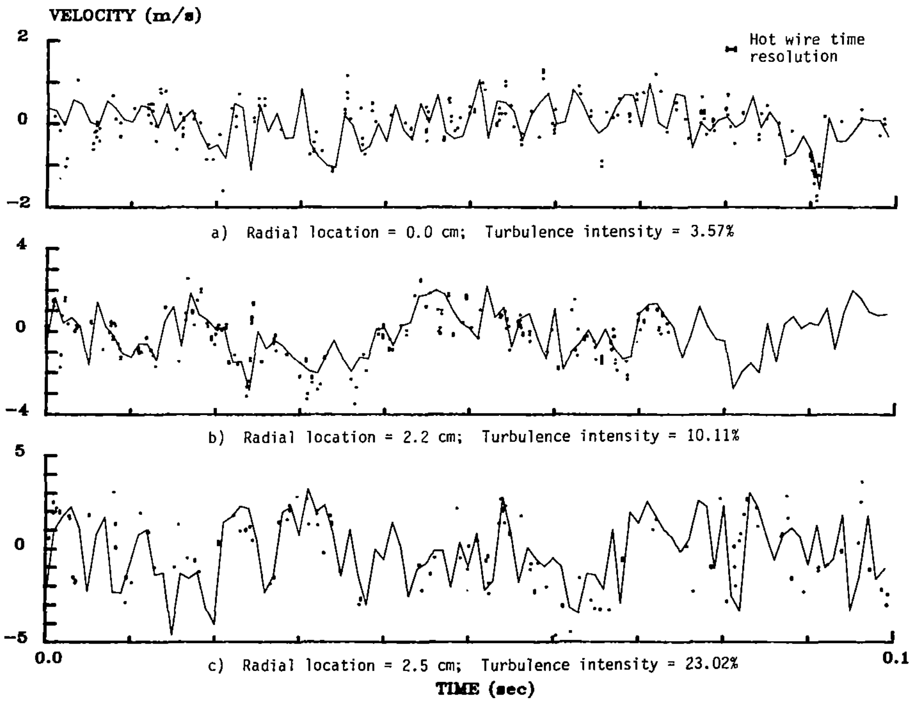
b) Radial location = 1.90 cm; Turbulence intensity = 2.332%

c) Radial location = 1.95 cm; Turbulence intensity = 4.23%

LV/HOT WIRE TIME HISTORY — PIPE

The pipe flow was driven from nominal 80 psi shop air via an adjustable regulator and a 1.25 cm diameter tube. The air from this tube expanded into a 1.35 m long, 5.0 cm diameter pipe which expanded again into a 38 cm long, 15.0 cm diameter settling chamber which contained a honeycomb and screens. The flow then contracted back into a 5.0 cm diameter pipe and exited into the atmosphere 6.60 m downstream. The pipe flow temperature was within 2 degrees Fahrenheit of the calibration facility temperature. Typical velocity time histories from the hot wire (continuous trace) and the laser velocimeter (each dot is a single particle velocity) obtained in the exit flow from the fully developed turbulent pipe are shown in the figure. Any significant deviation between the two measurements is due to the relatively low time resolution of 0.001 second of the hot wire due to the sample rate of the oscilloscope whereas the LV time resolution is one microsecond.

To examine the effect of the combined particle/water-alcohol mixture on hot wire response, the hot wire output was recorded with the air flow on, with and without the particle mixture in both the calibration facility and the pipe. In both cases the mass flow addition due to the seeding mixture was less than 1-percent of the total mass flow. In the calibration facility, switching the mixture on and off had no effect on the mean hot wire output. In the pipe, however, an apparent 3-percent increase in the mean output was noted, although no change was noted in the measure of turbulence intensity. This discrepancy is due to the fact that the calibration facility recirculated the surrounding particle-laden air. In the pipe, however, the source air was particle free and originated from a source away from the experiment. Two conclusions can be drawn from these results: first, while the seeded flow does not appear to influence the dynamic response of the hot wire, the overall level of the signal is influenced by a slight amount due to the slightly altered thermal properties of the seeded flow; and secondly, when the calibration and subsequent measurements were both carried out in the seeded flow, the level shift is effectively cancelled out.



a) Radial location = 0.0 cm; Turbulence intensity = 3.57%

b) Radial location = 2.2 cm; Turbulence intensity = 10.11%

c) Radial location = 2.5 cm; Turbulence intensity = 23.02%

VELOCITY MEASUREMENTS FOR AXIAL SCAN OF CAL RIG

The mean velocity measurements from the laser velocimeter for an axial scan along the 75-percent radial line in the calibration facility are shown in the top figure. The results indicate a smooth decay of the mean velocity as the axial distance is increased. This data was then corrected for velocity bias, reference 5, using the following equation:

$$\overline{U}_b = \frac{\Sigma A_i U_i}{\Sigma A_i} \qquad \text{where } A_i = \frac{1}{U_i}$$

and compared with the uncorrected data, i.e., $C_m = \dfrac{\overline{U}_b - \overline{U}}{\overline{U}}$

The results of this comparison are shown in the lower figure. Since the times between velocity measurements were measured, a time average of the laser velocimeter data could be made:

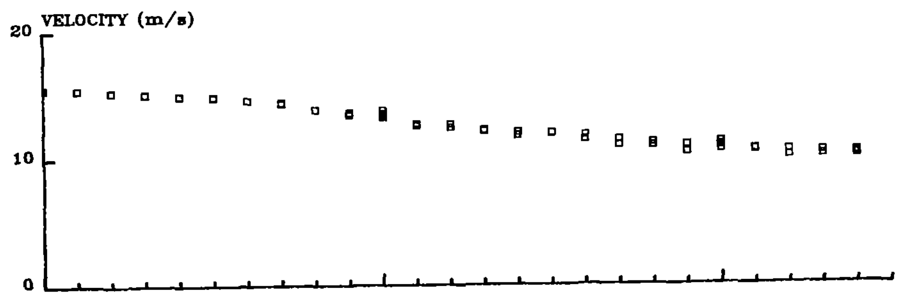
$$\overline{U}_t = \frac{\Sigma B_i \Delta t_i}{\Sigma \Delta t_i} \qquad \text{where } B_i = \frac{(U_i + U_{i-1})}{2}$$

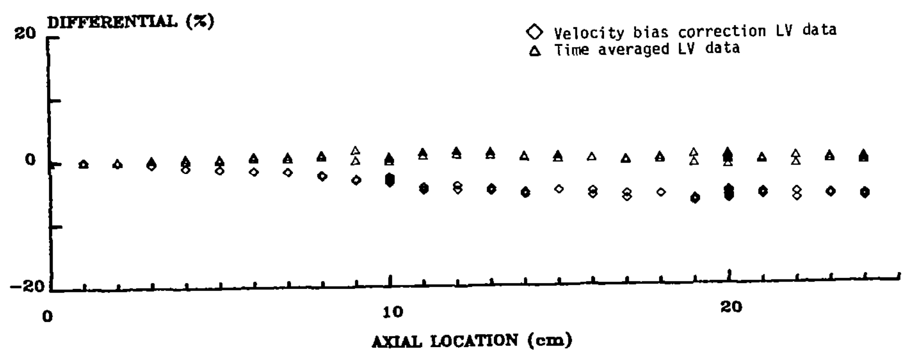
Δt_i = time between the ith velocity measurement and the i-1th velocity measurement.

A comparison of these results with the uncorrected data, i.e.,

$$C_m = \frac{\overline{U}_t - \overline{U}}{\overline{U}}$$

is shown in the lower figure.



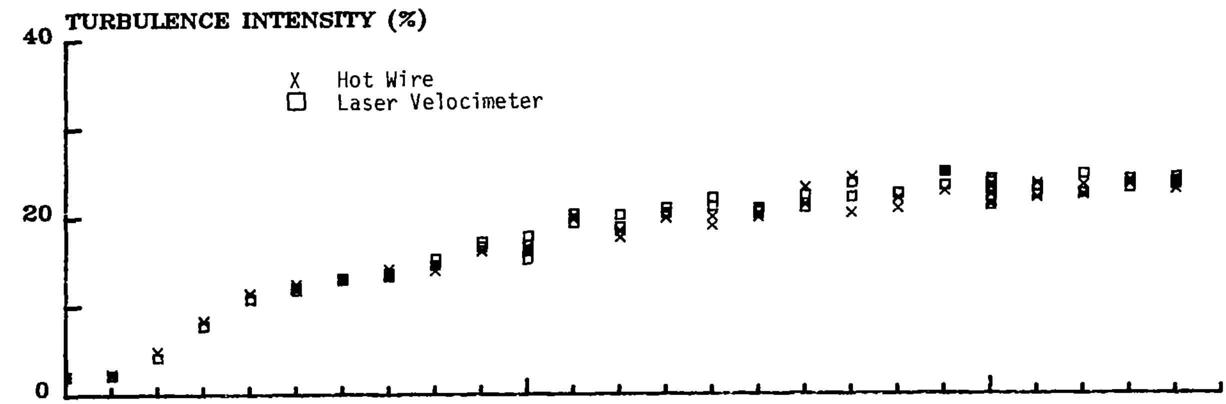


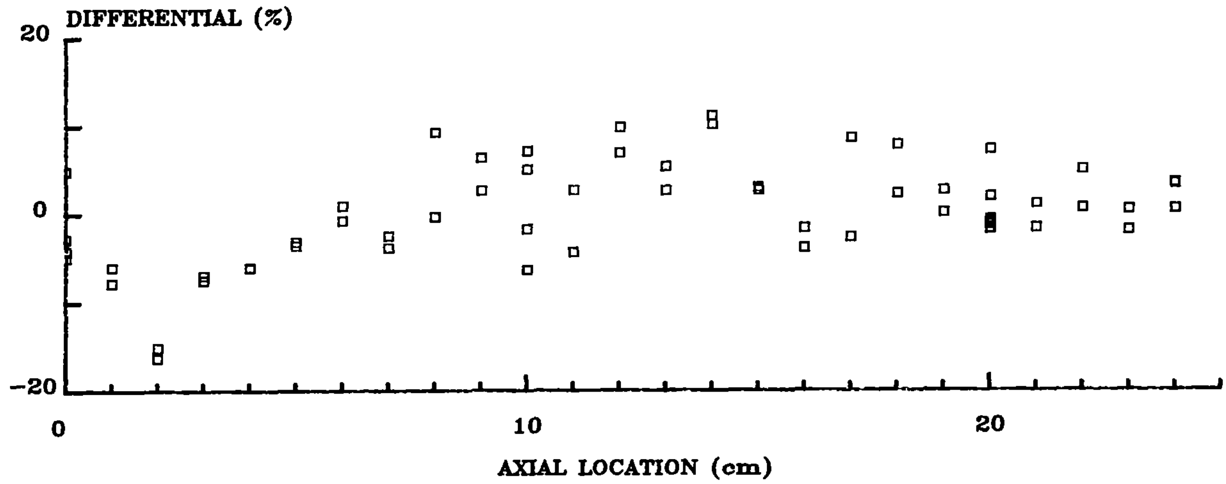
TURBULENCE INTENSITY FOR AXIAL SCAN OF CAL RIG — COMPARISON OF HOT WIRE/LV DATA

The turbulence intensity measurements from the hot wire and the laser velocimeter for an axial scan along the 75-percent radial line in the calibration facility are shown in the top figure. The results show a turbulence intensity of about 2 percent within the potential core, which begins to break down between 1 and 2 cm downstream. A large turbulence intensity gradient exists until approximately 5 cm downstream where the mixing region is entered. Due to the large gradient in turbulence intensity, the axial spacing of 2 mm between the hot wire and the laser velocimeter will cause the measurements from the laser velocimeter to be lower than the measurements from the hot wire since the hot wire is further downstream. With the exception of the data obtained in the large turbulence intensity gradient region, the comparison of the data from the hot wire with the data from the laser velocimeter, i.e.,

$$C_{ti} = \frac{TI_{lv} - TI_{hw}}{TI_{hw}}$$

yields a bias of 1.7 percent with the laser velocimeter measuring high with a standard deviation of 4.3 percent (lower figure).





TURBULENCE INTENSITY FOR AXIAL SCAN OF CAL RIG — COMPARISON OF HOT WIRE/BIAS CORRECTED LV DATA

The turbulence intensity measurements from the hot wire and velocity bias corrected laser velocimeter data for an axial scan along the 75-percent radial line in the calibration facility are shown in the top figure. The velocity bias correction was made to the data by computing the standard deviation with the following equation:

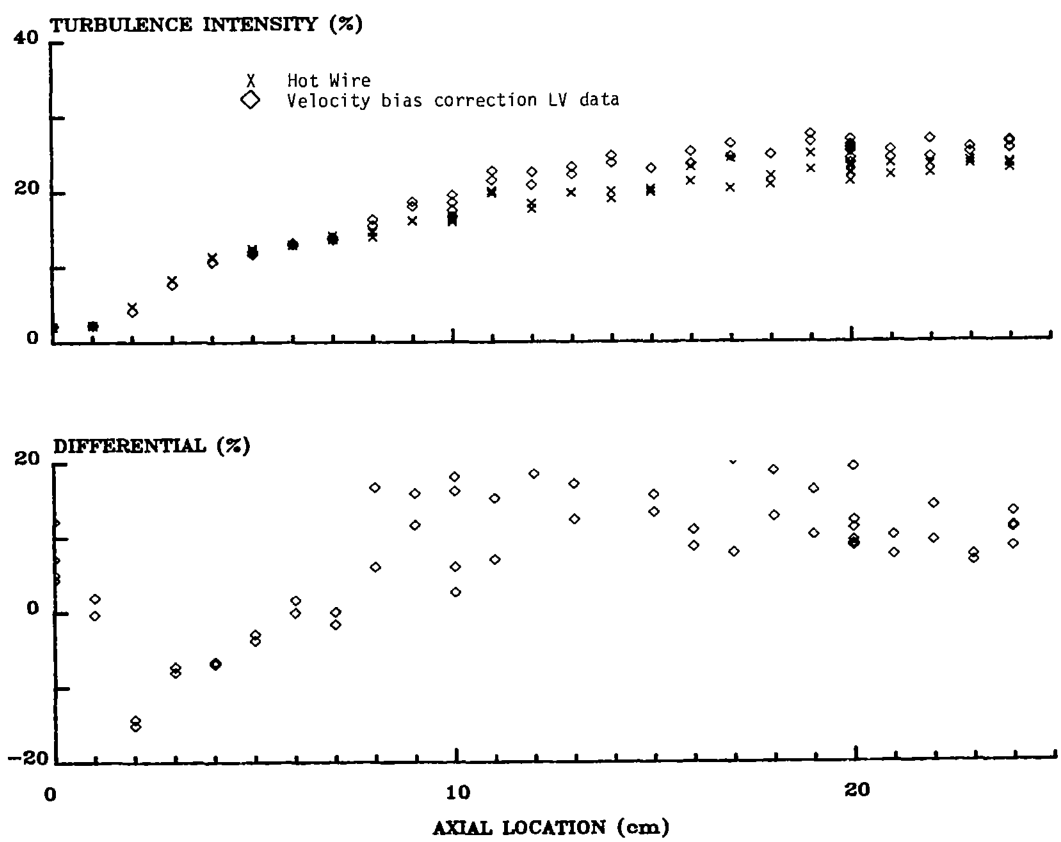
$$\sigma_b = \sqrt{\frac{\Sigma A_i (U_i - \overline{U}_b)^2}{\Sigma A_i}}$$

where $A_i = \frac{1}{U_i}$ and $\overline{U}_b$ = velocity bias corrected mean

and dividing the result by the velocity bias corrected mean to obtain turbulence intensity. With the exception of the data obtained in the large turbulence intensity gradient region, discussed previously, the comparison of the data from the hot wire with the velocity bias corrected data from the laser velocimeter, i.e.,

$$C_{ti,b} = \frac{TI_{lv,b} - TI_{hw}}{TI_{hw}}$$

yields a bias of 11.1 percent with the laser velocimeter measuring high with a standard deviation of 6.7 percent (lower figure).



TURBULENCE INTENSITY FOR AXIAL SCAN OF CAL RIG — COMPARISON OF HOT WIRE/TIME AVERAGED LV DATA

The turbulence intensity measurements from the hot wire and time averaged laser velocimeter data for an axial scan along the 75-percent radial line in the calibration facility are shown in the top figure. The time average was made to the data by computing the standard deviation with the following equation:

$$\sigma_t = \sqrt{\frac{\Sigma\ (B_i - \overline{U}_t)^2\ \Delta t_i}{\Sigma\ \Delta t_i}}$$

where $B_i = \frac{(U_i - U_{i-1})}{2}$

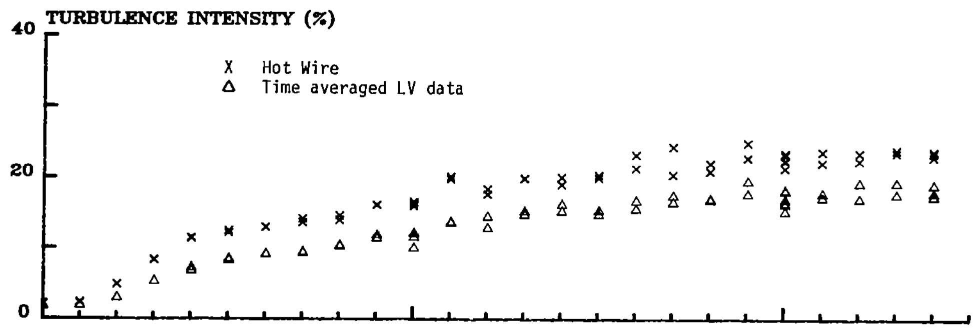
$\overline{U}_t$ = time averaged mean velocity

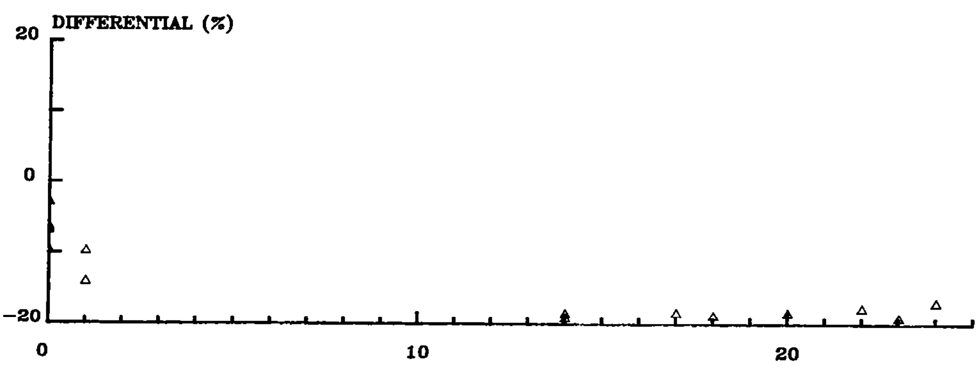
Δt_i = time between the ith measurement and the i-1th measurement

and dividing the result by the time averaged mean velocity to obtain turbulence intensity. With the exception of the data obtained in the large turbulence intensity gradient region, discussed previously, the comparison of the data from the hot wire with the time averaged data from the laser velocimeter, i.e.,

$$C_{ti,t} = \frac{TI_{lv,t} - TI_{hw}}{TI_{hw}}$$

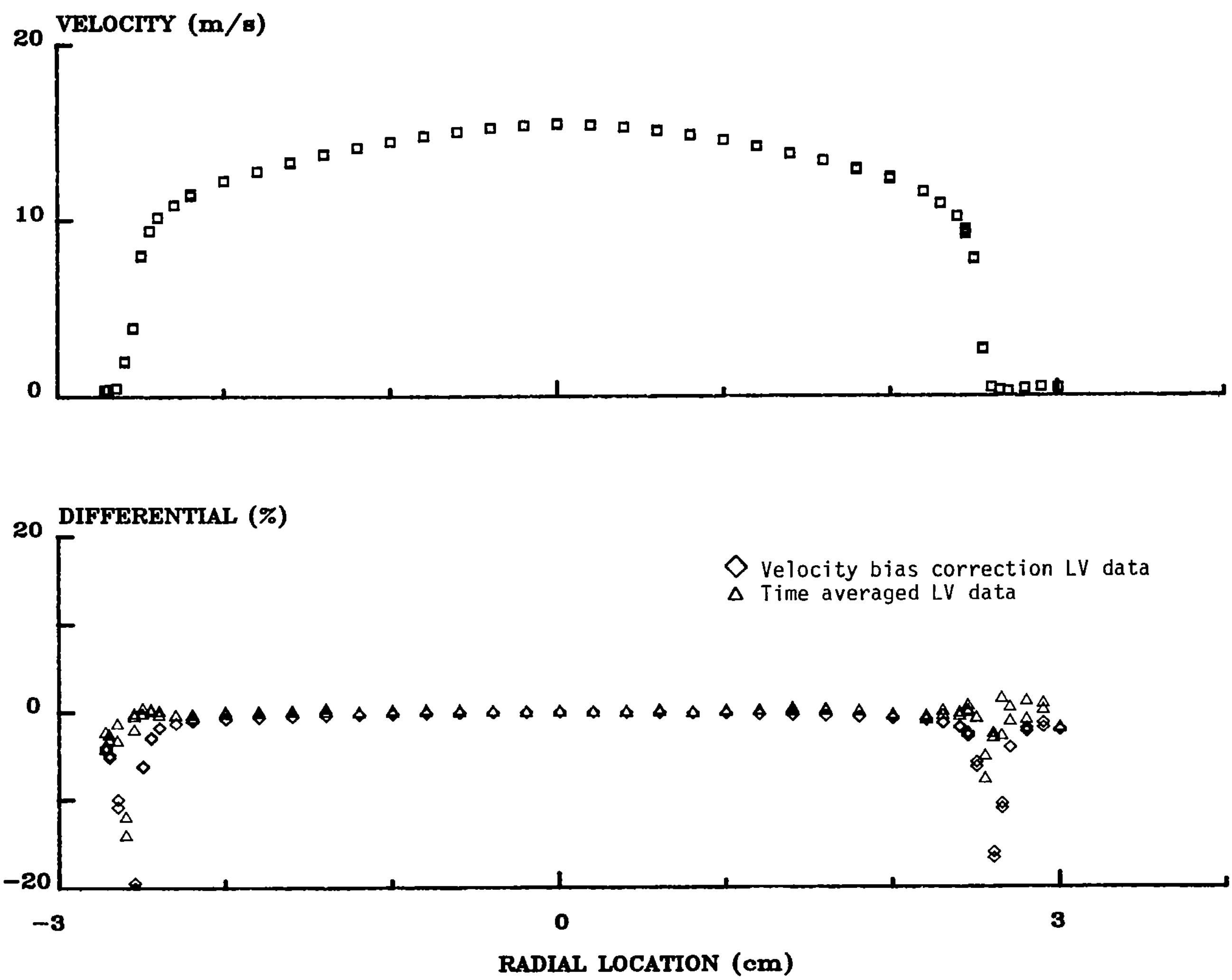
yields a bias error of 25.0 percent with the laser velocimeter measuring low with a standard deviation of 4.5 percent (lower figure).





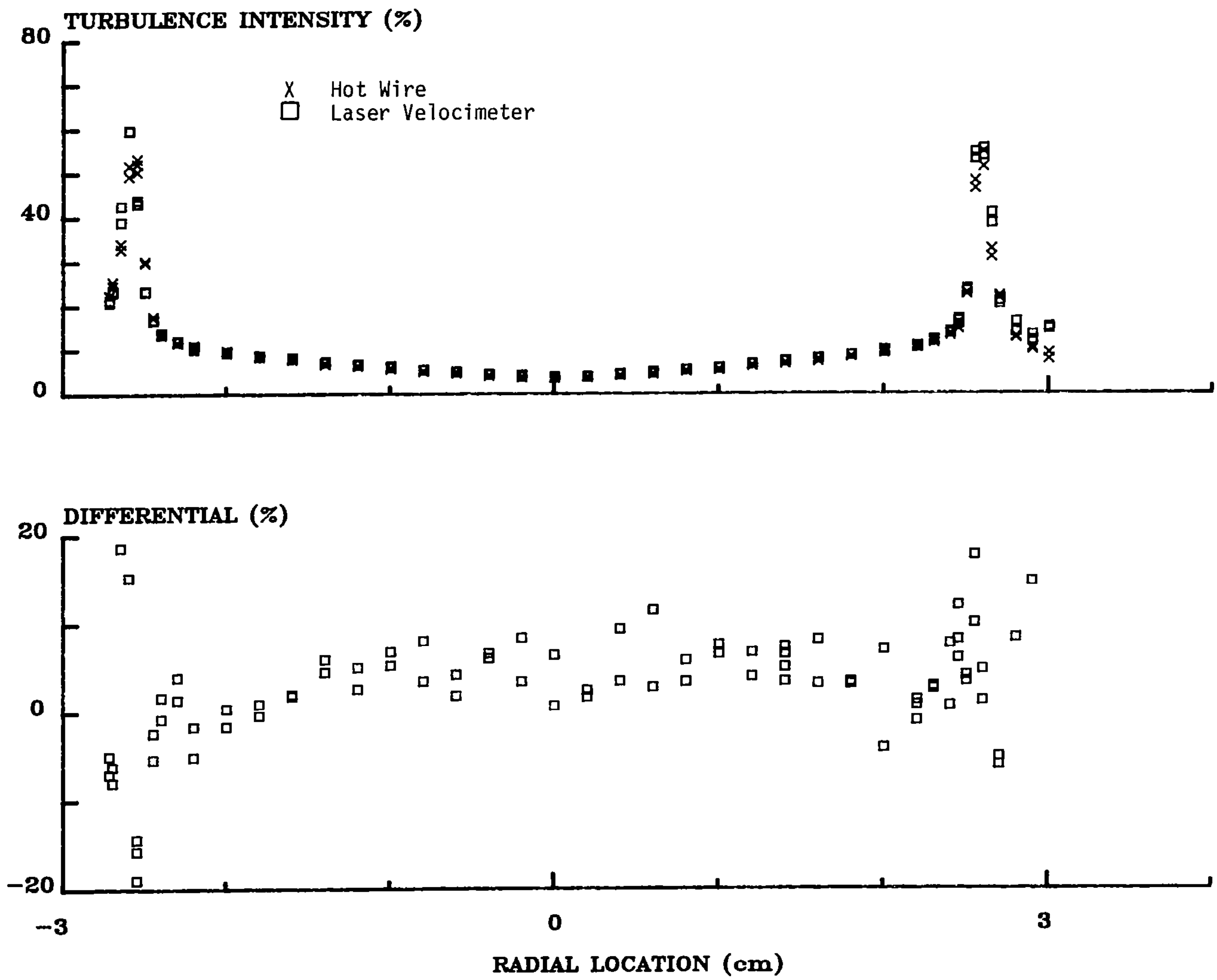
VELOCITY MEASUREMENTS FOR RADIAL SCAN OF PIPE (EXIT)

The mean velocity measurements from the laser velocimeter for a radial scan at the exit of the fully developed turbulent pipe are shown in the top figure. Velocity bias corrected data and time averaged data are compared to the uncorrected data in the lower figure.



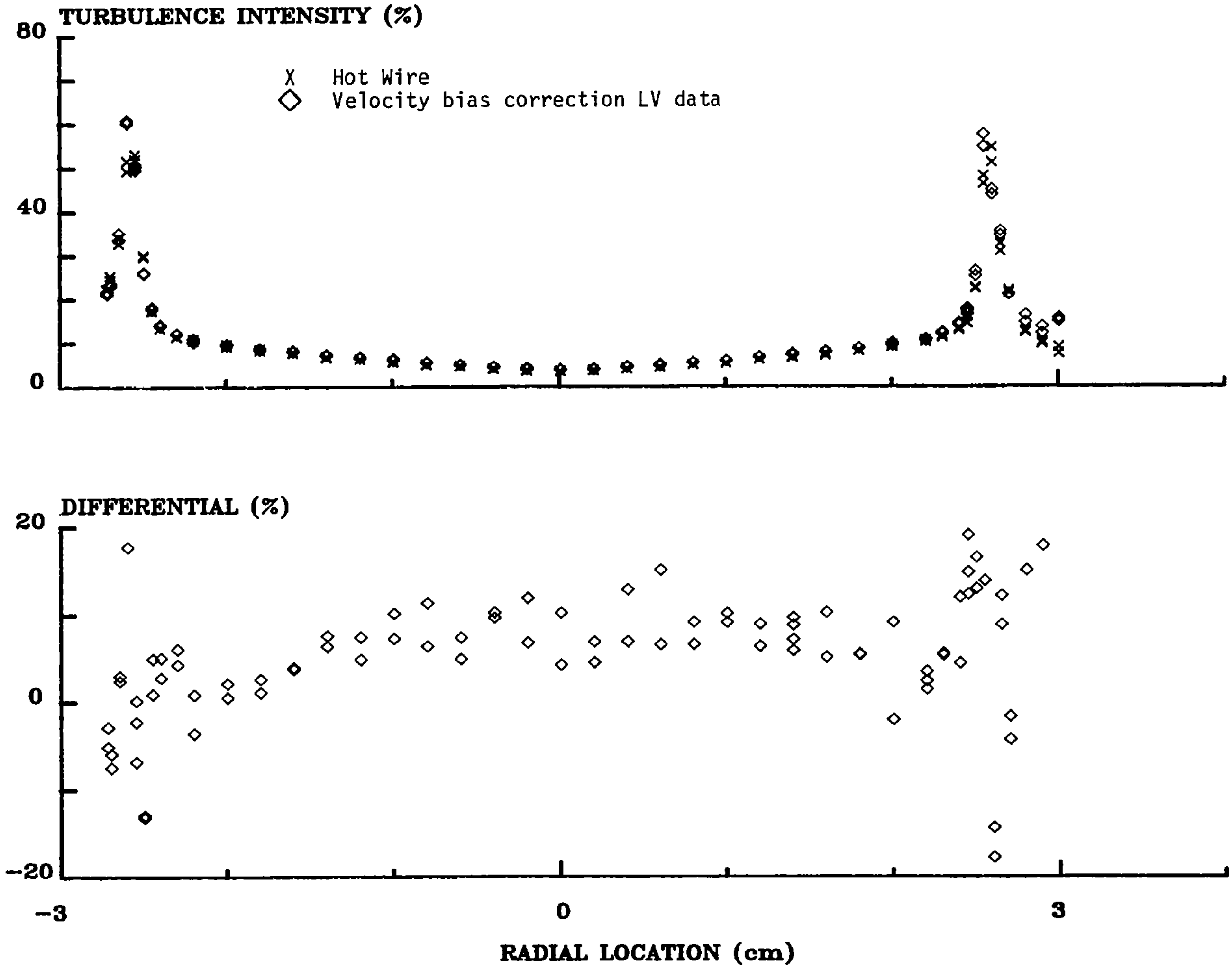
TURBULENCE INTENSITY FOR RADIAL SCAN OF PIPE (EXIT) — COMPARISON OF HOT WIRE/LV DATA

The turbulence intensity measurements from the hot wire and the laser velocimeter for a radial scan at the exit of the fully developed turbulent pipe are shown in the top figure. With the exception of the data obtained in the free shear region (radial locations greater than 2.5 cm), the comparison of the data from the hot wire with the data from the laser velocimeter (lower figure) yields a bias of 3.5 percent with the laser velocimeter measuring high and a measurement standard deviation of 3.6 percent. The turbulence intensity measurements within the free shear regions yielded results of up to 75-percent turbulence intensity by both instruments; however their agreement is not as good. This may be accounted for by several reasons: 1) the 2 mm axial spacing between the two probe volumes causing the instruments to measure different parts of the flow; 2) the averaging effect of the hot wire along its length, not present in the LV; 3) the increase in flow angle causing the hot wire approximations of being a one-component measurement device to no longer be accurate; and 4) seeding density gradients along the LV sample volume caused by the entrainment of cleaner ambient air causing the measurements to be inaccurate because of a biased sampling of the flow field.



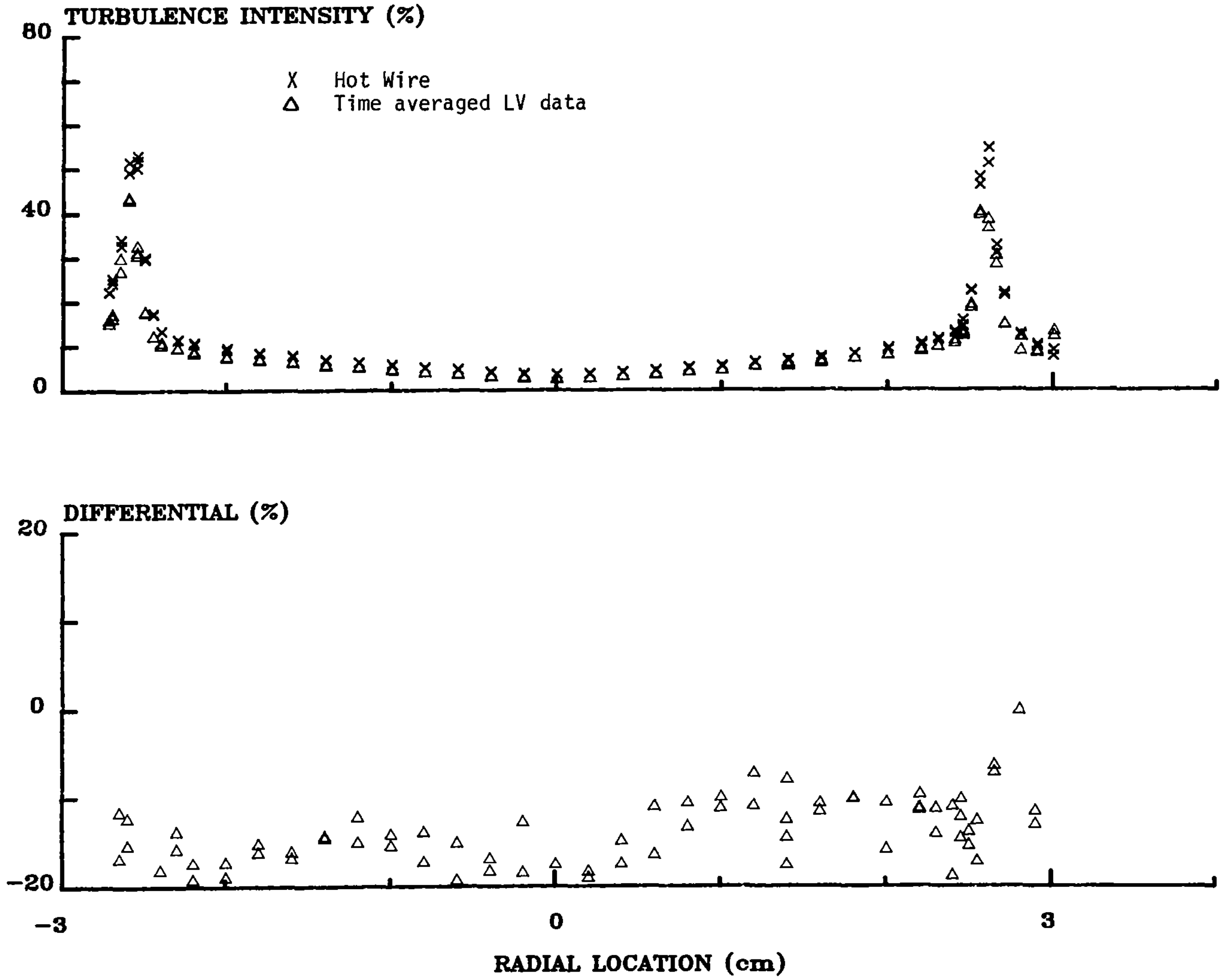
TURBULENCE INTENSITY FOR RADIAL SCAN OF PIPE (EXIT) – COMPARISON OF HOT WIRE/BIAS CORRECTION LV DATA

The turbulence intensity measurements from the hot wire and velocity bias corrected laser velocimeter data for a radial scan at the exit of the fully developed turbulent pipe are shown in the top figure. With the exception of the data obtained in the free shear region (radial locations greater than 2.5 cm), the comparison of the data from the hot wire with the data from the laser velocimeter (lower figure) yields a bias of 6.8 percent with the laser velocimeter measuring high and a measurement standard deviation of 4.3 percent.



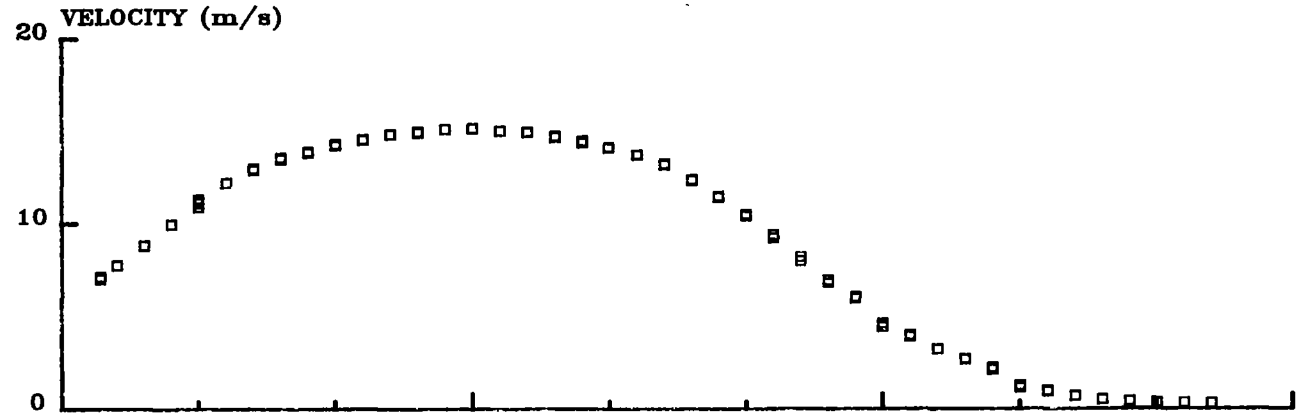
TURBULENCE INTENSITY FOR RADIAL SCAN OF PIPE (EXIT) – COMPARISON OF HOT WIRE/TIME AVERAGED LV DATA

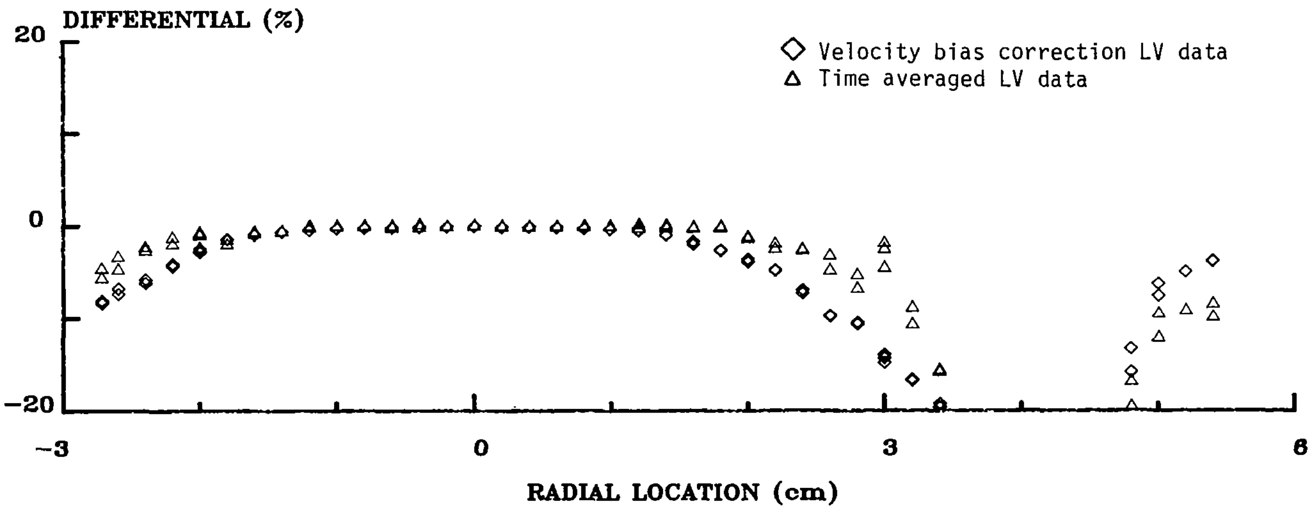
The turbulence intensity measurements from the hot wire and time averaged laser velocimeter data for a radial scan at the exit of the fully developed turbulent pipe are shown in the top figure. With the exception of the data obtained in the free shear region (radial locations greater than 2.5 cm), the comparison of the data from the hot wire with the data from the laser velocimeter (lower figure) yields a bias of 14.8 percent with the laser velocimeter measuring low and a measurement standard deviation of 4.1 percent.



VELOCITY MEASUREMENTS FOR RADIAL SCAN OF PIPE (12 cm)

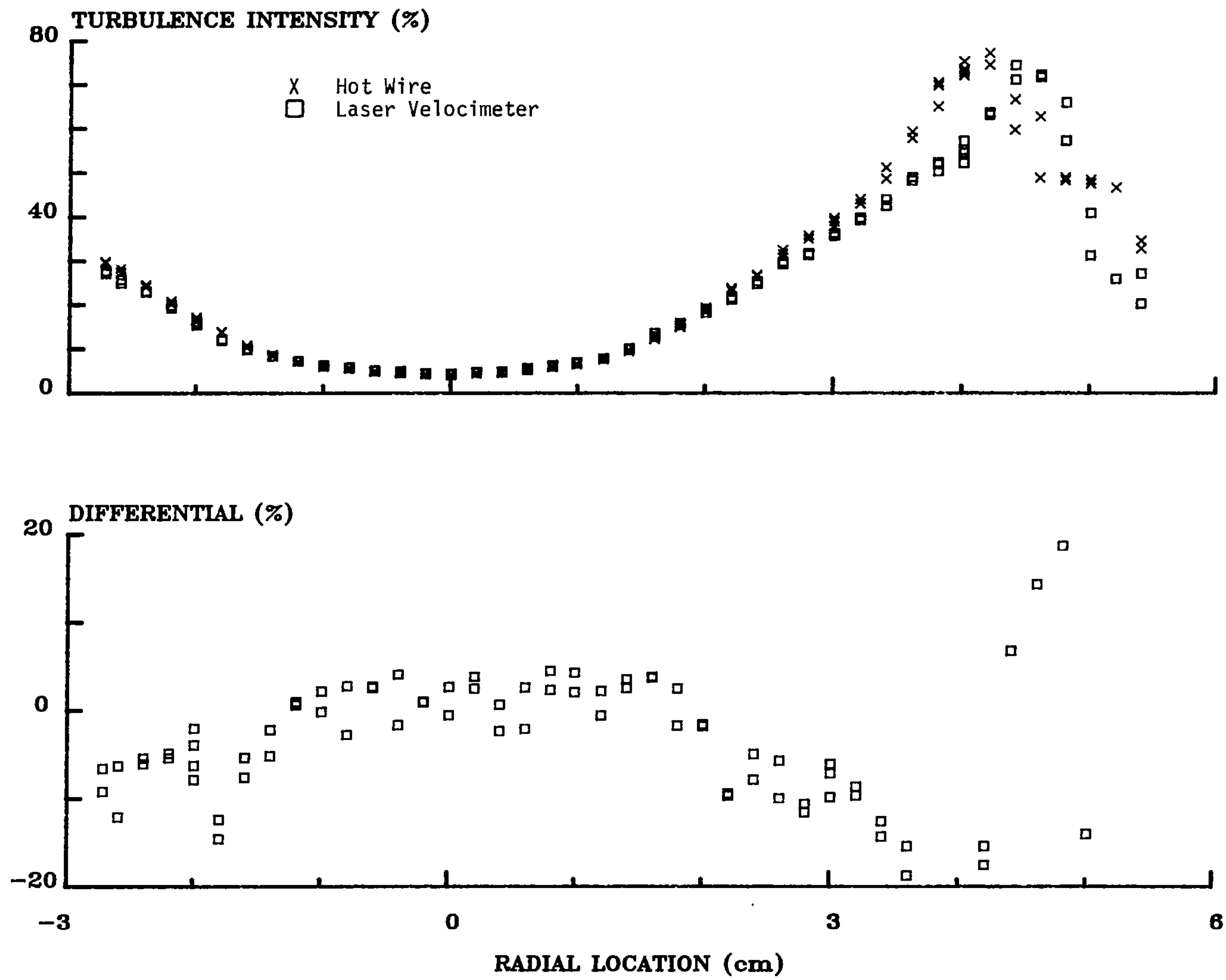
The mean velocity measurements from the laser velocimeter for a radial scan 12.0 cm downstream from the exit of the fully developed turbulent pipe are shown in the top figure. Velocity bias corrected data and time averaged data are compared to the uncorrected data in the lower figure.





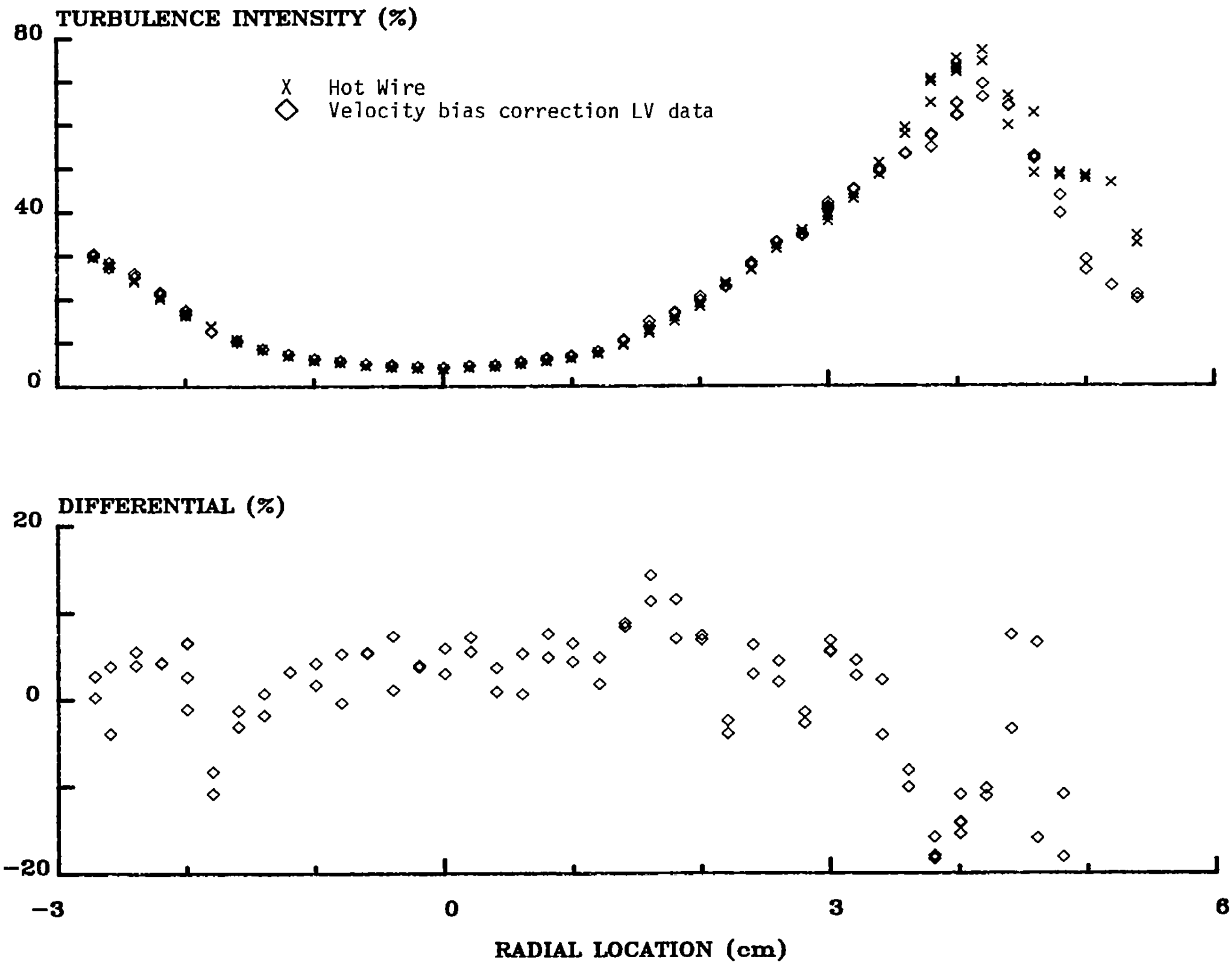
TURBULENCE INTENSITY FOR RADIAL SCAN OF PIPE (12 cm) – COMPARISON OF HOT WIRE/LV DATA

The turbulence intensity measurements from the hot wire and the laser velocimeter for a radial scan 12.0 cm downstream from the exit of the fully developed turbulent pipe are shown in the top figure. With the exception of the data obtained in the free shear region (radial locations greater than 2.0 cm), the comparison of the data from the hot wire with the data from the laser velocimeter (lower figure) yields a bias of 0.6 percent with the laser velocimeter measuring low and a measurement standard deviation of 4.3 percent. As the free shear region is entered, the turbulence intensity from the laser velocimeter rises at a much lower rate than the hot wire, due probably to the entrainment of clean ambient air. However, when the flow field is derived from the entrained air to a greater degree (radial locations greater than 4.0 cm), the comparisons with the hot wire become better since the bias due to seeding effects becomes weaker.



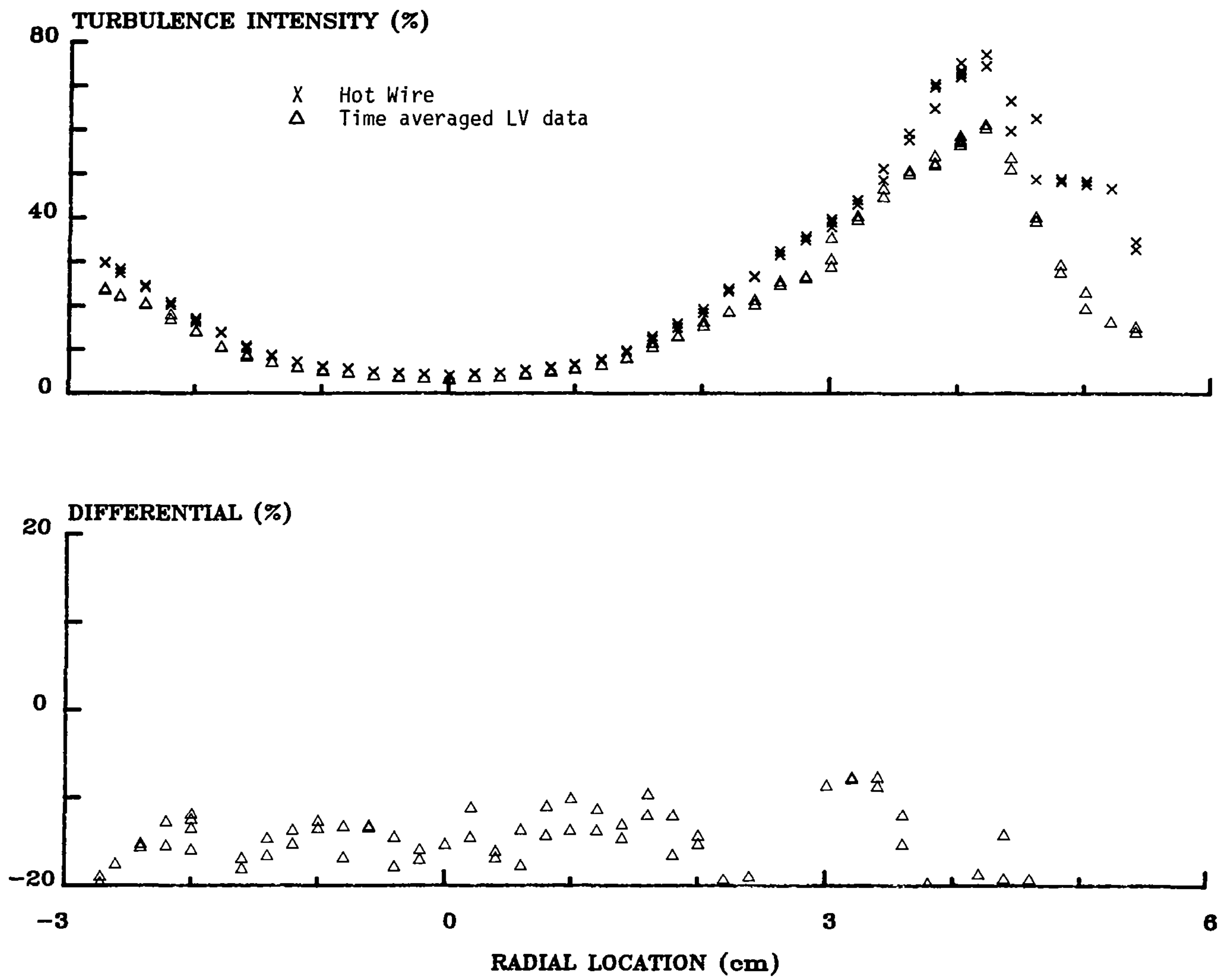
TURBULENCE INTENSITY FOR RADIAL SCAN OF PIPE (12 cm) – COMPARISON OF HOT WIRE/BIAS CORRECTION LV DATA

The turbulence intensity measurements from the hot wire and velocity bias corrected laser velocimeter data for a radial scan 12.0 cm downstream from the exit of the fully developed turbulent pipe are shown in the top figure. With the exception of the data obtained in the free shear region (radial locations greater than 2.0 cm), the comparison of the data from the hot wire with the data from the laser velocimeter (lower figure) yields a bias of 3.8 percent with the laser velocimeter measuring high and a measurement standard deviation of 4.7 percent. As the free shear region is entered, the velocity bias corrected data tracks the hot wire results better than the uncorrected data in the previous figure. Although the differences between the hot wire results and the corrected laser velocimeter data are large at radial locations greater than 4.0 cm, the overall turbulence intensity profile through the free shear region is much smoother than the uncorrected data or the hot wire data.



TURBULENCE INTENSITY FOR RADIAL SCAN OF PIPE (12 cm) – COMPARISON OF HOT WIRE/TIME AVERAGED LV DATA

The turbulence intensity measurements from the hot wire and time averaged laser velocimeter data for a radial scan 12.0 cm downstream from the exit of the fully developed turbulent pipe are shown in the top figure. With the exception of the data obtained in the free shear region (radial locations greater than 2.0 cm), the comparison of the data from the hot wire with the data from the laser velocimeter (lower figure) yields a bias of 14.7 percent with the laser velocimeter measuring low and a measurement standard deviation of 2.8 percent. The time averaged profile through the free shear region seems to have the lower slope of the uncorrected data but with the smoothness of the velocity bias corrected data.



RESULTS

A comparative study was conducted between a laser velocimeter and a single component hot wire in two free jet flows to determine if the LV could be used reliably to measure flow turbulence intensity. Great care was taken to reduce the known measurement uncertainties in both instruments. The possible measurement uncertainties in the hot wire were reduced by direct digitization of the hot wire signal and point-by-point conversion of the voltage to velocity, frequent calibrations of the hot wire, low velocity flows chosen to maintain isothermal conditions, and the determination of the effects of seeded flows. The possible errors in the laser velocimeter were reduced by using very small particles as the seed material, forward-scatter system to increase the output signal-to-noise, and off-axis receiver location to decrease the length of the sample volume.

The results of this study show good agreement between the hot wire turbulence intensity measurements and the measurements made with the laser velocimeter, thus indicating that indeed the laser velocimeter may be used to obtain reliable turbulence intensity measurements. An unexpected result of this study was that the velocity bias correction, which has been the accepted standard for several years, was found to be very questionable for turbulence intensity measurements.

BASE LEVEL OF CONFIDENCE ESTABLISHED IN LV MEASUREMENT OF TURBULENCE INTENSITY

TURBULENCE INTENSITY MEASUREMENTS FROM 1% TO OVER 75%

VELOCITY BIAS CORRECTION QUESTIONABLE

TIME AVERAGE DATA IS UNACCEPTABLE

REFERENCES

1. Yanta, W.J.; and Smith, K.A.: Measurements of Turbulence - Transport Properties with a Laser Doppler Velocimeter. AIAA 11th Aerospace Sciences Meeting, Washington, DC, January 10-12, 1973.

2. Lau, J.C.; Whiffen, M.C.; Fisher, M.J.; and Smith, D.M.: A Note on Turbulence Measurements with a Laser Velocimeter. J. Fluid Mech., vol. 102, pp. 353-366, 1981.

3. Meyers, J.F.; and Clemmons, J.I., Jr.: Processing Laser Velocimeter High-Speed Burst Counter Data. Third International Workshop on Laser Velocimetry, Purdue University, July, 1978.

4. Clemmons, J.I., Jr.: Laser Velocimeter (Autocovariance) Buffer Interface. NASA Technical Memorandum 83110, May, 1981.

5. Tiederman, W.G.; McLaughlin, D.K.; and Reischman, M.M.: Individual Realization Laser Doppler Technique Applied to Turbulent Channel Flow. Proceedings of Symposium on Turbulence in Liquids, Rolla, MO, 1973.